Stratigraphic Models For Deep-Water Sedimentary Systems

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Abstract

Stratigraphic models predict sedimentary architecture. Prediction requires understanding systems across a sufficient range of scales. To be predictive a model must address the interaction of multiple process-response relationships. For deep-water systems these processes include (1) subaqueous flow initiation and transformation, (2) linkages between channel, levee and lobe processes, and (3) shelf-to-basin profile evolution. Thickness, lithology and the geomorphic hierarchy of sedimentary bodies are responses that can be used to define phases in deep-water episodes recording both external (allogenic) and internal (autogenic) controls.

Shelf-to-basin studies of the Middle Permian Brushy Canyon Formation demonstrate that the more complete basinal record correlates to an incomplete shelf record; this incongruity impacts recognition of allogenic forcing. Preserving the signature of external controls, internal changes in local gradient and topography also impact the deep-water record requiring complete basin analysis. Independent but nested autogenic and allogenic stratigraphic models address these challenges and predict patterns of deep-water sedimentation.

Tectonics and climate modulate sediment supply and sea level, which are considered the principal allogenic controls on deep-water sedimentation as described by the phases of the AIGR (*Adjustment-Initiation-Growth-Retreat*) model. The complete AIGR cycle commences with the *Adjustment* (A) phase, which defines the initial profile gradient and topography. The *Initiation* (I), *Growth* (G), and *Retreat* (R) phases describe variations in sedimentary response.

Autogenic controls on deep-water sedimentation include (1) lateral offset and compensational stacking of lobes, (2) channel migration, switching and avulsion, and (3) longitudinal translation of the channel-lobe transition zone. The BCFS (*Build-Cut-Fill-Spill*) model describes autogenic controls on local gradient and confinement based on a hierarchy of channel-fill, channel-flank, and lobe sedimentary bodies, which vary in proportion and arrangement in each phase.

The sedimentation phases of the AIGR and BCFS models describe the systematic increase and decrease in sedimentation energy recorded in hierarchical stratigraphy. When linked to gradient, the models form the axes of a *sedimentary system energy matrix* (SSEM) for sedimentary architecture. The BCFS model for submarine channels is embedded within the AIGR basin model and, together they facilitate the correlation of a hierarchy of internally and externally generated stratigraphic cycles.

Introduction

Correlation of deep-water strata is a recent endeavor. This is because ocean basins were considered barren until the 1929 Grand Banks earthquake and slide, which showed that large volumes of sediment are transported to basins during very short-duration subaqueous flow events (Kuenen, 1952; Heezen and Ewing, 1952; Heezen and Drake, 1964; Piper *et al*., 1988). One of the principal agents of deposition, a turbidity current, was not described until the 1950's (Kuenen and Migliorini, 1952) and was not related to a repeatable facies succession until the 1960's (Bouma, 1962). The term submarine fan was first used in 1960 (e.g., Tarzana Fan; Sullwold, 1960).

Stratigraphic studies have followed a similar path. The first deep-water sedimentation models, published by Exxon geoscientists (Vail *et al*., 1977; Mitchum, 1985; Vail, 1987; Jervey, 1988) emphasize external (allogenic) controls operating primarily on the shelf and in point-sourced submarine canyons, presumably because reservoir grade sediment is largely derived from this setting. The sequence stratigraphic model correlates deep-water deposition to unconformities developed on the shelf and responsible for canyon incision during lowstands of sea level (Shanmugam and Moiola, 1982; Vail, 1987).

The genetic elements of the lowstand systems tract are derived from the conceptual model of Mutti (1985) (Thorne, 1992). Mutti's model for submarine fan deposition emphasizes how events on the shelf affect the composition, volume and efficiency of subaqueous flows through three stages of basin fill (Mutti, 1985; Mutti, 1992). In the lowstand systems tract, these stages correspond to the: (1) basin-floor/lowstand fan, (2) slope fan, and (3) prograding/lowstand wedge. This model is effective at describing patterns of basin fill at the scale of third- and fourth-order depositional and composite sequences, recording sedimentation patterns of 3.0 to 0.1 m.y. in duration and roughly corresponding to 500- to 20-meter thick stratal successions (Mitchum and Van Wagoner, 1991; Van Wagoner, 1995; Van Wagoner *et al*., 1998). Implicit in this model is the assumption that deep-water strata can be correlated to external controls.

More recently, Shell geoscientists working the central Gulf of Mexico formulated the "fill-and-spill" model (Prather *et al*., 1998; Booth and Dean; 2003). This model emphasizes the relationship between an imaginary equilibrium profile measured from the shelf/slope break to the basin floor and sea floor relief generated by deformation along this longitudinal profile (Ross *et al*., 1994). The difference between the slope equilibrium profile and the local sea floor topography separates above-grade ponded and healed slope accommodation from below-grade slope accommodation, which correlates to specific patterns of slope sedimentation. This model is more limited in its context because it attempts to explain local sediment filling and spilling across the evolving seafloor topography of salt withdrawal basins on the slope.

The predictive stratigraphic models presented in this paper build on these models by relating external (allogenic) and internal (autogenic) controls to high-resolution changes in deep-water architecture. Both models are based on studies of Permian deep-water strata in the Delaware Basin of West Texas and New Mexico and assume that (1) lithology, (2) thickness, (3) sedimentary body type, and (4) grain size, when placed within a hierarchy of stratigraphic cycles can be correlated to deep-water system energy.

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The AIGR (pronounced "Eiger" after the Swiss Mountain) and BCFS (see Gardner and Borer, 2000 and Gardner *et al*., 2003 for review) models describe the systematic increase and decrease in sedimentation energy recorded in the stratigraphy. Allogenic basin-scale controls modulate deep-water sedimentation as described by the phases of the AIGR (*Adjustment-Initiation-Growth-Retreat*) model. Autogenic channel and channel-related processes are described by the phases of the BCFS (*Build-Cut-Fill-Spill*) model. The nested and overlapping models are compatible and flexible because not all four energy phases defined in each model need to be present for their application. Similarly, the transition between phases does not have to be sharp or represented by a surface-defined boundary.

The AIGR and BCFS stratigraphic models are intended to guide subsurface data interpretation of sedimentary architecture by considering what parameters may be important to consider under a specified set of spatial and temporal conditions. When combined with the longitudinal (shelf – basin) gradient, the models form the temporal axis of a *sedimentary system energy matrix* (SSEM) to frame changes in deep-water architecture at multiple scales. This includes architectural elements and lithofacies distributions at a scale below subsurface data resolution.

The empirical observations that underpin both models are derived from numerous outcrop and subsurface examples including, but not limited to, the Brushy Canyon dataset (Blikeng and Fugelli, 2000; Navarre *et al*., 2002; Stevens, 2004; Delebo, 2005; Hadler-Jacobsen *et al*., 2005; Hadler-Jacobsen *et al*., 2007; Ochoa *et al*., 2007; Chaiwagosaen, 2007; Anderson *et al*., 2008; Lerch *et al*., 2008; Wolak and Gardner, 2008; Ragagnin and Moraes, 2008; Amerman *et al*., in-press, 2008).

The objective of this paper is to disseminate the models more widely to the geologic community. Only through rigorous consideration of the relationship between common system parameters and the repeatable trends and patterns observed in the Brushy Canyon Formation can we determine the global applicability of the models.

Stratigraphy of the Brushy Canyon Formation

The Brushy Canyon Formation is underlain by the Cutoff Formation and overlain by the Cherry Canyon Formation across the Guadalupe and Delaware Mountain outcrop belts (Figs. 1 and 2). The Brushy Canyon Formation and lower part of the Cherry Canyon Formation represent a diachronous deep-water episode (format *sensu* Forgotson, 1957) called the Brushy Canyon Episode (BCE). The reader is referred to the North American stratigraphic code for an explanation of the hierarchy for long- and short-term diachronous units called depositional episodes and phases, respectively; Easton *et al*., 2005, article 91, p. 1584; also see examples in Frazier, (1974) and Galloway, (1989).

Diachronous (diachronic) units represent a nonmaterial category of chronostratigraphic units defined by geologic age in the stratigraphic code (Easton *et al*., 2005; p. 1562). They are intended to complement material stratigraphic units defined by physical limits (*i.e*., surface-bounded units in allostratigraphy, sequence stratigraphy, and genetic stratigraphy). Because episodes and phases are time units, they reside in the only stratigraphic category that can account for surface-to-rock correlations that occur in laterally adjacent depositional environments along a longitudinal profile (*e.g*., genetic increments of strata of Busch, 1971).

Base of the Brushy Canyon Episode

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The lower boundary of the BCE is placed at the base of sandstone or siltstone that overlies a 4 m thick organic-rich siltstone draping underlying carbonate mass transport deposits. The pinch out of sand infilling ~100 meters of topographic relief is associated with a lateral change from sand to silt. The pinch out of deposits from five sixth-order cycles documents the diachronous nature of the lower boundary of the BCE (Fig. 3).

Sequential lateral facies changes associated with the pinch out of multiple deep-water sandstones against sea floor topography, regardless of how it is generated (*e.g*., erosional incision or inherited from a mobile substrate), precludes development of a consistent physical boundary for definition or rock units based on surface or lithologic criteria. Lateral sedimentation generated from compensational stacking and channel avulsion creates inherently diachronous stratigraphy. Significantly, surfaces-based correlation cannot account for lateral facies changes and it under-emphasizes stratigraphic modulation of architecture that occurs within discrete phases of sedimentation. For example, the pinch out of the five sixth-order cycles at the base of the BCE is associated with an upward change from lobeform- to channelform-dominated successions and an associated change from short- to tapered-pinch out geometries (Borer *et al*., 2002).

The lithology change from carbonates to clastics in this example generates a surface easily recognized in low-resolution and sparse subsurface data. This surface forms the lithostratigraphic boundary for these formations (Fig. 4). This surface, however, is not as time-significant as the top of a 4-m thick organic-rich siltstone drape overlying the carbonates and marking the onset of ~nine million years of diachronous deep-water clastic sedimentation.

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Given the limits of subsurface data resolution, the four-meter difference in the position of a time-significant boundary may seem acceptable, the “eighty percent solution”. Resource plays related to the in-situ generation of hydrocarbons within overpressured source rocks make this difference highly relevant. The prediction that organic-rich deposits cap deep-water episodes and organic enrichment reflects stratigraphic order is significant (Sageman et al., 1998; Locklair, 2007). The correlation of the base of sandstone across irregular topography generates a diachronous surface that doesn’t exist and fails to account for changes in reservoir architecture associated with the sequential filling of topography.

Brushy Canyon Dataset

The proposed stratigraphic framework is based on new data from 479 sedimentological profiles (~40 km of strata), most with outcrop scintillometer profiles and ~2200 paleocurrent measurements collected across the continuous shelf to basin exposures of the BCE (Fig. 1). The profile data are tied to ~300 photo-panels collected from the 255-km^2 area of the outcrop belt (Fig. 3). GIS-based mapping of faults, thirty-three 20-30 m thick intervals (sixth-order cycles), and ~400 submarine channels provide pinning points for correlations across multiple cliff faces.

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Twelve separate studies document the geology of the outcrop belt (Johnson, 1998; Kullman, 1999; Carr and Gardner, 2000; Pimley, 2000; Wagerle, 2001; Melick, 2002; Sinex and Gardner, 2004; Borer, 2005; Kling 2006; Hanggoro, 2007; Locklair, 2007; Amerman, in-press, 2008). Small-offset normal faults repeat the same stratigraphy on multiple cliff faces, which facilitated the development of a suite of three dimensional outcrop geological, petrophysical and geophysical models for ~55% of the outcrop (Johnson, 1998; Batzle and Gardner, 2000; Atan *et al.,* 2001; Umam, 2002; Clawson *et al.,* 2003; Borer, 2005; Baker, 2006; and Atan *et al.,* 2007). The transformation of the outcrop into subsurface models generated quantitative three-dimensional paleogeographic reconstructions.

Outcrop to subsurface lithology, facies and sedimentary body calibration and cycle correlation is achieved using three cores taken in the outcrop belt and seven cores from Cabin Lake Field located ~100 km northeast of outcrops along the northwestern basin margin. Johnson (1998) correlates 3D seismic & seven cores at Cabin Lake Field. To establish outcrop to nearby subsurface correlations and map the nine fifth-order cycles, Romans (2003) integrates 65 wells with 3 cores taken in the outcrop (Fig. 5). Baptista (2004) extends this stratigraphic framework in correlations across 2000 km^2 area of the 33,500 km^2 basin area. The 301 wells are tied to 1,675 km grid of reprocessed 2D seismic with roughly 70 m vertical resolution (Hutchings, 2000; Baptitsta, 2004). Most wells contain a full suite of modern logs (*e.g.,* gamma ray, bulk density, sonic, and deep resistivity) and penetrate the Cutoff Formation underlying the Brushy Canyon Formation (Figs. 5 and 6).

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Biostratigraphy and Chronostratigraphy

Despite the lack of higher resolution dates for this deep-water succession, the relative age of the stratigraphic hierarchy is established from the absolute dates for three chronostratigraphic stages in the Middle Permian Guadalupian series (Bowring *et al*., 1998) (Fig. 7). The Guadalupian biostratigraphy is based on the evolution of the conodont *Jinogondolella,* with fusulinaceans and amminoids also changing at stage boundaries (Mei *et al*., 1998; Lambert, 2000).

The Cisuralian–Guadalupian Series and Roadian Stage boundary is placed at the base of the Williams Ranch Member of the upper Cutoff Formation (Lambert, 2000; Amerman *et al*., in-press, 2008). Radiometric U-Pb dates from altered volcanic ash claystones in siltstone drapes, within carbonate mass transport deposits that bracket the Williams Ranch Member of the upper Cutoff Formation and the Brushy Canyon Formation and the lower part of the Cherry Canyon Formation, constrain the Roadian Stage to 2.6 ± 0.7 m.y. (Bowring *et al*., 1998). The Roadian (2.6 m.y.), Wordian (2.2 m.y.) and Capitanian (5.4 m.y.) stages correlate to four third-order deep-water episodes represented by the upper Cutoff Formation and Delaware Mountain Group, spanning a 10.2 ± 0.7 m.y. interval from 270.6 to 260.4 Ma (Glenister *et al*., 1999) (Figs. 2 and 7).

Stratigraphic Cycle Definition

A stratigraphic cycle represents a sequential succession of strata. The nesting of cycles within cycles creates a temporal hierarchy of different order cycles that each defines an episode of sedimentation of similar duration. The third-order deep-water episodes are the highest order cycles that can be temporally defined by biostratigraphic zonation calibrated to absolute dates from volcanic ash beds. Because a hierarchy of stratigraphic cycles is defined by geologic age, the higher order cycles must be estimated from the absolute dates of the lower order cycles. This step aligns the stratigraphic cycles with the chronostratigraphic episodes and phases emphasized in the stratigraphic models.

The third-order BCE records a threefold (fourth- to sixth-order) hierarchy of stratigraphic cycles that extends across the slope and basin profile exposed in outcrop (Fig. 8). The third- through fifth-order cycles can be correlated in the subsurface and across at least seven different shelf sediment sources rimming the basin (Figs. 9 and 10) (Gardner, 1997a; Baptista, 2004).

Higher order cycle durations (*i.e.,* fourth- through sixth-order) are averages estimated by dividing the number of higher order cycles by the duration of the next lower order cycle (Table 1). The two third-order cycles that span the Roadian Stage (~2.6 m.y.) also are estimated using this method. Seven fourth-order cycles (four in the upper Cutoff Formation and three in the Brushy Canyon Formation) compose these two third-order cycles. Simple division yields a ~371 ka age for each fourth-order cycle. Either dividing the Roadian Stage age by the two third-order cycles that compose it, or multiplying the average fourth-order cycle age by the three in the BCE yields a 1.1- 1.3 m.y. age. The two older third-order cycles are shorter in duration than the younger two cycles, which span stages dated at 2.2 m.y. and 5.4 m.y., respectively.

Dividing the four third-order cycles by the second-order cycle duration yields an average age of 2.6 m.y., which under-estimates the older and over-estimates the younger cycle durations. This illustrates the error created by simple chronostratigraphic division, which is assumed to decrease with cycle duration. Nonetheless, it is justified because the higher order cycles are material bodies defined by mapping and section/profile criteria that confidently establish their position within a geospatial hierarchy. To place higher order cycles defined by physical stratigraphy in a temporal hierarchy generally requires estimation of their duration.

Higher-order cycle boundaries are the most variable where sedimentation below wave base generates cyclic successions of strata deposited by subaqueous flow and pelagic and hemipelagic depositional processes. In such cases, cycles are bounded by either similar deposits (*e.g.,* deposition of fine-grained suspension deposits forming a drape and recording fan abandonment) or physical stratigraphic surfaces (*e.g.,* erosional surface overlain by strata recording a significant increase in grain size within a deep-water succession). Facies tracts, defined by the channel-lobe transition zone and/or position on the longitudinal profile, can be offset across cycle boundaries. Also, the expression of a cycle changes across the depositional profile.

Stratigraphic cycles, at all scales, are defined by conspicuous changes in grain size, organic matter and lithology that record both waxing and waning phases of sedimentation. The first occurrence of sand or silt recording the onset of an episode of sedimentation from shelf-derived, subaqueous flows defines cycle bases. Cycle tops consist of fine-grained pelagic and hemipelagic deposits that form extensive drapes and can be correlated for long distances. These drapes show a conspicuous decrease in grain size, organic enrichment and preservation of volcanic ash beds, concentration of fossils and heavy minerals and/or other indicators of prolonged disruptions in shelf-derived, subaqueous flow deposition.

Stratigraphic Hierarchy

Second- to sixth-order stratigraphic cycles compose a fivefold temporal hierarchy recorded by the basin-restricted siliciclastic deposits of the second-order upper Cutoff Formation and Delaware Mountain Group (~10.2 m.y.) (Figs. 2 and 8). The third-order cycles contain higher order cycles defined by carbonate/sandstone bases and organic-rich siltstone tops. Mapping these and other internal siltstone horizons in outcrop permits recognition of a fourfold hierarchy of stratigraphic cycles based on correlation length and organic richness (Figs. 3 and 4). Within the third-order BCE (1.1-1.3 m.y.), three fourth-order cycles (371-433 ka), nine fifth-order cycles (122-124 ka), and 33 sixth-order cycles (25-33 ka) are recognized (Gardner and Borer, 2000; Carr and Gardner, 2000; Gardner *et al*., 2003; Borer, 2005).

Intermediate Third- and Fourth-Order Cycles

Given the lack of independent dates for the third- and fourth-order cycles and their overlapping thickness and areal distributions, these intermediate-scale cycles are the most uncertain in the hierarchy. Prior to the work of Amerman (in-press, 2008), the Williams Ranch Member of the upper Cutoff Formation was considered the lower fourth-order cycle of the third-order BCE. It is now interpreted as a third-order cycle based on the following observations (Fig. 11).

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The Williams Ranch Member represents a carbonate succession that locally contains sandstone at its base and it is capped by the 4 m thick very organic-rich siltstone at the base of the Brushy Canyon Formation. Though it is composed of predominantly carbonate mass transport deposits, there is a surprisingly high degree of organization in the upper Cutoff strata across the 20 km segment studied in outcrop (Amerman, in-press, 2008). Siltstone drapes permit definition of four discrete mass transport events. The four siltstone-bounded, carbonate mass transport deposits (MTDs) are correlated to four, fourth-order carbonate ramp sequences of the lower San Andres Formation (Guadalupe 1-4 (186 m) of

Kerans and Fitchen, 1995). These MTDs have an areal extent of more than 20,000 km^2 and reach a maximum thickness of at least 113 m (Fig. 12; Romans, 2003). Organic-rich siltstones in the upper part of the Cutoff succession resemble the one at its top. The organic richness in its uppermost siltstone is greater than the third-order siltstone that caps the overlying BCE. This uppermost Cutoff siltstone has been considered part of the Brushy Canyon Formation since King (1965) first defined it as the Pipeline Shale Member. However, it is now considered to define the top of the third-order Cutoff deep-water episode (UCE). The thickness of the lower Brushy Canyon fourth-order cycle shows an compensatory relationship with respect to the underlying paleobathymetry established prior to and/or during deposition of the UCE (Johnson, 1998; Carr and Gardner, 2000; Romans, 2003; Baptista, 2004).

Including the Pipeline Shale in the UCE eliminates the need to explain its organic enrichment by an additional sea level cycle or correlate sediment starvation to the onset of an episode of siliciclastic sedimentation. This correlation does potentially reduce the duration of the BCE significantly. The duration of these two third-order cycles is difficult to assess because they span the current absolutes dates for the Roadian Stage. Furthermore, estimates for the duration of mass transport events are highly speculative, because emplacement is short lived and there is not correlation between size and duration. However, the siltstone drapes that bracket them could record long periods of sediment starvation between events. Amminoids change across the upper two siltstones in the UCE and indicate considerable time. The third-order UCE provides a consistent framework with cycle durations comparable to deep-water cycles recognized in the recent and other ancient systems. This stratigraphic framework is described in the following section.

Middle Permian Second-Order Stratigraphic Cycle

The Paleozoic sedimentary record of the Delaware Basin contains one nine-million year episode of siliciclastic deep-water sedimentation, represented by the up to 1,070-m thick Delaware Mountain Group (DMG) (Fig. 2). When combined with the 113 m thick carbonate mass transport deposits of the upper Cutoff Formation, the base of this second-order deep-water episode records an estimated 160 m eustatic sea level change near the termination of the deglaciation of Gondwanaland (Silver and Todd, 1969; Meissner, 1972; Caputo and Crowell, 1984; Crowley and Baum, 1991; Crowley, 1994; Ye and Kerans, 1996).

Continental flooding of the Western Interior of North America in the Middle Permian (1) drowned an older early Permian carbonate platform rimming the Delaware Basin, (2) shifted shelf depositional systems landward and away from the basin, and (3) aided in the preservation of early Permian eolian sandstone source terrains in the hinterland (Fischer and Sarnthein, 1988; Gardner, 1992; Ye and Kerans, 1996).

During the subsequent sea level fall, a younger middle Permian carbonate ramp developed and it was separated basinward by a 15 km wide submerged shelf formed on top of an older early Permian platform (Fig. 8) (Fitchen, 1992; Kerans and Fitchen, 1995). Carbonate turbidites of the upper Cutoff Formation, derived from the younger prograding ramp, accumulated and failed across the older platform margin and they were resedimented in the basin as mass transport deposits of the Williams Ranch Member of the Cutoff Formation (Harris, 1982; Harris, 2000; Amerman *et al.*, in-press, 2008). Submarine canyons incised the early Permian platform margin (*e.g.*, Victorio Peak Formation at Shumard Canyon). These erosional features were initiated during upper Cutoff time and enhanced by later deep-water erosion and sand bypass (Harris, 1982; Rossen, 1985; Kirkby, 1988; Gardner and Sonnenfeld, 1996). The regional karst unconformity development in the younger ramp interior correlates to sandstone and siltstone of the Brushy Canyon Formation (Zelt and Rossen, 1995; Gardner and Sonnenfeld, 1996; Beaubeouf et al., 1999).

Second-order changes in glacio-eustatic sea level affected all sedimentary environments encompassing the basin. Carbonate systems rimming the basin evolved from low-angle ramps to steeply dipping, deep-rimmed reefs (Meissner, 1972; Kerans *et al.*, 1993; Figs. 2 and 8). There was a corresponding contraction of carbonate facies tracts, increased preservation of siliciclastics on the shelf, and high-frequency alternation of siliciclastic-carbonate facies (Candelaria, 1989; Borer and Harris, 1991; Kerans *et al*., 1992; Kerans *et al*., 1993; Sonnenfeld and Cross, 1993; Kerans and Fitchen, 1995). Recording the coupling of shelf and basin depositional environments, deep-water limestones increase in number and frequency upward through the DMG (Tyrell, 1969; Silver and Todd, 1969; Meissner, 1972; Bozanich, 1979; Gardner, 1997; Hutchings, 2000). Basin-restricted evaporites up to 600 m thick overlie the second-order cycle and record the silling of the ocean connection and demise of this long-lived (~232 m.y.) Paleozoic basin (Anderson and Kirkland, 1987). This second-order cycle (270.6 to 260.4 Ma) correlates to the Laingsburg and Karoo deep-water systems of the Ecca Group (275-255 Ma) in the Karoo basin of South Africa (Fildani *et al*., 2007).

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Second-order map patterns

Thickness patterns at this scale suggest sediment was delivered to the Delaware Basin from the north. Changes in sediment delivery to the basin are obscured by equilibration of successive third-order cycle thicknesses. With the third-order episodes undifferentiated, the second-order cycle maps reveal little about the record of basin sedimentation.

Third-order Episodes

Four third-order deep-water episodes compose the second-order cycle corresponding to the Guadalupian Series and the Williams Ranch Member of the Cutoff Formation and the Delaware Mountain Group. The oldest third-order cycle consists almost entirely of carbonate mass transport deposits. The overlying three sandstone-dominated episodes decrease in thickness but increase in duration upward through the DMG. The first two third-order episodes record deep-water sedimentation predominantly below the physiographic break of the two older carbonate platforms (Figs. 2 and 8; King, 1948; Harris, 1982; Rossen, 1985; Fitchen, 1992; Kerans and Fitchen, 1995; Gardner and Sonnenfeld, 1996; Gardner and Borer, 2000). The third-order deep-water episodes that compose the second-order cycle correspond to the following lithostratigraphic units (Fig. 2):

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1. UCE: Williams Ranch Member of the Upper Cutoff Formation

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2. **BCE: Brushy Canyon Formations-lower portion of Cherry Canyon Formation to genetic top siltstone marker (~450 m)**
3. **CCE: Getaway Limestone Member of Cherry Canyon Formation to Radar Limestone Member of Bell Canyon Formation (~310 m)**
4. **BEE: Radar Limestone to Lamar Limestone Members of Bell Canyon Formation (~240 m).**

The Delaware basin margin is defined by the depositional limit of four third-order carbonate buildups that cluster in a narrow 20 km wide belt rimming the basin. Outcrops along the northwest margin expose these basin margin buildups. They document the BCE pinch outs in submarine canyons incised into the early Permian carbonate platform overlapped by the Cherry Canyon deep-water sandstone tongue (King, 1948; Rossen, 1985; McDaniel and Pray, 1988; Sarg and Lehman, 1988; New, 1988). The lower part of the Cherry Canyon sandstone tongue contains the genetic top siltstone marker capping the BCE (Gardner and Sonnenfeld, 1996). In the southern Guadalupe Mountains, the Manzanita Limestone Member overlies the Cherry Canyon sandstone tongue, but these sandstones interfinger with overlying carbonates in the northern Guadalupe Mountains. The Manzanita Limestone Member is the downlap surface for the overlying Capitan Limestone, the carbonate buildup equivalent to the BEE.

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Three deep-water sandstone episodes up to 450 m thick contain mass transport deposits and/or sandstone at their base and organic-rich siltstone/carbonate mudstone intervals at their top. The coarsest sediment is generally associated with channelization, which occurs throughout the three deep-water episodes. The interval containing the highest channel density varies within third-order cycles, but is in the middle part of the BCE, the lower and middle part of the CCE and the middle and upper part of the BEE; the BCE contains the highest density of channels. Channels in the upper part of the CCE are interbedded within limestones of the Manzanita Limestone Member (Gardner, 1997b). The rest of this paper will focus on the BCE.

Brushy Canyon Episode

Third-order cycles are recorded on the shelf and in the basin. The BCE correlates to a shelf unconformity; in this case, a karsted surface within the interior carbonate platform deposits (Fig. 8) (Rossen, 1985; Sarg and Lehmann, 1986; Sarg *et al*., 1988; Fitchen, 1992; Kerans and Ruppel, 1994; Kerans and Fitchen, 1995; Fitchen, 1997; Ye and Kerans, 1996). This deep-water succession up to 450 m thick records the evolution of the basin margin from a fixed and inherited carbonate escarpment with a steep and high gradient, to a lower gradient constructional margin recording depositional and deformational outbuilding and expansion of a siliciclastic slope.

Four siltstone-bounded, carbonate mass transport events of the UCE contributed to the initial seafloor topography encountered by the sand-rich flows of the BCE (Carr and Gardner, 2000; Romans, 2003; Kling, 2006; Hanggoro, 2007; Amerman *et al*., 2008, in press). Siltstone and sandstone at the BCE base drape and in-fill this rough topography with siltstones showing an upward decrease in organic enrichment. The conspicuous thickness variation at the base is not resolved in third-order isopach maps.

Siltstone, resembling the drape at the top of the UCE, is also found at the top of the BCE (Figs. 3 and 4). This younger siltstone interval (genetic top succession) thins basinward and records an upward increase in organic enrichment. The uppermost organic-rich siltstone within this succession (genetic top siltstone marker) represents a downlap surface for the overlying CCE (Figs. 2 and 3).

In outcrop, mixed carbonate/siliciclastic MTDs of the overlying Getaway Limestone Member of the Cherry Canyon Formation locally incise into the upper Brushy Canyon top and complicate correlations of the BCE top. In addition, Cherry Canyon strata records the onset of sediment sourced from the east and transported across the filled Midland Basin and Central Basin Platform (Fig. 9).

Third-order map patterns

Third-order thickness and lithology maps document changes in sediment dispersal around the basin. Sedimentation starts in the west-northwest during the BCE, shifts to the east in the CCE, and finally it is predominantly from the northeast during the BEE. At this scale, both the BCE and CCE maps resemble opposing submarine aprons flanking the northwestern and eastern margins of the basin respectively. The BEE depocenter sits between the older “aprons” and forms an elongate, narrow (10 km wide by >100 km long) sediment thick (*i.e.*, “Ramsey sand channels”) that is sand-rich and contains a high density of channels. Despite the limited lateral resolution imposed by the line spacing, the third–order cycles can be mapped in the 2D seismic grid.

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This scale map fails to resolve submarine fan depositional patterns or detect the presence of the seven different shelf sediment sources in the BCE. Channel fairways defined by a high density of channels occupy the same outcrop area throughout the BCE and create more lateral (along-strike) than longitudinal variation in thickness, but this scale thickness and lithology map fails to reveal these discrete sedimentation regions (Fig. 13). Well-log attributes based on lithology-calibrated thickness and changes in log shape can help define channel fairways.

Fourth-Order Stratigraphic Cycles

The fourth-order cycles in the BCE correspond to the informal lower (LBC), middle (MBC), and upper Brushy Canyon (UBC) members of Zelt and Rossen (1995), Gardner and Sonnenfeld, (1996), and Beaubouef *et al.*, (1999) and Guadalupe 5-7 of Kerans and Fitchen (1995). These fourth-order cycles represent sand-rich successions up to 150 m thick that can be correlated throughout the 255 km^2 outcrop area and across the basin with a lower degree of confidence (Gardner, 1997; Johnson, 1998; Romans, 2003; Baptista, 2004) (Fig. 10). Sandstone beds generally thicken and coarsen upward and change from lobeform to channelform sedimentary bodies in the middle to upper part of the succession. In the upper part, sandstone beds thin and fine upward as weakly confined channelforms, lobeforms, silty sandstones and/or as thin interbeds in continuous siltstone drapes.

The fourth-order cycle boundaries contain thicker, more organic-rich siltstones than higher frequency cycles, and form the most continuous siltstones within the BCE (Fig. 3). In the subsurface, the cycle boundaries are mapped based on seismic impedance contrast and reflector continuity with a moderate degree of confidence (Baptista, 2004). Each fourth-order cycle contains three fifth-order cycles and can have up to five sixth-order cycles (Fig. 4). Channel types change upward through a fourth-order cycle reflecting their position within higher order cycles. These slope and basin deposits resemble the lowstand systems tract of a fourth-order high-frequency sequence (Mitchum and Van Wagoner, 1991).

The LBC strata form the thickest 4th-order cycle along the western margin of the Delaware Basin. The MBC strata are thickest along the north-northeast margin, with UBC strata showing significant sediment thickening along the southeastern and northwestern margins. The fourth-order depositional limits are farthest from the depocenter in the LBC, within 20 km of the MBC depocenter, the most basinward positioned and thickest 4th-order cycle, and are about 40 km basinward of the UBC depocenter, the most shelfward positioned (Fig. 10). The LBC contains the most lobeforms, the MBC the most and largest channelforms, and the UBC the most diverse facies tracts ranging from a constructional and deformational slope succession, mixed channel and lobe architecture, and silty sandstone encasing the largest sandstone sheets on the basin floor. These patterns record the change from a relict carbonate margin forming a steep, fixed slope onlapped by LBC and MBC strata to the constructional slope of the UBC.

Lower Brushy Canyon (LBC) fourth-order cycle

The lower Brushy Canyon fourth-order cycle is the interval most commonly bracketed by thick siltstone. Across the 28 km distance from the western basin margin, the LBC strata double in thickness (50-110 m) and quadruple in sandstone percent (20- 95%). The LBC depocenter is parallel to, and 35 km from, the western margin. There is a 50-100 km wide area of thin but widespread strata basinward of the LBC depocenter, defined by an area containing 80% of the interval thickness (Fig. 14; Romans, 2003).

The LBC shows very unimodal grain-size distributions in outcrop, where 40 m thick siltstone successions flank topographic highs positioned 20 to 30 km from the margin (Fig. 11). In the intervening topographic low, the LBC is predominately sandstone. Multiple sandstone pinch outs in the basin record ~l00 meters of depositional filling of this irregular topography (Borer *et al*., 2003) (Fig. 11). The dominant facies includes ungraded, structureless sandstone with floating siltstone clasts, local soft-sediment deformation, and dewatering features (Hanggoro, 2007; Fig. 15). Shelf-derived fusulinids are present, but in low proportions. Load amalgamation of sandstone beds to form bedsets is more common than amalgamation due to erosive truncation. The average sandstone bed thickness is about 0.5 m thick.

Distributary channels are the dominant LBC channel type. The distributary channels are encased in sandstone lobes to form tabular sandstone sheets producing a high interchannel sandstone percent. These channel bases lack drapes and generally show only minor erosion (<5 m) and in many cases appear to infill underlying bed topography (Hanggoro, 2007). The largest multistory channel complex is positioned 24 km from the basin margin and has 20 m of erosional relief, which requires a moderate gradient (Fig. 15). The contrasting channel and lobe architecture provides conflicting evidence for interpretation of gradient; whereas the interchannel lobes record low gradient, the deep incision and multi-story channel architecture indicates a high gradient (Figs. 3 and 15). One explanation for this architectural conundrum may be the poorly integrated channel systems traversing a rough and complex topography. Seafloor topography can generate local gradients that exceed the longitudinal profile gradient and produce divergent sedimentation patterns (Hadler-Jacobsen *et al*., 2007). Additionally, more frequent sand over-spilling from filled channel sites can also help explain the encasing sheet sandstones.

Middle Brushy Canyon (MBC) fourth-order cycle

The MBC depocenter is the thickest and farthest basinward in the BCE. This is the largest volume fourth-order cycle (Fig. 16). It is the most channelized part of the outcrop and contains the largest channels. Sediments coarsen and sandstone beds thicken upward through the middle part of the MBC. Over 190 mapped channels cluster in the middle part of the 160 m thick interval exposed across a 11.6 km long segment of the central Delaware Mountains outcrop belt (Wagerle, 2001; Borer, 2005). The upper part of the MBC consists of weakly confined channelforms that form high-aspect, biconvex sandbodies, interdigitated laterally with sandstone lobeforms and record lateral infilling of depositional topography. The channels show an upward change from multilateral and isolated geometries, to multistory and vertically stacked architectures, to weakly confined zones of amalgamation (Fig. 17). These channel patterns repeat at multiple scales (Fig. 18).

Sandstone beds in the upper part of the MBC (upper part of fan 5 and including the 40-ft siltstone interval of Zelt and Rossen (1995)) fine upwards and there are more siltstone and volcanic ash interbeds, carbonate allochems and silty sandstone. The 40-ft siltstone interval thickens toward the northwestern margin and caps the MBC succession across most of the outcrop belt (Fig. 3). Along the northwest margin, these siltstones fill the remaining basin margin topography inherited from the older carbonate margin (Fig. 8). In more distal (southern) outcrops, where the MBC is 50 meters thinner, this discrete siltstone interval thins to a <1 meter thick bed near the top of a 20 m thick succession of silty sandstone. This marks a significant increase in silty sandstone, which is the dominant UBC lithology at this profile position (Kling, 2006).

Upper Brushy Canyon (UBC) fourth-order cycle

Along the western margin of the Delaware Basin, the upper Brushy Canyon depocenter is within the northern Delaware Mountains and Guadalupe Mountains outcrop belt (Fig. 19). The upper Brushy Canyon is the only fourth-order cycle within the BCE that has a siltstone-rich depocenter positioned on the slope. The shelfward shift in this depocenter culminates in the partial filling of submarine canyons and deposition of a thick (200 m) succession of fine-grained deposits that record outbuilding of the slope (Fig. 3). The thick slope siltstone succession shows evidence of slumping and mass wasting. Slope outbuilding and attendant gravity-driven deformation generated local topographic depressions that pond sand (Kane, 1992; Johnson, 1998).

The constructional UBC slope focused sediment down-profile into narrow and linear channel fairways that almost halve in thickness (200-110 m) and double in sandstone percent (45% to 86%). across the 17 km distance from the margin. There is little variation in thickness of aggradational multilateral to multistory channel complexes that span a 9 km strike outcrop transect located 17-26 km from the basin margin (Fig. 20; Melick, 2002). At 31 km from the margin, the UBC strata are thinner (55 m) and there is less sandstone (60%) within strata that are less amalgamated. Low gradient channel complexes at this position are flanked by siltstone levees that show rapid lateral thickness changes that complicate lateral correlation of sixth-order cycles.

Upper Brushy Canyon strata contain the most diverse facies and grain size. Furthermore, fusulinid conglomerates, bioturbated beds and volcanic ash beds are most abundant in this interval (Fig. 21). These strata show an upward increase in shelf-derived carbonate allochems (>50%), a decrease in sand percent (<40%), and an increase in the thickness and organic richness of siltstones (>300%) (Fig. 21). Though the cycle-bounding siltstones can be correlated for long distances, they show abrupt lateral thickness changes, reflecting their increased abundance as beds of varying correlation length. Siltstones (1) fill channels, (2) construct levees, (3) drape channel bases, (4) cap channel fill sandstones in fairway locations, and (4) form thick, basinward-thinning sediment wedges (Fig. 20). Because infrequent flows leave channels open and subsequently draped by siltstone, slurry beds, representing fine-grained debrites, are most common in the UBC (Lowe and Guy, 2000; Haughton *et al*., 2003; Kling, 2006). Fine-grained debrites primarily occur in overbank deposits flanking channels or within drapes at channel bases. The abundance of preserved volcanic ash beds points to reduced dilution related to decreased flow frequency. This is consistent with enrichment of organic matter in silt and a decrease in sand, upward through the interval.

Upper Brushy Canyon channels have the highest proportion of siltstone drapes at their base, with some channels completely filled by siltstone (Fig. 20). Interpretation of these channel-base drapes has centered on whether they record deposition from the tail of bypassing flows or abandonment and infrequent flow deposition. Eastward thinning of UBC strata, combined with aggradational channel stacking, suggests that these drapes record decreased flow frequency rather than significant bypass.

The smooth UBC profile produced more mixing of grain sizes, which obscures thickness and lithology correlations. The constructional slope of the UBC shows a more gradual decrease in grain size and facies. High proportions of silty sandstone, feldspar enrichment, more organic matter and detrital carbonate mud characterizes UBC strata on the basin floor (Kling, 2006). The increase in silty sandstone and feldspar content records hydraulic fractionation of grain size and mineralogy within these subaqueous flows (see map in Fig. 3) (Kling, 2006). It appears this profile configuration promoted stability enabling longitudinal flow evolution and transformation of a more diverse suite of smaller volume and less frequent flows.

Fourth-order map patterns

Fourth-order maps start to resolve submarine fan depositional patterns and distributions related to the seven shelf sediment sources for the BCE. At this scale, lateral thickness and lithology changes reflect fairway-interfairway sedimentation regions. The different fan depocenters overlap with the third- and fifth-order scale isopach maps. The fourth-order cycles partially mimic depositional patterns of the larger third-order cycles (Figs. 9 and 10).

Fifth-Order Stratigraphic "Fan" Cycles

The nine fifth-order "fan" cycles represent siltstone-bounded successions up to 90 m thick that also can be correlated across the 255 km^2 outcrop belt and, with a lower confidence level, across the subsurface Delaware Basin (Fig. 22; Gardner, 1997a; Johnson, 1998; Romans, 2003; Baptista, 2004). Seven of the nine fifth-order cycles contain sandy slope and basin deposits that show thickness patterns that suggest they developed a submarine fan geomorphology, and are referred to as "fan" cycles (Johnson, 1998; Wagerle, 2001; Melick, 2002; Borer, 2005; Kling, 2006; Hanggoro, 2007). The other two sandstone-poor fifth-order cycles (the 40-ft siltstone marker and the genetic top siltstone succession) form basinward-thinning siltstone wedges that bracket the thick, slope-centered UBC depocenter (Figs. 3 and 19).

The uppermost fifth-order cycle of the BCE, termed the genetic top succession, is a basinward thinning siltstone. This interval records the progressive enrichment of organic matter in siltstones bracketing sixth-order cycles that contain upper slope channels arranged in a back-stepping stacking patterns and filling submarine canyons (Gardner and Sonnenfeld, 1996; Sageman *et al*., 1998; Melick, 2002; Bohacs *et al*., 2005; Locklair, 2007; Melick and Gardner, in-review, 2009). More pervasive burrowing and organic enrichment are interpreted to reflect a progressive decrease in flow frequency and sediment starvation (Fig. 22; Sageman *et al*., 1998).

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All fifth-order cycles show more silty sandstone near the top of the succession recording fan abandonment. This could reflect changes in bulk sediment composition related to sediment trapping on the shelf during sea level rise. It could also record smoothing of the profile near the end of an episode of fan sedimentation. Regardless of process, the distribution of these facies is most strongly modulated in the fifth-order fan cycles.

Vertical trends in grain size, bed thickness, sedimentary body and lithology resemble those of the larger fourth-order cycles. There is an upward change in channel type through a fan cycle from multilateral to multistory to vertically stacked zones of amalgamation. Lateral changes in the density of channelform sedimentary bodies define channel fairway regions that also contribute to changes in cycle thickness and architecture (Fig. 13). Along-strike changes in sediment delivery from the seven shelf sediment sources are best detected at this scale. Stratigraphic correlations across the seven recognized shelf sediment sources rimming the basin suggest an evolution in sedimentation attributed to relative sea level changes (Fig. 22; Gardner, 1997; Hutchings, 2000; Baptista, 2004).

The fifth-order fan cycles are comparable in scale, lithology, and architecture to the fans of the middle Permian Ecca Group of the Tanqua Karoo basin in South Africa (Johnson *et al*., 2001; Grecula *et al*., 2003; Hadler-Jacobsen *et al*., 2005; Hodgson *et al*., 2006). Sandstone-dominated fan cycles, in turn, consist of even higher-frequency sixth-order cycles, bounded by siltstone intervals of shorter correlation length (Fig. 4). The stacking pattern of these sixth-order cycles determines the thickness and channel architectures of the fan cycles.

Fifth-order map patterns

Fifth-order cycles are the optimum scale for mapping of this system because this scale interval can be correlated across the basin yet map patterns can be directly related to geomorphic process and sedimentary body distribution. Fan cycle maps resolve lateral changes in fairway and interfairway and source-proximal and source-distal sedimentation regions within submarine fans. Lateral changes in lithofacies and sedimentary bodies between fairway-interfairway regions are greater than longitudinal variations, but changes across the seven different shelf sediment sources produce more significant change. At this scale, longitudinal variations are more affected by profile roughness than profile position.

Fan depocenters are better defined at this resolution but overlap in thickness with those of the fourth- and sixth-order scale maps. This overlap is particularly relevant where confined channel complexes span multiple sixth-order cycles. The fifth-order map patterns partially mimic those of the smaller sixth-order cycles.

Sixth-Order Stratigraphic Cycles

The sixth-order cycles represent the smallest mappable units in outcrop (Figs. 3 and 4). These <50 m-thick siltstone-bounded packages can be correlated for 10s of km across the outcrop (Gardner and Sonnenfeld, 1996; Johnson, 1998; Carr and Gardner, 2000; Wagerle, 2001; Melick, 2002; Borer, 2005; Kling, 2006; Hanggoro, 2007). Vertical trends in grain size, bed thickness, sedimentary body and lithology resemble those of the larger fourth- and fifth-order cycles. The cycle-bounding siltstones are commonly eroded or laterally replaced by sandstones in channel fairways and show the most variation in thickness and organic richness. Outcrop mapping has highlighted that the number of sixth-order cycles varies laterally across fairway and interfairway sedimentation regions and between coeval fans derived from different shelf sediment sources (Figs. 3). This is interpreted to reflect the role of local channel modulation on sediment supply and autogenic cyclicity. Therefore, there are a variable number of sixth-order cycles within the fifth-order fan cycles.

Sixth-order cycle deposits typically consist of up to six composite channelforms that define channel fairway and interfairway regions and that also control the cycle architecture (Fig. 13). Both the fifth- and sixth-order cycles record phases of deposition that can be directly related to submarine channel evolution described by the BCFS model (Fig. 23). This scale cycle forms the model layers in a family of geological, petrophysical and geophysical models generated from the outcrop (Johnson, 1998; Batzle and

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Gardner, 2000; Atan *et al*., 2001; Clawson *et al*., 2002; Uman, 2002; Borer, 2005; Atan *et al*., 2005).

Sixth-order map patterns

Sixth-order cycle maps resolve lateral changes in channel, channel-flank and interchannel lobe sedimentation that define fairway and interfairway regions of the fan. In addition, a geomorphic hierarchy of trunk, distributary and crevasse channels affecting lateral thickness and lithology can be resolved in these maps. This is the optimum scale for modeling the layers in a reservoir model because this scale best captures body stacking patterns and lithofacies distributions. Depocenter stacking patterns reflect autogenic channel migration, switching and avulsion. Depocenter distributions are of limited extent and show minor overlap in thickness with fifth-order isopach maps. This is particularly relevant in basin-floor settings where depositional thinning generates similar thickness fifth- and sixth-order cycles.

Sedimentary Architecture Revealed by Different Scale Maps

Not surprisingly, the thinner the interval the more closely maps of thickness and lithology reflect the environment of deposition. The varying resolution of different scale maps affects the correlation of thickness and lithology to depositional process and sedimentary architecture. This data bias is comparable to the challenges with interpreting different resolution subsurface data (*i.e*., different frequency seismic). The geomorphic interpretation of map pattern from thickness changes artificially with scale. Third- and fourth-order maps suggest a ramp to apron (Figs. 9 and 10), whereas fourth- and fifth-order maps show submarine fan patterns (Fig. 22), and fifth- and sixth-order maps resolve multiple channels clustering in channel fairways. Unfortunately, the scales overlap and there is no real correlation between geomorphic expression and stratigraphic order. Taken alone, the thickness depicted in each scale map conveys a different geomorphic pattern, which limits its utility in interpretation. Generating maps at multiple scales however does help assess the data resolution and scale appropriate for geologic interpretation. Appreciation of this issue highlights the value of a hierarchy of stratigraphic cycles, where the additive and dampening effect of different order cycles must be accounted for to predict variations in sedimentary architecture.

Correlation Strategies: The BCFS and AIGR Models

This section introduces the BCFS and AIGR stratigraphic models and compares these to sequence stratigraphic models for deep-water systems (Vail *et al*., 1977; Mitchum, 1985; Jervey, 1988; Weimer and Posamentier; 1993; Beaubouef *et al*., 1999; Pirmez *et al*., 2000). Fluctuating system energy through time produces cyclic rock packages that show a hierarchical self-similarity (Fig. 4). In this paper, we are correlating and characterizing sedimentation cycles that record these fluctuations, thus the departure from the term Brushy Canyon Formation and adoption of Brushy Canyon Episode (BCE). As chronostratigraphic units, depositional episodes correlate different lithologies and architectures that are expressions of varying stratigraphic and geographic position. Furthermore, it is well accepted that processes vary dramatically from the plate tectonic to the sedimentologic scale. In consideration of a hierarchy of stratigraphic cycles, the nested AIGR (*Adjustment, Initiation, Growth, and Retreat*) and BCFS (*Build, Cut, Fill, Spill*) basin and channel models, respectively, assess overlapping allogenic and autogenic process-response patterns and trends.

Autogenic BCFS Stratigraphic Model

Internal or autogenic stratigraphic models for deep-water systems emphasize submarine channel-lobe avulsion and thickness compensation patterns (Mutti and Sonnino, 1981). The autogenic BCFS model emphasizes sedimentation phases (build, cut, fill and spill) recorded by alternating periods of degradation and aggradation and attendant channel-lobe migration (Fig. 23). The BCFS model is summarized briefly here to emphasize the parallel construction of this and the AIGR, independent but related stratigraphic models. Specifically, the BCFS model describes processes that generate local topography, driving channel placement and lateral sedimentation in the growth of a submarine fan. The BCFS phases correlate to sedimentation from confined, partially confined, and unconfined flows that form channel, overbank wedge, and lobe sedimentary bodies, respectively.

In a stratigraphic succession, sedimentary body type, diversity, and distribution differentiate evolutionary phases of channel-lobe systems. The model compares the architecture and evolution of channel-fill, channel-flank, and lobe strata across several scales of sedimentary bodies. These range from tens of meters to several kilometers wide, by meters to hundreds of meters thick. Areal distribution of sedimentary bodies at each scale responds to specific controls, such as flow momentum and topography. The model describes how composite channels record alternating periods of degradation, aggradation, and migration (shelfward vs. basinward) of the channel-lobe transition zone (Wynn *et al*., 2002).

The Channel-Lobe Transition Zone

The channel-lobe transition zone (CLTZ) describes where a flow exits confinement parallel to the flow axis (Mutti and Normark, 1987; Fig. 23). This can occur at any position on a topographic profile, depending on the local gradient and the instantaneous flow size and type (Mutti and Normark, 1987; Normark and Piper, 1991). Vertical successions of channelized deep-water strata that change upward from lobes to channel bodies, or *vice versa*, record the longitudinal offset of the channel-lobe transition across that depositional site through time (i.e., the basinward to shelfward shift). Because the CLTZ marks the change from confined to unconfined flow, it is associated with facies changes, related to flow transformations caused by fundamental changes in flow support mechanisms (Mutti, 1992). The coarsest sediment is commonly found at this transition and records the decreased competence of flows to carry their coarsest fraction beyond the confinement (Fisher, 1983; Mutti *et al*., 1999). Down-profile deposition of sandy, unconfined flows produces facies that reflect the remaining grain-size population carried by the flow.

Multiple episodes of channel cutting, filling, and overspilling produce a hierarchy of sedimentary bodies of similar form but varying scale. Cyclic successions of channelized strata that record, in a vertical profile, the translation of the channel-lobe transition reflect alternating phases of sand deposition from confined and unconfined flows. It is very important to emphasize the scalar hierarchy of sedimentary bodies described by the autogenic BCFS model. Based on a high-resolution outcrop dataset, bed-scale sedimentation events form the model building blocks. The smaller-scale features can then be related to larger-scale (*e.g.*, geomorphic) architectural elements. Specifically, the smallest-scale migration of the CLTZ along the channel thalweg can be recognized to occur within larger open channel courses. Seemingly paradoxical, yet similar to Samuel *et al*. (2003) and Deptuk *et al*. (2003), we recognize unconfined deposits within confined sediment pathways – an expression of the overlap of two scales: channel thalwegs within larger open channel courses and channel courses within larger erosional valleys and/or channel fairways.

Build-Cut-Fill-Spill (BCFS) Phases

The BCFS model links lithology, facies, and sedimentary bodies at a given position on the longitudinal profile to the phases of submarine channel sedimentation (Gardner and Borer, 2000). The BCFS phases document the basinward to landward translation of the CLTZ associated with increasing to decreasing flow-scale efficiency. Each phase describes the dominant process(es), which changes with time, at a common channel site recording the migration of the CLTZ through time.

Simply put, the BCFS model describes the vertical succession of (1) non-channelized (build phase) deposits, incised by (2) channelized (cut and fill phase) deposits, flanked by overbank deposits (cut phase) that are then typically capped by (3) non-channelized (spill phase) deposits. Channel incision during the cut phase promotes significant overbank sedimentation related to flow-stripping, over-spilling and super-elevation flow processes. The BCFS model aids in establishing the state of confinement, because sedimentation phases recording translation of the CLTZ are represented by different lithology, facies, and sedimentary bodies that vary with position on the depositional profile (Gardner and Borer, 2000).

Periods of degradation and bypass (cut phase) can generate outsized erosional depressions (Fig. 23). This confinement promotes channel reoccupation of the same site, which produces complex channel margins consisting of remnant truncated channel fill bodies, inclined conglomerate lags, and fine-grained deposits that drape the base of long-lived, open channel courses. Fine-grained overbank deposits are preserved high on the channel flanks and represent intrachannel levees and/or large, composite siltstone drapes (Camacho *et al*., 2002; Deptuck *et al*., 2003; Campion *et al*., 2005). Periods of aggradation (fill phase) generate more fully preserved sand-rich channel elements with fewer channel remnants, basal lags and fine-grained drapes. Frequent channel switching and migration of the CLTZ equilibrates fairway-interfairway lithology and anneals local topography and channels migrate freely across the fairway.

In down-profile positions, distributary channel branching decreases channel depth and flow confinement as a result of decreased gradient and lateral and longitudinal flow changes. For this reason, the facies and architecture of BCFS channel cycles can be linked to position on the depositional profile (Gardner and Borer, 2000). This is because the CLTZ often marks a local change in gradient, which can occur anywhere along a slope to basin profile (Adeogba et al., 2005; Hadler-Jacobsen *et al*., 2007). In general, deposits associated with the *build* and *spill* phases represent a greater sediment volume at sites down the depositional profile, at the expense of those representing the cut-and-fill phases. Longitudinal changes in BCFS channel architecture overlap with AIGR patterns that correspond to depocenter position and channel type within the submarine fan.

Like the AIGR model described below, not all phases of the BCFS model need to be present for model application. For example, composite channels that fine upwards indicate channel abandonment and/or a related decrease in sand sedimentation during the final, waning phase of channel deposition (Navarre *et al*., 2002). In this case, the lack of a spill phase points to a specific style of channelization - either channel abandonment or underfilling. Similarly, the absence of sandstone lobes below a composite channel reflects the absence of the build phase and generally indicates a higher gradient setting.

Allogenic AIGR Stratigraphic Model

The AIGR (pronounced “Eiger,” after the Swiss mountain) stratigraphic model assumes that allogenic controls modulate distinct lithologies, sedimentary bodies, and arrangements of sedimentary bodies. These attributes produce repeatable trends and patterns representative of the four AIGR

(*Adjustment-Initiation-Growth-Retreat)* sedimentation phases (Figs. 3 and 24). Not all four energy phases defined in the model, however, need to be present for its application. In its complete form, the four sedimentation phases produce distinct styles of sedimentary architecture and that repeat within a hierarchy of stratigraphic cycles. These genetically related deep-water packages may include correlative conformity surfaces and intervals recording marine condensation.

A complete AIGR cycle of sedimentation commences with the *Adjustment* phase, which defines the important initial conditions of profile gradient and topography (Ross *et al*., 1994; Einsele, 1991; Cronin *et al*., 1998). This phase can be represented by a surface (*e.g*., unconformity), a mass transport deposit or a lithologic or architectural change within the succession. Overlying the *adjustment* phase, the base of the *initiation* phase generally shows the most variable surface relief and lithology change within an IGR succession. It is the most diachronous surface, particularly if there is significant seafloor relief at the base of the initiation phase deposits.

The onset and main phases of clastic deposition (i.e., the "*initiation*" and "*growth*" phases, respectively) represent discrete periods of slope bypass that result in a down-profile depositional thick produced by increasingly more integrated channel systems (Fig. 24). The most channelized deep-water deposits represent the *growth* phase, and combined with the *initiation* phase, often resemble the upward change from lobes to channels depicted in the basin-floor fan of the sequence model.

A shelfward shift in sedimentation and back-stepping cycle stacking patterns characterizes the *retreat* phase. The retreat phase deposits generally form an up-profile depositional thick during a phase of waning system energy. This often slope-centered sediment thick records slope expansion and thins and downlaps basinward. Retreat phase deposits can correlate to either the slope fan or the prograding wedge, depending on whether the cycle stacking pattern is interpreted as shelfward- or basinward-stepping. The IGR patterns repeat at multiple scales and combine to produce variations that reflect the varying frequency and magnitude generated by a hierarchy of stratigraphic cycles (Fig. 24). The boundaries of the IGR phases correspond to the cycle boundaries used to establish the hierarchy of stratigraphic cycles.

Each IGR phase is characterized by a progressive increase in grain size (both maximum size and range) and channelization, as well as a shift in both lateral and longitudinal depocenter positions in the basin. Erosional confinement concentrates sedimentation in channels that produce topography, which modulates channel offset and placement within channel fairways (Fig. 13). Submarine channels are classified by architecture, which reflects gradient and the frequency of flow transmission within a network of trunk, tributary and crevasse channels (Fig. 18). The different channel types are arranged in a spatial hierarchy that increases from elementary, to composite, to channel complex in scale (Gardner *et al.,* 2003). Six channelform types are recognized and summarized in Table 2.

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Comment [7]: Pretty choppy paragraph, not sure what you want to say here, might consider dropping? It sounds like a series of coarsening up packages, or that each package is coarsening up, not what I remember.

lercc
Comment [8]: Much of this is already stated in preceding sections or will be stated later within this section. Can it be reduced some?

Adjustment Phase

The adjustment phase is likely to occur during tectonic and climatic events that modulate sea level change, such as the turnaround from sea level rise to fall, or during structural movements along the basin margin. This is the period when slope adjustment processes establish gradient, topography, and basinal sediment dispersal patterns regardless of the adjustment mechanism(s) (Fig. 8). Including the adjustment phase in a deep-water episode, may require genetically linking the strata across the correlative conformity of a shelf sequence boundary (Fig. 7). In such cases, the correlative conformity surface and/or deposits record the time between the adjustment phase and the onset of basinal sand deposition (Fig. 7). Correlation of deep-water strata across a correlative conformity is appropriate because the shelf sequence boundary surface cannot predict significant changes in architecture created by internal controls operating entirely below the shelf break. The initial conditions generated in the adjustment phase determine the gradient, topography, and basinal sediment dispersal patterns for the succeeding IGR phases of deposition (Fig. 8). The adjustment phase may be recognized in the form of:

1. **emplacement of multiple and/or closely spaced mass transport deposits (due to shelf edge and slope failure events near the basin margin),**

2. **change in lithology (*e.g.,* predominantly carbonate to siliciclastic**

sedimentation),

3. **faulting, diapirism and/or structural movement related to gravity sliding and expansion,**
4. **change in sediment dispersal directions indicated by channel trends or paleocurrent data,**
5. **enrichment and preservation of organic matter and concentration of elemental and isotopic signatures,**
6. **change in deep-water system type (*e.g.,* debrite vs. turbidite dominated sedimentation),**
7. **missing biozones,**
8. **change in seafloor gradient and relief generated from deformation and mass wasting.**

In this Middle Permian example, adjustment is recorded at the base of the second- and third-order deep-water episodes (Fig. 2). Within the Delaware Mountain Group, the three third-order deep-water episodes contain evidence of destabilization and slope adjustment at their base. The second-order adjustment is the most conspicuous and contains all of the recognition criteria listed above. Deposits recording adjustment phases occur at the base of three large-scale, basin-restricted episodes roughly coinciding with the Brushy, Cherry, and Bell Canyon Formations (Fig. 2). Characterizing every adjustment phase, basinally extensive submarine slide deposits set up and/or adjust the profile's gradient, topography, and run-out length of gravity flows.. Recognition of adjustment is less evident in shorter duration cycles, and superimposed higher frequency IGR patterns can persist throughout a longer duration deep-water episode.

JesseMelick
Comment [9]: DMG elsewhere, might do a search and replace on all occurrences after the first...

Adjustment is manifested by changes in both internal and external controls of second- and third-order cycles. Adjustments recorded in the basin often correlate to changes in the shelf depositional systems. Continental slopes located downdip of large deltas and rivers are prone to adjustment in the form of sediment creep, slumping, and gravity sliding (Cobbold and Szatmari, 1991; Cobbold *et al.*, 1995; Calassou and Moretti, 2003; Brun and Fort, 2004; Amerman *et al.*, in-press, 2008). Adjustment/deformation processes include deep-water extensional growth faults, fold/thrust belts, and diapiric movements associated with a mobile and ductile substratum. As the Delaware basin illustrates, adjustment processes do not require the presence of a mobile substratum (Fig. 2). If the shelf system is perturbed, the basin adjusts to this change, which is most easily recognized in the lower order cycles. Adjustment in a deep-water basin is controlled by:

1. **shelf width and coastal hypsometry (land elevation relative to sea level),**
2. **magnitude and rate of relative change in sea level,**
3. **size, number and type of shelf sediment delivery system(s),**
4. **gravitational deformation and synsedimentary mass wasting on the slope and in the basin.**

Mass Transport Events

Sea floor topography can have a profound effect on depositional patterns. Mass wasting along basin margins promotes submarine canyon formation and development of mass transport deposits (MTD), contributing to sea floor topography (Kuenen, 1952; Shepard, 1981; Martinsen and Bakken, 1990; Ross *et al*., 1994; May and Warme, 2000). The topography generated by MTDs can affect the gradient of the subsequent depositing flows. Topography affects the local ponding of deep-water sands, including locally thickened successions of MTDs (Fig. 11) (Amerman *et al*., in-press, 2008). Subaqueous flow processes are more effectively linked to sedimentation patterns when mass transport events (MTE) are included in the important, first phase of a cycle of deep-water sedimentation. The importance of this linkage may be highlighted by systematic changes in lithology, thickness and architecture through an episode of deep-water sedimentation.

The adjustment phase is comparable to the phase of sequence boundary development, in that they both define a genetically related episode of sedimentation (Van Wagoner *et al*., 1995). Seafloor topography, related to ongoing gravity sliding, synsedimentary deformation, and/or active structural growth can produce adjustments in the basin that have no equivalent event on the shelf (Hadler-Jacobsen *et al*., 2007). Identifying the time when gradient and topography are changed in the basin is as important as establishing the key external controls on sedimentation outside the basin.

The adjustment phase is the period when basin changing events, often manifested in unconformity development, are likely to occur. It does not, however, restrict this expression to stratal surface development. The recognition that basin reorganization can be represented by both surfaces and/or rocks, which change from one to the other along the shelf-to-basin profile, is considered more robust than surface-to-surface correlation. Sequence stratigraphic and allostratigraphic methods correlate discontinuity-bounded (surface-to-surface) rock packages that are readily apparent in lower resolution subsurface data. With the exception of low-order regional unconformities (*e.g.*, super-sequences of Sloss, 1962), the existence of widespread surfaces cannot be substantiated from high-resolution outcrop studies, where the correlation from rocks to surfaces across a depositional profile can be demonstrated (Gardner, 1993; Gardner *et al.*, 2004; Plint *et al.,* 2004; Bhattacharya and Willis, 2005). This suggests that the emphasis on surface-to-surface correlation approaches is largely an artifact of data resolution. Surface-based correlation methods do not accurately reflect time in stratigraphy. This limits their utility in predictive stratigraphy based on surface-to-rock correlation and the attendant sedimentary response. The data and/or its resolution should not form the basis for stratigraphic correlation. Time-stratigraphic correlation requires consideration of how the expression of time in material (rock) and nonmaterial (surface) domains changes across the dynamic Earth.

Adjustment Phases of the Upper Cutoff Formation and Getaway Limestone Member of the Cherry Canyon Formation

Second-order adjustment in the Delaware Basin is recorded by the third-order Upper Cutoff deep-water episode. At least six separate mass transport deposits (MTDs) compose four siltstone-bounded mass transport events (Amerman *et al*., in-press, 2008). These MTDs are composed of carbonate mudstone turbidites and are separated by thin (≤ 6 m) intervening hemipelagic siltstone drape intervals (Fig. 11). MTD thickness and deformational intensity generally decrease upward.

In the second-order adjustment phase recorded by the UCE, a younger carbonate ramp (lower San Andres Formation) nucleates inboard and on top of a submerged carbonate platform (Victoria Peak Limestone; Kerans and Fitchen, 1995). Carbonate turbidites, originating from the younger buildup, become mass transport deposits basinward of a shelf break formed by the older platform and incised by submarine canyons. Initiation phase sedimentation in the basin is affected by events in the adjustment phase (Figs. 2 and 14). The Upper Cutoff MTDs and LBC sandstones both thicken into a pre-existing paleotopographic low, where the intensity of deformation in the MTDs is greatest. Across the Delaware basin, second-order adjustment established slope topography, new shelf sediment systems, and is likely when the submarine canyons formed.

Third-order adjustment is illustrated by the Middle Permian Getaway Limestone Member of the Cherry Canyon Formation, which locally incises the underlying BCE and marks the change from westward to eastward sediment delivery recorded by the CCE. Outcrops along the northwestern margin expose MTDs consisting of sandstone, siltstone, and limestone blocks that failed obliquely into the axis of the upper slope fairway of the underlying Brushy Canyon Formation <7 km from the mouth of a submarine canyon (Fig. 3). Mass movement and emplacement of the remobilized channel sandstones generated contraction and bed shortening. The event cut ~100 meters into the top of the underlying upper Brushy Canyon strata (Fig. 3). Large, rafted sandstone blocks up to 20 m thick are present within the third-order MTD. This particular example shows bed contraction associated with channel sandbodies, transported *en masse* within an upper slope fairway subjected to a massive lateral slope failure. Multiple Getaway MTDs however are positioned over UBC channel fairways, spanning the three shelf sediment sources recognized along the western basin margin. The MTDs widen and increase in areal extent in the oblique down-profile trend exposed southward across the outcrop belt (Fig. 3). The basin-wide extent of this adjustment event is indicated by Getaway MTDs derived from the Central Basin Platform along the eastern basin margin (Baptista, 2004).

Initiation Phase

The initiation phase is a period of efficient slope bypass accompanied by basin floor sand deposition (Fig. 24). Initiation phase sediments show the most partitioning of lithology and thickness reflecting surfaces and deposits of the adjustment phase. If the basin margin is fixed, like along high-gradient and under-filled continental margin basins, then failure-generated flows from shelf margin deltas deliver significant volumes of coarse sediment to the basin (Hadler-Jacobsen *et al*., 2005). The fixed, high-gradient slopes promote efficient sediment bypass (Fig. 8).

The initiation phase is the time when small, elongate basin-floor fans with minor slope deposits develop (Carr and Gardner, 2000; Romans, 2003; Baptista, 2004; Hanggoro, 2007; Kling, 2006). If deep-water deposition initiates on complex seafloor topography, then overlying deposits show a conspicuous partitioning of sand and mud. Initiation phase sands generally coarsen, thicken and change upward from lobeform to channelform bodies. Because the channel systems are poorly integrated, they often show a mixed architecture consisting of channels/scours and lobes. In low-gradient and over-filled basins, such as cratonic foreland basins, the initiation phase records a change in shoreline trajectory and stacking pattern, with deep-water sand deposition focused at the base of prograding slope clinoforms (Hadler-Jacobsen *et al*., 2005; Fig. 13).

Initiation Phases of the BCE

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Despite the restricted grain size population of the BCE, third- and fourth-order initiation phase deposits show pronounced lateral and vertical segregation of sand and silt. This is associated with an upward progression from lobeform to channelform sedimentary bodies (Carr and Gardner, 2000; Hanggoro, 2007). These changes correlate to sedimentation during periods when the seafloor was the most irregular (Fig. 25). Sandstone thickening in topographic depressions controls LBC production in the Delaware Basin (Broadhead and Luo, 1996; Johnson, 1998; Baptista, 2004). The facies, lithology, and architecture resemble the fill-spill patterns described from sand-rich, ponded mini-basin fills in the Gulf of Mexico (Booth and Dean, 2003).

Channel systems traversing complex topography generally are poorly integrated and therefore do not form long-lived transmission sites (Fig. 15). Channel bases often lack drapes and generally show less erosion (<5 m) and in many cases appear to infill underlying bed topography (Hanggoro, 2007). The fourth- and fifth-order initiation sandstones, recorded by deposits of fifth- and sixth-order cycles, respectively, all coarsen upward and contain more multi-lateral and/or weakly confined distributary channelforms. Channel fairways are poorly defined and channel-overbank-lobe sedimentary bodies are interdigitated and record sedimentation patterns from mobile and poorly integrated channel systems. Frequent channel switching and migration of the CLTZ equilibrates fairway-interfairway lithology and channels migrate freely across the fairway. Both build and spill-phase lobes separate channels laterally. Initiation and build phase lobes are less amalgamated and show more compensational bed stacking. Initiation phase deposits that in fill irregular topography from mass transport deposits of a lower order adjustment are less widespread and uniform in thickness as those that overlie higher order IGR cycles.

Second-order adjustment phase deposits, represented by the third-order UCE carbonate MTDs, are overlain by growth phase deposits of the third-order BCE, sandy channel fills, along the western margin of the Delaware Basin. The absence of a second-order initiation phase, in part, reflects sedimentation that starts along the western margin, with the BCE displaying initiation phase patterns underlying the growth phase of the CCE along the eastern basin margin. Another factor may be the high sediment accumulation rates at the onset of this terminal basin-filling event, with sedimentation energy naturally decreasing upward through the second-order cycle. The most diachronous surface within the succession separates the second-order adjustment from growth phases. The basal five sixth-order cycles in the BCE record the progressive infilling of topography generated, in part, by the second-order adjustment. Higher frequency initiation phases contain more sandstone rich strata as evidenced by sandstones at the base of both the third-order UCE and BCE in outcrop.

Growth Phase

The growth phase is the main period of basin deposition, reflecting high sediment flux from multiple shelf sediment sources and the most basinward depocenters (Fig. 24). The slope is an active bypass site and channels extend the farthest into the basin in fully integrated channel systems organized into well-defined channel fairways. Channel fairways are sand-rich regions defined by a high density of channels (Fig. 13). Growth phase deposits contain the most and largest confined multi-story channel complexes.

JesseMelick
Comment [10]: Would help to add some visuals here. Sentence is rather abstract and if you can paint a little picture, then it will be easier to grasp.

JesseMelick
Comment [11]: Really hard to follow this one... Not sure what you are saying. Didn't the initiation phase just bypass this high gradient region?

This is because the growth phase is a period of maximum fan degradation, when large flows efficiently transport the coarsest sediment across an incised profile and the farthest into the basin.

JesseMelick
Comment [12]: Makes it sound like the channels eat up the fan... maybe "channel degradation"? Following paragraph talks about thicks associated with these channels.

Large erosional depressions span entire sixth-order cycles and focus sand delivery into outsized and long-lived valley depressions developed on the slope and in the basin. Coarse sediment confined to these depressions contributes to the greatest disparity in fairway-to-interfairway lithology and thickness. The outsized depressions restrict channel migration and are effective sediment traps, as evidenced by the enrichment in organic matter in flanking interfairway deposits (Fig. 18). Confinement also promotes channel reoccupation, which produces complex channel margins consisting of remnant channel fills, inclined conglomerate lags, and fine-grained deposits that drape the base of long-lived, open channel courses. In these outsized depressions, fine-grained overbank deposits are preserved high on the confinement flanks and represent intrachannel levees and/or large, composite siltstone drapes (Camacho *et al*., 2002; Deptuck *et al*., 2003; Campion *et al*., 2005).

Despite significant lateral changes in sixth-order cycle thickness, high sediment flux generates more uniform fourth- and fifth-order depositional patterns (compare Figs. 10 and 12). This can obscure the recognition of discrete fan morphologies and growth phase successions may be classified as aprons or ramps because of the more uniform thickness (Stow and Mayall, 2000; Lowe, 2004). The position of higher-order growth phases (e.g., fifth-order) within lower-order cycles can vary. If the initiation phase is present then growth phase channels are present in the middle of the lower order cycle. If the initiation phase is absent, then growth phase channels occur at the base of the lower order cycle.

JesseMelick
Comment [13]: Further contradicting the statement of max fan degradation.

Basin-floor sandstones are dominated by distributive channel and lobe sandbodies, but over-spilling from filled channels produces encasing sheet sandstones that increase the sand percent of basin-floor deposits (Gardner and Borer, 2000; Lien *et al*., 2003; Kling, 2006).

JesseMelick
Comment [14]: Not sure what this adds.

Growth Phases of the BCE

The MBC (the fourth-order cycle recording the third-order growth phase of the BCE) is the most channelized and contains the largest channels and its depocenter is the thickest and farthest basinward.

This is the largest volume interval in the BCE (Fig. 16). The growth phase correlates to the coarsest sediment and the most basinward positioned depocenters at all scales (Fig. 25).

Growth phase channels form the largest sedimentary bodies and range from ponded, to multi-story channel-levee, to erosionally confined types. In the most source-distant outcrops, the growth phase contains the only multi-lateral channels on the basin floor. In lower order cycles, growth-phase channels are encased by initiation and retreat phase channels, which together show an upward change from multi-lateral and isolated geometries, to multistory and vertically stacked architectures, to weakly confined zones of amalgamation. In the BCE, these channel patterns repeat at three temporal scales (fourth-through sixth-order scales) and reflect the compounding and composite nature of superimposed and hierarchical AIGR cycles (Fig. 17). For this reason, higher-order growth phase deposits within an overall retreat phase can add ambiguity to the interpretation of cycle stacking patterns. For example, within the BCE, the UBC has the most disputed stacking pattern, particularly in the slope depocenter where growth phase channels show significant incision and the fifth-order initiation and growth phases offlap because they record expansion of the depocenter.

JesseMelick
Comment [15]: This has never been officially defined...

The focusing of sedimentation and subsequent buildup of depositional topography is related to the development of large erosional depressions that form during the maximum growth phase. Lateral thickness changes reflect well-defined channel fairway and interfairway sedimentation regions. Major fairways are separated by minor fairways that generally record early- and late-stage filling, respectively, by more weakly confined channels. The sandstone proportion within channel fairways can be as much as 20-40% greater than flanking interfairway areas.

Retreat Phase

During the retreat phase, deposition is shifted shelfward, typically to the slope (Fig. 24). Slope centered sedimentation causes the slope to expand. With deposition concentrated on the slope, submarine canyons fill and the upper slope deposits receive a high proportion of less efficient, low-concentration flows, characterized by thick, rippled sandstone successions in the BCE (Rossen, 1985; Gardner and

Sonnenfeld, 1996; Johnson, 1998; Batzle and Gardner, 2000; Sinex and Gardner, 2004).

The retreat phase can record increased shelfal accommodation. Because the shelf is becoming more submerged, in carbonate settings it can become an active depositional site and there may be an added "biogenic" contribution to the gravity flow composition. For example, in the BCE, this is reflected in increased carbonate mud and carbonate allochem conglomerates (Fig. 21).

Because retreat culminates in the cessation of an episode of deep-water deposition, the upper part is characterized by thick successions of organic-rich and fine-grained deposits, containing a high proportion of lower concentration flows that encase large-scale aggradational channel complexes positioned on the slope. Under-filled channels recording less frequent flows are likely in this phase. However, this pattern is also likely to occur in channels crossing broad slopes and in muddier systems containing a high percentage of channel fills that fine upward.

The shelfward shift in depocenters recorded by the retreat phase is more likely in basins with a fixed and inherited shelf/slope break like the Delaware Basin. Prograding shelf breaks may simply record the back-filling of slope channels, which cause the system to shift laterally (*i.e.*, back-filling of canyons incised into prograding clinoforms) (Fig. 13). In these shallower bathymetry basins (*i.e.*, foreland basins), the retreat phase may be poorly represented and only record a change in shoreline trajectory and/or stacking pattern within a succession of sand poor, deep-water clinothems (Hadler-Jacobsen *et al*., 2005).

Retreat Phases of the BCE

In the third-order retreat phase of the BCE, multiple UBC depocenters are mostly located within 20 to 30 km of the basin margin (Baptista, 2004). Retreat phase deposits record significant longitudinal and lateral thinning which is reflected in shrinkage and narrowing of both the channel fairway and the submarine fan morphology (Figs. 19 and 22). The retreat phase can mark the onset of adjustment recorded by a shift in sediment delivery sites along the basin margin (Fig. 25). For instance, the southeastern margin of the Delaware basin is the only site where UBC strata show an increase in the areal extent of deposition during third-order retreat.

Though the sediment volume is reduced in the retreat phase, the preceding initiation and growth phase deposits tend to smooth the longitudinal profile, which promotes longer flow run-out lengths. Sediment transport along smoothed depositional profiles developed during the retreat phase enables more complete flow evolution and transformation and the longitudinal fractionation of grain size and mineralogy. These lithologic variations reflect the evolution of the longitudinal gradient affected by the deposition of successive IGR phases.

In general, the sandstone bed thickness decreases, whereas the number of siltstone beds and facies diversity increases upward in the third-order retreat of the BCE (Fig. 21). This suggests less frequent deposition from progressively more diverse flow types. Retreat deposits generally fine upward and consist of weakly confined depositional channel, silty sandstone, and poorly amalgamated lobe deposits. Under-filled channels are best developed in the retreat phases, which record the most distinct decrease in sand supply and increase in shelf-derived carbonate allochems (Gardner and Sonnenfeld, 1996; Johnson, 1998; Melick, 2002; Sinex and Gardner, 2004; Kling, 2006). Basinward thinning of the UBC combined with aggradational channel stacking and under-filled channel fills, suggests that the channel-base drapes record decreased flow frequency rather than significant bypass.

Because the depocenter shifts toward the basin margin in the retreat phase, this is the only time when significant sand deposition occurs and weakly confined depositional channels are present on the higher gradient slope. Sandstones in the fourth-order retreat phases of the LBC and MBC onlap the inherited carbonate margin. The uppermost retreat phase siltstones correlate to the only back-stepping, upper slope channels that partially fill submarine canyons.

JesseMelick
Comment [16]: What is this doing here?

The effect of sedimentation from the preceding phase on the gradient of the succeeding phase is reflected by changes in channel architecture. In such cases, the short-term change in local channel gradient can exceed the longitudinal basin gradient. Because the retreat phase records the final phase of sedimentation within a deep-water episode, the deposits in-fill the remaining depositional topography. This is when channel avulsion is likely, which can mask the focused sedimentation patterns generated by the preceding growth phase channels.

JesseMelick
Comment [17]: Section seems to just end here. Might want to add a little conclusion restating in simplest terms possible the take homes for the AIGR model.

Stratigraphic Hierarchy and Nested AIGR and BCFS Cycles

The stratigraphic record consists of stratigraphic cycles of varying duration (order) that can be superimposed in a hierarchy if defined by the same criteria. Different temporal orders of stratigraphic cyclicity combine to increase and/or dampen the composite amplitude of system energy recorded by sediment transport and deposition (Sloss, 1962; Wheeler, 1964a, b; Allen, 1964; Syvitski, 1990; Gardner, 1995; Borer and Harris, 1991; Sonnenfeld and Cross, 1993; Cross and Lessenger, 1998; Tipper, 2000; Gardner *et al*., 2004). Second- to sixth-order stratigraphic cycles compose a fivefold hierarchy recorded by the Delaware Mountain Group (Figs. 2 and 4). The AIGR and BCFS models describe this stratigraphic hierarchy.

Resolving the composite signal of superimposed AIGR and BCFS cycles increases the predictability of sedimentary body and lithofacies distributions. For example, the fourth-order growth phases (LBC (I), MBC (G), and UBC (R) strata) can be compared to changes in the architecture of multistory channel complexes of fifth-order fans (LBC fan 2 (IG), MBC fan 5 (GG), and UBC fan 7 (RG)). These erosionally confined channel complexes form the largest channel bodies in their respective fourth-order cycles. Significantly, the fan 7 channel complexes (RG) record fourth-order retreat during a higher frequency fifth-order growth phase and contain the most continuous channel-base drapes, as illustrated in Figure 20. The high drape continuity reflects increased preservation related to the aggradational channel stacking pattern. Truncated channel-base drapes are present in the fan 5 channel complexes (GG) shown in Figure 17. The erosional bases of successive channel fills show increased incision within these degradational channel complexes. Normalized to the UBC and LBC profile positions, the LBC erosionally confined channel complexes (IG in Figure 15) lack channel-base drapes. This example illustrates how small-scale features, like channel-base drapes, can be predicted from the larger-scale channel stacking pattern generated by the composite signal from a hierarchy of

JesseMelick
Comment [18]: What does this mean?

stratigraphic cycles.

The importance of interpreting sedimentary patterns from the context of a hierarchy of stratigraphic cycles is highlighted by the interpretation of submarine channels within the UBC third-order retreat phase. Large erosional depressions (1.5 km wide by 20 m deep) occur in the middle part of the upper Brushy Canyon (RG). These composite features record multiple erosional events during the most active phase of sedimentation (Fan 7, fifth-order growth phase) during the overall retreat of the third-order BCE. These aggradational channel complexes preserve fine-grained drapes and are filled with the most sand-poor, but carbonate-allochem rich deposits (Fig. 20). The large channel size has been advanced as evidence for offlap/progradation of the upper Brushy Canyon (Zelt and Rossen, 1995; Beaubouef *et al*., 1999), despite the fact that the largest channel depressions and coarsest sediment occur in the middle of the MBC (GGG phase; Fig. 17; ~2 km wide and ≥40+ m deep).

Michael Gardner 2/7/09 10:27 PM
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JesseMelick
Comment [19]: Inconsistent usage. Previous usage called this the 4th-order retreat, see previous paragraph.

JesseMelick
Comment [20]: Again, see comment 27. Need to decide which way to say this; I agree with how it is stated here, however in the previous paragraph you use different orders. Needs to be clear why if it really should be stated differently here.

The AIGR/BCFS models are inclusive and consider, but are not dependent on, recognition of all possible energy configurations (Figs. 23 and 24). These models focus on conditions in the basin and correlate depositional phases to sediment volumes, architectural elements and lithofacies distributions. The AIGR and BCFS models emphasize high-frequency events that change sedimentation (Fig. 24). Gradient and topography (defined by surfaces), and flow grain size and run-out length (recorded in deposits) represent important parameters governing the efficiency of subaqueous flows and the interpretation of energy from their deposition (Fig. 27). The models are not reliant on linking sedimentation phases to a single forcing function like sea level or concept like accommodation space (Miall 1986; Haq *et al*., 1987; Jervey, 1988; Thorne, 1992; Arnott, 1995; Embry, 1995; Muto and Steel, 2000). Instead, sedimentation energy is directly measured by grain size and erosion, and indirectly by proxies like surface morphology and relief, facies offset and trend, the size, diversity and sedimentary body type, and the lithology and thickness distributions within equivalent-order cycles of energy change.

JesseMelick
Comment [21]: e.g., example here would help

JesseMelick
Comment [22]: Unclear.

Comparison of Sequence and AIGR Stratigraphic Models

The AIGR/BCFS and sequence stratigraphic models for deep-water systems emphasize time-stratigraphic correlations (Fig. 26) (Mitchum, 1985; Beaubouef *et al*., 1999; Pirmez *et al*., 2000; Campion *et al*., 2005). The sequence stratigraphy model has proven to be a powerful predictive tool because recognition of stacking patterns and facies changes in sequences of strata has been demonstrated in all the sedimentary basins around the world. Sequence stratigraphy models, however, do not adequately treat high frequency events that exist within a sequence. These high frequency events generate a spatial hierarchy of sediment volumes, sedimentary bodies and lithofacies distributions that represent attributes that are correlated to the temporal phases in the AIGR and BCFS models. These sedimentary attributes are clearly a response to internal processes and do not generate a unique pattern that can be correlated outside the local system. However, these attributes can be used to recognize changes in system energy.

JesseMelick
Comment [23]: Isn't this mixing time and rock?

Sequence Stratigraphy Model for Deep-Water Systems

The sequence model places the time of deep-water clastic deposition in the lowstand systems tract during a relative fall in sea level (Fig. 26). Because the lowstand systems tract correlates to a shelfal unconformity, the base of the lowstand systems tract is correlative to the shelf unconformity surface. The first major flooding surface across the shelf, called the transgressive surface, forms its upper boundary (Van Wagoner *et al*., 1988; Van Wagoner, 1995). The transgressive system tract is bounded by the transgressive surface below and the downlap surface or maximum flooding surface above. Internally, shelf strata are arranged in cycles showing a back-stepping stacking pattern. The maximum flooding surface correlates to a condensed section in the basin (Fig. 26).

Using AIGR and BCFS to Resolve Limitations of Sequence Stratigraphy

Because they account for higher frequency sedimentation events, the AIGR and BCFS models highlight four limitations to established sequence stratigraphic model for deep-water systems; these include:

(1) Recognition that deep-water sedimentation can occur at any time during a cycle of relative sea level change. This is illustrated in the Brushy Canyon dataset by significant deposition of shelf-derived sediment during sea-level rise (*i.e*., retreat phase), which spans both the late lowstand and transgressive systems tracts of the sequence model (Fig. 25). Confining shelf-derived, sand caliber sediments to the lowstand systems tract reflects the consideration of only one condition for deep-water sedimentation. This restrictive requirement correlates only one temporal configuration (sea level fall) to one profile position (lowstand systems tract), which restricts the material (rock) record to a specific time at a singular place. These limitations restrict shelf flooding to the highest stands of sea level regardless of shelf width or climatic condition (*e.g.,* icehouse vs. greenhouse). The sequence model fails to account for back-stepping, deep-water slope channels bounded by the first major flooding surface and maximum flooding surface.

The following observations demonstrate that the UBC retreat phase deposits correlate to the transgressive systems tract (Melick and Gardner, 2009, in-review). Both slope expansion and back-stepping of aggradational upper-slope channels record decreased flow efficiency and a shift in deposition toward the basin margin. More elongate basin-floor thicks reflect decreased sediment volume and narrowing of channel fairways (Gardner, 1997; Johnson, 1998; Romans, 2003; Baptista, 2004; Kling, 2006). The overall decrease in sandstone percent and vertical sandstone connectivity, but increase in organic richness of siltstones, suggests a decrease in regional sediment supply. Increased carbonate allochems and lime mud point to enhanced carbonate productivity due to a sea level rise and shelf submergence (Fig. 22). These sedimentation patterns record gradual sea level rise that commences within the upper part of the BCE.

(2) The correlation of a shelf unconformity to its correlative conformity at the base of a deep-water sandstone succession excludes the real possibility that along the slope and basin profile a surface will correlate to a rock volume in time. Using this correlation strategy, the sequence boundary, an unconformity surface, is the only attribute for recognition of significant phases of basin reorganization,

JesseMelick

Comment [24]: Redundant and distracting from main point.

which are accounted for by multiple criteria in the adjustment phase of the AIGR model.

Second- and third-order events affecting both the shelf and the basin will most likely be manifested by attributes beyond just a single isochronous surface. One manifestation of slope adjustment is mass wasting, which is the fundamental (first) phase that sets up conditions governing subsequent subaqueous flow sedimentation. Basin margin adjustment is considered more important than, and often spans, unconformity development on the shelf. Furthermore, as the cycle frequency increases the area of stratal surface development decreases making the correlation of surfaces over wide areas less likely at the scale of most fifth- and six-order cycles.

(3) Stratigraphic cycles are not consistently defined in the sequence model; cycle definition changes with scale. Shorter duration parasequences are defined by flooding surfaces, but are embedded within longer duration, unconformity-bounded sequences. Consequently, the model cannot account for the dynamic additive and dampening effect of superimposing a hierarchy of energy-defined cycles. This contributes to the plethora of static sequence configurations leading to multiple addenda—a model for every occasion (Miall, 1992).

(4) The dependence of too few parameters to explain stratigraphic cyclicity, (*i.e.,* eustasy, tectonics and sediment supply) removes high frequency process and response as a metric for measuring change during a period of time (see Fig. 27 for comparison). Stratigraphic models that isolate one parameter and consider it more important than others (*e.g*., the initial emphasis on eustasy as *the* defining control on cycle stacking patterns in early models of sequence stratigraphy (Vail, 1987; Haq *et al*., 1987), ultimately fail because other parameters, operating at different temporal scales, combine to produce a composite control that a single parameter cannot explain. Though the dimensionless accommodation-sediment supply ratio (A/S) (units of Nm/Nm; see definition in Gardner *et al.,* 2004) represents an important simplification and provides a more direct link to formative process-response relationships, the list of processes directly correlated to the A/S ratio is still too short and restrictive for the scale of process(es) required to predict lithofacies and sedimentary body architecture. For this reason the A/S

ratio fails to account for the high frequency processes contributing to sedimentary architecture.

Discussion

For too long, stratigraphic models have been constrained by an inability to portray all the dynamic temporal and spatial configurations possible for an ancient sedimentary system. This inflexibility reflects over simplification and overly static representations of complex systems. It also points to models that cannot account for variation generated by a diverse suite of formative parameters that combine in many different ways. Such models are insufficient because they (1) oversimplify the formative parameters, (2) are derived from too few examples, and (3) reflect an incomplete system description. For example, it is well known that shelfal accommodation is a composite response to eustatic, tectonic, and sediment supply controls on shallow-marine shelf sedimentation (Cotton, 1918; Swift, 1968; Curtis, 1970; Frazier, 1974; Coleman and Roberts, 1988; Ross *et al*., 1995; Helland Hansen and Martinsen, 1996; Jervey, 1988). In this well-studied shallow water example, no single parameter, (*i.e*., eustasy), controls shelfal accommodation. This example also illustrates how the composite effect that results from combining different parameters generates variations in sedimentary architecture (*i.e*., type I or type II sequence boundaries of Van Wagoner *et al*., 1988; Van Wagoner, 1995).

Mike Gardner 2/12/09 5:58 PM
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JesseMelick
Comment [25]: Which one?

More general relationships, like the *accommodation to sediment supply* (A/S) ratio have been used to frame temporal variations in sedimentary architecture (Curtis, 1970; Jervey, 1988; Sonnenfeld and Cross, 1993; Cross and Lessenger, 1999; Tipper, 2000; Gardner *et al*., 2004). This dimensionless term is fundamentally an energy relationship that describes changes in sediment flux through the space made available by some combination of fundamental tectonic and climatic controls on sedimentation (Fig. 27). Despite improvements in flexibility and portability made possible by this elegant simplification, the A/S ratio cannot predict meter-scale sedimentary architecture, because it fails to link higher frequency processes to the A/S ratio. The A/S ratio also fails to sufficiently link temporal and spatial changes in sedimentation, when both are required to predict reservoir-scale sedimentary architecture.

JesseMelick
Comment [26]: Confusing placed here.

AIGR and BCFS Applications

Application of the AIGR and BCFS models is intended to guide outcrop and subsurface interpretation (Figs. 23 and 24). The models force interpreters to ask specific questions about their data. The *sedimentary system energy matrix* (SSEM), described below, provides a framework for the subsurface interpretation of sedimentary architecture (Fig. 28). Multiple temporal scales can be analyzed at any spatial window. The models provide a systematic and iterative approach to subsurface data analysis, which is summarized in Table 3. The initial observations generate geologic attributes within a hierarchy of stratigraphic cycles that can be correlated to sedimentary patterns predicted by AIGR/BCFS phases linked to a set of formative parameters.

Sedimentary System Energy Matrix (SSEM)

The AIGR and BCFS stratigraphic models combine to form the vertical (temporal) axis of a time-space matrix for all possible deep-water sedimentary patterns. The sedimentary system energy matrix relates sedimentary patterns to a given temporal and spatial phase and gradient condition during an episode of deep-water sedimentation. The energy matrix defined by AIGR/BCFS temporal phases and gradient account for the 23 architectural configurations documented from the Brushy Canyon study, a sand-rich deep-water system.

The axes of a SSEM plot temporal (vertical) and spatial (horizontal distance) changes in dimensionless system energy for the entire sedimentary system (Fig. 28). Temporal changes in system energy (dE/dt) during a diachronous episode of deep-water sedimentation are described by the increasing and decreasing energy phases in both the AIGR (allogenic) and BCFS (autogenic) models. Spatial variations in system energy reflect both erosion and sedimentation, and gradient (dE/dx). Plotted together, they define the space where all possible energy conditions can exist for a sedimentary system. Variations in sedimentation patterns within the SSEM reflect changes imposed by the combination of temporal and spatial conditions for that position within the matrix. For example, the adjustment phase represents the

JesseMelick
Comment [27]: Doesn't sedimentation include erosion?

phase where stratal surface formation is most important as the sedimentary system adjusts to a major change in system inputs.

JesseMelick

Comment [28]: Might want to include other attributes to emphasize that the stratal surface does not have to be present and adjustment may be recorded by other attributes, i.e., paleocurrent changes, significant folding etc. Good place to emphasize the suitcase of attributes to help identify adjustment phase in any setting.

The SSEM simply provides a temporal and spatial matrix for framing variations in deep-water sedimentary architecture likely to occur when a certain set of parameters combine to generate a stacking pattern and lithofacies distribution (Fig. 28). All possible energy combinations in a sedimentary system are accounted for in the SSEM, but local conditions or external controls can still modify the pattern, such that only the matrix transcends the variations inherent in comparisons of different examples from the same system. For this reason, no standard or singular model or pattern is recommended. Instead, the SSEM relates the formative parameters that are likely to combine to generate a repeatable sedimentary architecture for a given set of system conditions (Fig. 27).

Total System Matrix (SSEMt): Understanding the System

Changes in the accommodation-sediment supply ratio, which is a lower resolution proxy for system energy, result from changes in a varying number of finite parameters that combine to produce discrete sedimentation patterns. These system parameters describe the architectural variations in the SSEM (Figs. 27 and 28). Each of the 23 Brushy Canyon sedimentation patterns in the SSEMt (P1-23) can be linked to formative parameters that define the pattern architecture. Multiple co-varying parameters can be estimated from subsurface proxies (*e.g.*, channel stacking pattern can be used to infer the preservation of fine-grained channel-base drape), to help validate the interpretation. The ability to measure the formative parameters for a particular pattern from a specific set of observational attributes helps establish the uncertainty in the geologic interpretation. The SSEMt in Figure 28 is normalized to show fairway architecture at each profile position. Temporal changes at the same gradient position reflect the evolution of the deep-water system recording both internal and external controls. Longitudinal changes in architecture record changes documented across the profile outcrops of the BCE.

Channel and Lobe Matrices (SSEMc and SSEMl): Reservoir Prediction

The SSEMt can be filtered into component architectural element plots that feature and emphasize changes in the dominant sedimentary bodies. In the case of deep-water systems, channelforms and lobeforms are the two most common sedimentary body types. The SSEM for each body type is shown in Figures 29 and 30. By highlighting the channel and lobe elements in each body pattern in the matrix, the dominant formative processes are more directly related to the sedimentation pattern. These SSEMs can also be used to predict facies distributions (Fig. 31). These more detailed plots are useful in reservoir prediction, where lithology and shape information define reservoir architecture and control property distributions below the resolution of the subsurface data.

The IGR phases in the SSEMc correlate to changes from (1) multi-lateral, (2) multistory and (3) vertically stacked zones of amalgamation. These channel architectures are classified as (1) freely migrating and compensationally offset, (2) erosionally to depositionally confined, and (3) weakly confined and depositional channel types (Fig. 18). The distribution of these channel types is not haphazard, with their position in the SSEMc reflecting different temporal and spatial conditions. Similarly, the distribution of lobes in the SSEMl illustrates that they occur at all profile positions, highlighting the importance of local gradient and that different formative processes can generate similar architecture (Fig. 30). It also confirms that channel-lobe migration occurs at all profile positions but during different phases of sedimentation. The combination of energy conditions recorded at a particular profile and gradient position combine to produce a spectrum of possible sheet-like architectures. These range from ponded slope sandstones to lobes encasing channels, to basin-floor distributary channels and lobes forming sandstone sheets.

Facies Matrix: Predicting Facies Distributions

In general, extracting sedimentological process from a succession of deposits combines multiple unrelated physical processes. Correlating facies to the higher resolution BCFS phases minimizes this inaccuracy. The time-space Wheeler diagram at the bottom of the matrix in Figure 31 summarizes how averaged temporal conditions of erosion, sandstone deposition, and sediment starvation/condensation change with longitudinal position. Down-profile (longitudinal) gradient and flow evolution generate a dynamic continuum of evolving depositional processes and responses. These longitudinal changes however are not haphazard and correspond to different sedimentation phases during an episode of autogenic channel and channel-related sedimentation as shown in Figure 31. This plot emphasizes the scale invariant record of sedimentation energy preserved in stratigraphy. Differences exist, not because there is a limit to the hierarchical record of energy in sedimentary systems, but because the mode and tempo of processes generating sedimentation energy operate at different temporal and spatial scales. Therefore, these differences are expressed by sedimentary elements of different scale and duration. For this reason, the stratigraphic record is self-similar, but not fractal in origin (Schlager, 2004). Self-similarity can be exploited when applying a hierarchical approach to the extraction of sedimentation energy, operating at and generating products of different scale and origin.

JesseMelick
Comment [29]: What is a "mode of process"? Might be less ambiguous to say: "type and rate"

Modeling the System: Framework of SSEMs

In the case of most deep-water systems, there is a more direct relationship between the offshore basin configuration and sedimentation patterns. This may not be the case in onshore structural basins subjected to repeated episodes of tectonic deformation. Consequently, most onshore basins reflect the present structural basin configuration and combine segments of multiple, unrelated sedimentary basins (Wheeler, 1959; Sloss, 1963; Sloss, 1988). In such cases, the SSEM must be reconstructed for the complete sedimentary basin and not just its present structural incarnation.

The SSEM provides a framework that explicitly accounts for architectural variations within the same sedimentary system. The SSEM can be used to place environments of deposition within the context of their sedimentary basin. Subsurface interpretations placed within the hierarchy of SSEMs presented here facilitate comparisons with both larger- and smaller-scale attributes of the system and ensure their consistent application and appropriate use in the evaluation of the interpretation. Because the patterns in the SSEM are embedded with predictive rules (*e.g.*,Walther's Law of facies correlation), and the rules with parameters (Fig. 27), the SSEM forms the starting point for detailed interrogation of a set of subsurface observations leading to interpretation and prediction. Together these energy matrices describe changes occurring across a range of scales that span a single sedimentation event to the creation of an entire submarine fan (Figs. 28 through 31).

Controls on AIGR and BCFS Patterns

Depositional outbuilding of a basin margin by deep-water sediments is achieved by channel extension and deposition of lobes that extend submarine fans farther into the basin than the preceding lobe and fan. This extends channel lengths and generates depositional knick points within the basin and along submarine channel courses, such that the channel can pinch out upstream and incise downstream. This relationship is illustrated in Figure 32 by a cumulative thickness cross-section across the Delaware Basin. Flattened on the base upper Cutoff Formation, the cross section shows the relative position and limits of the Cutoff MTDs and nine BCE fifth-order fan cycle depocenters. Thickness distributions can be correlated to different channel patterns documented in outcrop. Growth phase fan cycles extend farther into the basin and contain the largest and highest density of channels in outcrop. Because depositional outbuilding likely reflects an external forcing on sediment supply, more efficient flows are required to travel beyond the depositional limit of the previous fan. The change in topography that occurs due to the preceding fan depositional limit creates a gradient change or "depositional" knick point. As the channel extends beyond the previous depositional limit the increased local gradient causes the channel to erode upstream (Fig. 32). Growth phase channels that make it past the depositional limit of the previous fan get larger going upstream from this knick point. As the process repeats the channels incise, extend and then back fill as recorded by BCFS phases recording translation of the CLTZ. During deposition of the LBC and MBC, the basin margin was fixed yet the channel architecture still show systematic changes that reflect deposition without slope progradation or movement of the shelf break. These relationships emphasize the need to reevaluate the gradient after each cycle of fan sedimentation.

JesseMelick
Comment [30]: Unlinked phrases.

The depositional limit of a fan or lobe provides a self-limiting control on deep-water systems at the scale of the basin and the channel, respectively. This causes the CLTZ to migrate shelfward and the fan to retreat. For example, the fans in the UBC retreat phase (RG) do not extend beyond the depositional limit of the MBC growth phase fans (GG) (Fig. 32). This suggests that they consist of deposits from many small flows, as evidenced by the high proportion of thin-bedded sandstones in the UBC. These deposits show less organized depositional patterns and less sequential organization in basin-floor channel architecture. Upper slope channels in this interval, however, do show an organized upward change from degradational to aggradational channel types reflecting waning energy in the depocenter of the retreat phase.

Variations in AIGR and BCFS Patterns

Variations in AIGR and BCFS sedimentation patterns reflect different combinations of formative parameters. Three formative parameters are presented to illustrate how the SSEM can be calibrated. These parameters contribute to the spectrum of architectures documented for deep-water systems (Barnes and Normark, 1985; Reading and Richards, 1994; Clark and Pickering, 1997; Stow and Mayall, 2000; Mutti *et al*., 2003). Variations in these processes alter the expression and presence of AIGR/BCFS phases. Demonstration of the application of the AIGR and BCFS models to other deep-water systems is beyond the scope of this paper, but is considered important and is the focus of ongoing research; the important formative parameters considered here include:

- gradient
- mud percent and grain size
- flow size and frequency

Gradient

Gradient is one of the most important, but more complicated of the parameters. It is difficult to measure and its estimation usually is dependent on grain size and architecture proxies. More than one gradient is relevant to sedimentation, these include: the local channel longitudinal and lateral gradients and longitudinal profile gradient, measured from the shelf break to the lowest point on the basin floor, each contributing and one often dominant. It is difficult to correlate gradient to basin type (*i.e*., passive or active margin), yet gradient is influenced by bathymetry and the mobility of the shelf break. The dynamic generation of depositional and deformational seafloor topography adds a temporal component to gradient definition in deep-marine systems, which is reflected in the AIGR phases. The impact of gradient is greatest in the initiation and retreat phases. Despite these complications, gradient is a critical factor in determining the energy potential of sedimentation.

JesseMelick
Comment [31]: What's this?

The amount of basin margin relief can modulate the frequency and magnitude of both adjustment and retreat phases within an AIGR cycle, but tectonic setting and sediment accumulation rate also contribute. Because deep-water sedimentation in active and high-gradient settings commences with an energy burst, the initiation phase is often represented as a surface at the base of growth phase deposits. Consequently, the initiation phase is less represented in tectonically active basins with generally higher longitudinal gradients (e.g., Mutti, 1977; Ricci Lucchi, 1975; Mutti et al., 1994; Mutti et al., 2003).

JesseMelick
Comment [32]: Adjustment phase too?

The regional gradient measured from the shelf break to the basin floor is less important than the shelf width and shelf sediment accumulation rate in determining the mode and tempo of basin-margin adjustment. In this setting, flow initiation is more often generated by *en masse* failure (*e.g.*, 1929 Grand Banks event (Kuenen, 1952; Heezen and Ewing, 1952; Heezen and Drake, 1964; Piper *et al.*, 1988), but shelf width and shelf sediment accumulation rate modulate the frequency and magnitude of failure events. The longitudinal gradient does affect the flow initiation processes, with higher gradients more prone to failure (Normark and Piper, 1991). Higher gradients in general produce more frequent, but smaller sediment failures, which can contribute to a higher number of lower-volume, gravity driven sedimentation events (e.g., Mutti and Ricci Lucchi, 1972). The frequency of failure-generated sedimentation events, however, must be considered with other flow initiation processes, like river floods, the size of littoral cells in longshore drift, and storms. River floods are more likely to occur along active basin margins characterized by small drainage basins, narrow shelves, and limited floodplain mud storage (Mulder and Syvitski, 1992). However, river floods deliver predominately sand-silt grade sediment with coarser deep-marine sediment often correlated to active continental margins where tectonics generate high gradients and narrow shelves (Ochoa *et al*., 2007; Anderson et al., 2008).

Mud Percent and Grain Size

Mud content and grain size affect the rheology and efficiency of momentum-driven subaqueous flows. Flow efficiency is defined by the distance a flow can transmit its sediment into the basin (Mutti, 1992). The relative proportions of mud, sand, and gravel determine flow efficiency. More efficient systems generally show greater offset in the facies belts developed during IGR phases. Less efficient deep-water systems like the BCE, show more compressed and attached facies belts. A retreat phase is more likely when the margin is fixed. This makes it easier to recognize AIGR phases because the initiation and retreat phases are not decoupled from the growth phase. This is why the sedimentary patterns documented in the SSEM for the BCE may differ from other fan systems and basin margin configurations. The relative flow efficiency will not change the temporal and spatial conditions framed by the SSEM. Varying mud content and grain size however will generate architectural variations.

JesseMelick
Comment [33]: Seems out of place?

Flow Size and Frequency

Flow density and volume reflect the grain size population being transported within a flow across a gradient. The frequency of these sedimentation events represents the material (rock) record of changes in sedimentation energy through time. Energy in deep-water systems is linked to the subaqueous flow as kinetic energy and to gradient representing the potential energy. If individual flow volumes remain constant, then flow frequency must be increased to increase system energy. If the flow frequency is constant, then the system energy is constant. Therefore, changes in sedimentation energy through time reflect both changes in flow size and frequency.

Sedimentation energy trends derived from successions of flow deposits can indicate how far into the basin subsequent flows went, whereas the flow frequency impacts how sand is distributed. For a given gradient position, more frequent flows have fewer pelagic mud deposits between sandy flow deposits. High volume flows may extend farther into the basin simply because they have more momentum. In order for the deep-water system to retreat, the flow size must decrease. The conspicuous increase in thin beds in the retreat phase depocenter of the UBC suggest decreased flow volume, and in this case, increased siltstone interbeds document a decrease in flow frequency(Fig. 21).

In more down-profile positions within the UBC, increased bed amalgamation in sandstone sheets in the growth of the retreat phase (RG) points to increased flow frequency. This distal pattern may reflect more efficient flows produced by the increased carbonate mud made available by the submergent shelf conditions occurring during this period. UBC strata show the largest disparity between thin-bedded sandstones in the slope depocenter and thick-bedded sandstones on the basin floor. This discrepancy may reflect more efficient, but less frequent UBC flow events. The decreased flow frequency may reflect increased shelf accommodation in the retreat phase, with the increased shelf storage generating higher volume, but less frequent and more efficient flow events; this reflects both decreased sediment flux and change in flow composition. Therefore, the relationship between flow size and flow efficiency remains an open question.

Considering the time value of the underlying upper Cutoff Formation and overlying Cherry Canyon Formation, Brushy Canyon strata record much less time (1.1-1.3 m.y.), about one third less than previously thought. If these age estimates are valid, the third-order BCE records higher sediment accumulation rates (409 m/m.y.) than in comparable deep-water episodes from the sand-rich Late Miocene Isongo Formation (181 m/m.y.), on the continental margin of west Africa, and from outcrop studies of Cretaceous foreland (86 m/m.y.) and forearc (10 m/m.y.) basins (Chaiwongsaen, 2007; Ochoa *et al*., 2008; Wolak and Gardner, 2008). The Delaware Mountain Group and the Permian Laingsburg and Karoo deep-water systems in South Africa (Fildani *et al*., 2007), however, show remarkably similar second-order accumulation rates (118 m/m.y. vs. 120 m/m.y.). For comparison, these deep-water accumulation rates are much lower than estimates from Paleogene shelf-margin depocenters (500 and 1000 m/m.y.) in the Gulf of Mexico (Galloway and Williams, 1991).

At the opposite end of the hierarchy, the BCE sixth-order cycles (25-33 ka) are thinner and appear to be longer in duration than channel-levee systems (<10 ka) from the Amazon Fan, which are typically 20 km to 40 km wide and ~175-440 m thick (Manley and Flood, 1988; Flood *et al*. 1991;

Pirmez and Flood, 1995; Hiscott *et al*. 1997; Piper and Normark, 2001). Individual Amazon channel-levee systems tend to stack laterally and/or vertically into larger complexes (Flood *et al*. 1991; Piper and Normark, 2001). The modern Amazon Fan and BCE sixth-order elements show comparable durations, similar stacking patterns, body types and areal distributions. Differences are related to the higher sedimentation rates in the Amazon fan system. The consistent lobe-channel-levee seismic architecture observed within the modern Amazon and Zaire Fans and West African subsurface datasets reflects a common pattern that can be correlated to the scale of sixth-order cycles (Navarre et al., 2002; Adeogba et al., 2005; Droz *et al*. 2003; Hadler Jacobsen et al., 2007).

Summary and Conclusions

Recognition and documentation of different sedimentation patterns is not enough for prediction. It is equally important to identify the external and internal process controls modulating these changes. The AIGR (allogenic) and BCFS (autogenic) stratigraphic models relate external and internal controls to variations in sedimentary architecture (Figs. 23 and 24). The strength of these models lies in their flexibility. They do not relate a specific parameter to the generation of a specific pattern. Rather, the models focus on recognition of high frequency sedimentation trends and patterns that reflect waxing and waning of sedimentation energy, reflected within a hierarchy of stratigraphic cycles. Different contributions from the same parameters produce different sedimentation patterns. These pattern and process changes reflect the modulation of system energy that can be categorized in a SSEM (Figs. 28-31). For this reason, there is no one-to-one correspondence between architecture, lithology, and parameter forcing functions. Rather, sedimentary architecture reflects the expression of the composite energy produced by multiple parameters that combine in different ways through AIGR and BCFS cycles. Linking sedimentation patterns to their energy phase is considered preferable in that it relaxes the requirement for a unique pattern link to a specific process parameter (Fig. 27). In this way, the model does not ask more from the data than can be extracted to reach a conclusion and prediction.

The much maligned, but enduring divisions of the Bouma sequence are a good example of how to apply the phases of the AIGR and BCFS models. One neither needs nor expects all of the divisions of the Bouma sequence to be preserved when applying the Bouma model to sedimentological interpretation of a vertical facies succession (Bouma, 1962). In fact, preservation of the complete Bouma sequence is the exception and not the rule. Sedimentologists still debate the formative processes governing the Bouma divisions, but the fact that there is an organized framework for comparison contributes to our understanding (Shanmugam, 2002). Both partial and complete Bouma sequences predict temporal and spatial variations in velocity from the grain size and vertical succession of sedimentary structures (Bouma, 1962; Allen, 1991; Kneller, 1995). Similarly, the complete or partial representation of AIGR and BCFS phases provide insight into sedimentation energy at the scale of the deep-water system, the channel and the flow. Each phase is governed by local and regional gradient and grain size population changes that can be linked to diversity and type of facies and sedimentary body. These attributes relate stratigraphic changes in channel type to sediment and lithology distributions in the basin.

For example, the absence of spill-phase sandstone lobes capping a channel-fill succession, suggests abandonment rather than backfilling of the channel depression. Similarly, the absence of the initiation phase in an AIGR cycle, points to external forcing (*e.g.,* tectonics) that can abruptly initiate an episode of deep-water sedimentation without transition from the preceding condition. Adjustment can be manifested in many ways and is not dependent on recognition of a singular criterion, like a mass transport event, despite the fact that this is a common element likely to occur during the adjustment phase.

Simply put, these nested stratigraphic models represent a flexible workflow that guides scientific inquiry. The models are derived from the Brushy Canyon Formation study, but replication of these sedimentation patterns is not required for model application. This study simply represents a complete but singular example of deep-water system behavior and evolution, where all possible configurations exist and, more importantly, have been documented in detail through long-term support of an outcrop study.

The stratigraphic models force the user to ask questions of their data, approach data analysis systematically, and analyze multiple temporal scales at any spatial window. In this way, the models deploy Bayesian logic trees that ask a series of guided—if/then—questions that reduce the number of options through iterative analysis. As with the application of any model, success is dependent on data constraints (quality and quantity) and understanding of the model limitations. For example, it is important to consider scale when defining depocenters for AIGR definition. If only the retreat phase deposits of the UBC in outcrop are considered (roughly equivalent to a 3 mile by 3 mile Gulf of Mexico lease block), then it represents the thickest interval. Based on this limited data window, this observation has been advanced as evidence of offlap and not onlap (Zelt and Rossen, 1995; Beaubouef *et al*., 1999). When considered at the scale of the basin, however, the UBC strata represent the smallest volume unit that happens to be positioned near the basin margin, where the outcrop exposes a biased view (Figs. 19 and 25; Romans, 2003; Baptista, 2004).

The concept of sedimentary system energy is considered more all-encompassing (and realistic) than seeking to unravel individual internal and external forcing functions from the composite and incomplete signal preserved as the sedimentary record. Combined with gradient, the temporal energy phases of the AIGR and BCFS models provide a matrix for all possible deep-water sedimentation patterns.

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