Sequence stratigraphy: common ground after three decades of development

O. Catuneanu[1*], J.P. Bhattacharya[2], M.D. Blum[3], R.W. Dalrymple[4], P.G. Eriksson[5], C.R. Fielding[6], W.L. Fisher[7], W.E. Galloway[8], P. Gianolla[9], M.R. Gibling[10], K.A. Giles[11], J.M. Holbrook[12], R. Jordan[13], C.G.St.C. Kendall[14], B. Macurda[15], O.J. Martinsen[16], A.D. Miall[17], D. Nummedal[18], H.W. Posamentier[19], B.R. Pratt[20], K.W. Shanley[21], R.J. Steel[22], A. Strasser[23] and M.E. Tucker[24]

Abstract

Sequence stratigraphy emphasizes changes in stratal stacking patterns in response to varying accommodation and sediment supply through time. Certain surfaces are designated as sequence or systems tract boundaries to facilitate the construction of realistic and meaningful palaeogeographic interpretations, which, in turn, allows for the prediction of facies and lithologies away from control points. Precisely which surfaces are selected as sequence boundaries varies from one sequence stratigraphic approach to another. In practice, the selection is often a function of which surfaces are best expressed, and mapped, within the context of each case study. This high degree of variability in the expression of sequence stratigraphic units and bounding surfaces requires the adoption of a methodology that is sufficiently flexible to accommodate the wide range of possible scenarios in the rock record. We advocate a model-independent methodology that requires the identification of all sequence stratigraphic units and bounding surfaces, which can be delineated on the basis of facies relationships and stratal stacking patterns using the available data. Construction of this framework ensures the success of the method in terms of its objectives to provide a process-based understanding of the stratigraphic architecture and predict the distribution of reservoir, source-rock, and seal facies.

[1] *Department of Earth and Atmospheric Sciences, University of Alberta, 1-26 Earth Sciences Building, Edmonton, Alberta, T6G 2E3, Canada.*
[2] *Geosciences Department, University of Houston, Houston, Texas 77204-5007, USA.*
[3] *ExxonMobil Exploration Company, Houston, Texas 77060, USA.*
[4] *Department of Geological Sciences and Geological Engineering, Queen's University, Kingston, Ontario K7L 3N6, Canada.*
[5] *Department of Geology, University of Pretoria, 0002 Pretoria, South Africa.*
[6] *Department of Geosciences, University of Nebraska-Lincoln, Nebraska 68588-0340, USA.*
[7] *Jackson School of Geosciences, The University of Texas at Austin, Austin, Texas 78712, USA.*
[8] *Institute for Geophysics, The University of Texas at Austin, Austin, Texas 78758-4445, USA.*
[9] *Dipartimento di Scienze della Terra, Polo Scientifico e Tecnologico, Via Saragat 1 - Blocco B, 44100 Ferrara, Italy.*
[10] *Department of Earth Sciences, Dalhousie University, Halifax, Nova Scotia, B3H 4J1, Canada.*
[11] *Institute of Tectonic Studies, New Mexico State University, P.O. Box 30001, Las Cruces, New Mexico 88003, USA.*
[12] *Department of Geology, The University of Texas at Arlington, Texas 76019-0049, USA.*
[13] *Jordan Geology, Centreville, Delaware, USA.*
[14] *Department of Geological Sciences, University of South Carolina, Columbia, South Carolina 29208, USA.*
[15] *The Energists, 10260 Westheimer, Suite 300, Houston, Texas 77042, USA.*
[16] *StatoilHydro Technology and New Energy, PO Box 7200, 5020 Bergen, Norway.*
[17] *Department of Geology, University of Toronto, Toronto, Ontario, M5S 3B1, Canada.*
[18] *Colorado Energy Research Institute, Colorado School of Mines, Golden, Colorado 80401, USA.*
[19] *Chevron Energy Technology Company, Houston, Texas, USA.*
[20] *Department of Geological Sciences, University of Saskatchewan, Saskatoon, Saskatchewan S7N 5E2, Canada.*
[21] *The Discovery Group, 1560 Broadway, Suite 1470, Denver, Colorado 80202, USA.*
[22] *Department of Geological Sciences, The University of Texas at Austin, Austin, Texas 78712, USA.*
[23] *Department of Geosciences, University of Fribourg, CH-1700 Fribourg, Switzerland.*
[24] *Department of Earth Sciences, Durham University, Durham DH1 3LE, UK.*
* *Corresponding author, E-mail: octavian@ualberta.ca*

Introduction

Since its inception in the 1970s, sequence stratigraphy has developed into the fundamental approach for understanding and predicting the distribution of sediment bodies. Using this approach, stratal stacking patterns are analysed within a temporal framework. Stratal stacking patterns evolve in response to the interplay of accommodation (space available for sediments to fill) and sedimentation, and reflect combinations of depositional trends that include progradation, retrogradation, aggradation, and downcutting (e.g., Posamentier et al., 1988; Galloway, 1989; Mitchum and Van Wagoner, 1991; Hunt and Tucker, 1992; Posamentier and Allen, 1999; Plint and Nummedal, 2000; Schlager, 2005; Catuneanu, 2006; Catuneanu et al., 2009; Neil and Abreu, 2009). Thus, sequence stratigraphy is a genetic, process-based approach to stratigraphy, unlike other methods including lithostratigraphy and biostratigraphy which aim for subdivisions that involve as little interpretation of process as possible.

Sequence stratigraphy is a working methodology that emphasizes the importance of breaks in the stratigraphic record for the definition of sequences. It is also an analytical procedure that provides a framework for stratigraphic units and their bounding surfaces elated to their genesis. The sequence stratigraphic approach yields depositional patterns through the analysis of the order in which strata were laid down, and explains the geometric relationships of sedimentary strata and the elements formed by the strata. Different possible sequence stratigraphic expressions also may dependent on the allochthonous versus autochthonous nature of the sediment (e.g., terrigenous versus carbonate or evaporite settings). Combining these affords the prediction of the nature of sedimentary deposits at locations away from data control points.

A sequence stratigraphic framework provides the context within which to understand the origin of depositional elements within any particular depositional setting. This framework can be established through the analysis of a variety of datasets that include core, well logs, seismic data, petroleum production data (e.g., formation pressure), and outcrops. Local differences in depositional processes, topography, and tectonics often mean that one conceptual depositional model is more appropriate or easier to apply and specific to a particular setting than others. This can make choosing the appropriate approach a preference of the individual interpreter. The interpreter also may be guided towards a specific choice of approach by the type of data available in each particular case study.

In spite of its popularity among geoscientists in academia, industry, and government organizations, sequence stratigraphy remains a stratigraphic method that is not formalized in stratigraphic guides or codes. This reflects the existence of different approaches for applying sequence stratigraphy to the rock record (Figures 1 and 2). To acquire formalization, sequence stratigraphy requires the definition of a model-independent methodology that honours the various approaches but transcends their differences. A single set of terms is also required so as to facilitate communication between geoscientists adopting this approach.

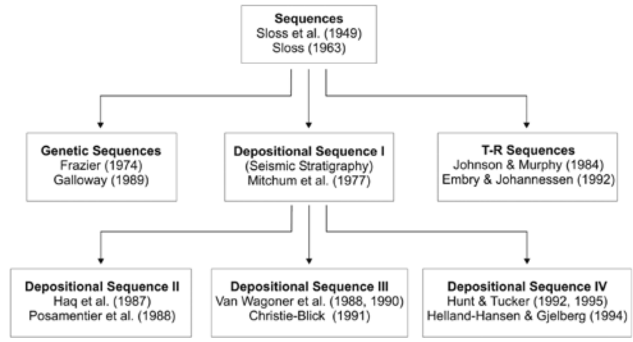

***Figure 1** Evolution of sequence stratigraphic approaches. Modified from Catuneanu et al. (2009).*

The present paper is the result of the continuing effort to identify a solution for the inclusion of sequence stratigraphy in international stratigraphic guides and codes. Work started in 2006 with the premise that a large and inclusive working group, as reflected in the authorship of this paper, is required to address this issue. With this paper we summarize in part, and build upon, the work published by Catuneanu et al. (2009).

Building blocks of the sequence stratigraphic framework

Fundamental principles

A sequence stratigraphic framework may consist of three different types of sequence stratigraphic unit, namely sequences, systems tracts, and parasequences. Each type of unit is defined by specific facies relationships, stratal stacking patterns, and bounding surfaces. The definition of these units is independent of temporal and spatial scales, and of the mechanism of formation.

The sequence stratigraphic framework records the response to both allogenic and autogenic controls on sedimentation. Autogenic mechanisms, such as channel avulsion or delta lobe switching, modulate the internal architecture of facies successions and depositional elements within the larger scale allogenic-controlled frameworks. The relevance of allogenic controls to the sequence stratigraphic architecture increases with the vertical and/or lateral scale of observation, whereas the importance of autogenic processes becomes more evident at smaller scales of observation. Sequences and systems tracts are commonly attributed to allogenic controls, whereas parasequences may be generated by either allogenic or autogenic mechanisms.

Allogenic factors, such as tectonism, climate, and sea-level change, control accommodation which is the space available for sediments to fill (Jervey, 1988). At any specific time and location within a sedimentary basin, the amount of available space, or accommodation envelope, is defined at the top by a surface of equilibrium up to which sediments can aggrade (or degrade), and at the base by the top of the sediment column

(Posamentier and Allen, 1999; Holbrook et al., 2006). Through time, the accommodation envelope may increase (i.e., positive accommodation) or decrease (i.e., negative accommodation) in response to the interplay between the various allogenic controls on basin evolution and sedimentation (Miall, 1997; Posamentier and Allen, 1999; Catuneanu, 2006).

Positive accommodation results in aggradation, potentially accompanied by progradation or retrogradation. Negative accommodation results in degradation and the formation of erosional surfaces. Autocyclicity affects sediment dispersal patterns, and hence it modifies the amount of sediment that is delivered to a particular location through time. Fluctuations in sediment supply also may be triggered by allogenic mechanisms, such as climate change. This can affect, in terrigenous settings, the rates of weathering as well as fluvial discharge and transport capacity, and in carbonate settings, circulation and salinity which influence the carbonate factory. Consequently, both allogenic and autogenic kinds of controls, as well as changes in accommodation or sediment supply, may result in the formation of cycles in the rock record.

Sequences

A 'sequence' was originally defined as an unconformity-bounded stratigraphic unit (Sloss et al., 1949; Sloss, 1963). The concept of sequence was subsequently revised to include 'a relatively conformable succession of genetically related strata bounded by unconformities or their correlative conformities' (Mitchum, 1977). The continued development of the sequence stratigraphic paradigm in the 1980s and 1990s resulted in a diversification of approaches and the definition of several types of sequence (Figures 1 and 2): depositional sequences, bounded by subaerial unconformities and their marine correlative conformities (e.g., Posamentier et al., 1988; Van Wagoner et al., 1988, 1990; Hunt and Tucker, 1992); genetic stratigraphic sequences, bounded by maximum flooding surfaces (Galloway, 1989); and transgressive-regressive (T-R) sequences, also referred to as T-R cycles, bounded by maximum regressive surfaces (Johnson and Murphy, 1984; Johnson et al., 1985). The T-R sequence was subsequently redefined by Embry and Johannessen (1992) as a unit bounded by composite surfaces that include the subaerial unconformity and the marine portion of the maximum regressive surface.

A depositional sequence forms during a full cycle of change in accommodation, which involves both an increase (positive) and decrease (negative) in the space available for sediments to fill. The formation of depositional sequence boundaries requires periods of negative accommodation.

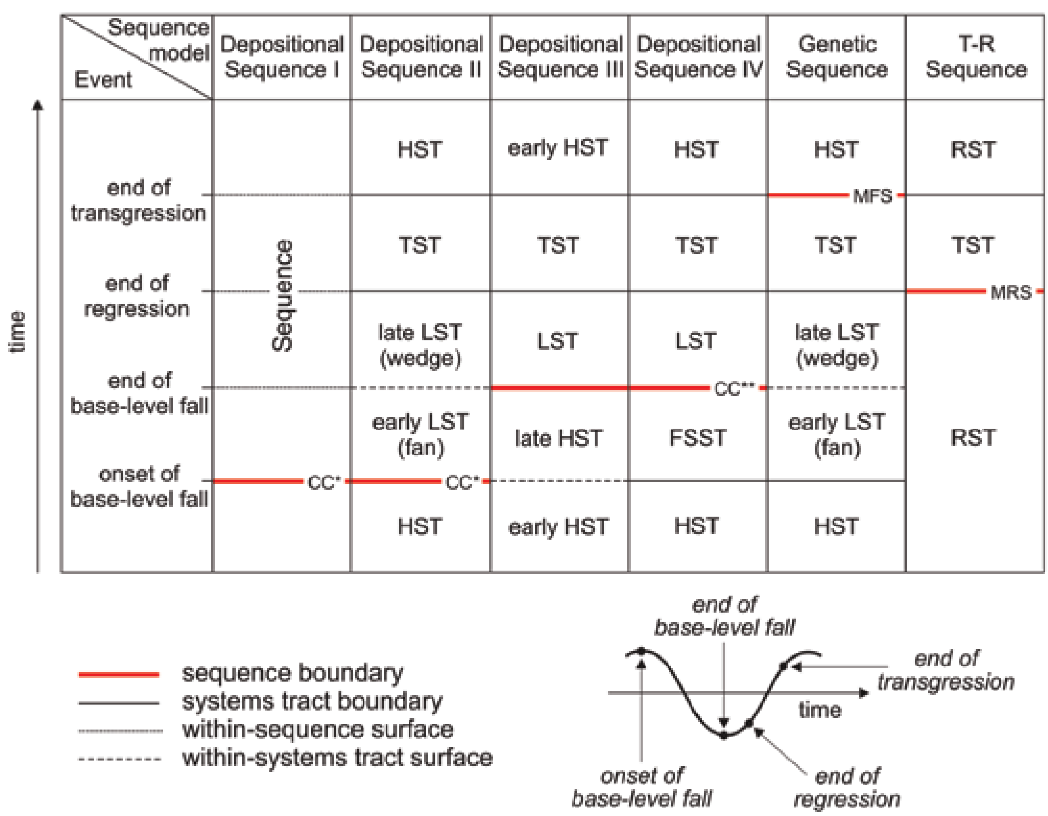

Figure 2 *Nomenclature of systems tracts, and timing of sequence boundaries for the various sequence stratigraphic approaches. LST – lowstand systems tract; TST – transgressive systems tract; HST – highstand systems tract; FSST – falling-stage systems tract; RST – regressive systems tract; T-R – transgressive-regressive; CC* – correlative conformity in the sense of Posamentier and Allen (1999); CC** – correlative conformity in the sense of Hunt and Tucker (1992); MFS – maximum flooding surface; MRS – maximum regressive surface. References for the proponents of the various sequence models are provided in Figure 1.*

The dependency of depositional sequences on negative accommodation (whether in continental or marine environments), in addition to the nature of bounding surfaces, separates depositional sequences from other types of sequence stratigraphic unit, the formation of which may not require negative accommodation (i.e., parasequences, genetic stratigraphic sequences, T-R sequences in the sense of Johnson and Murphy (1984), and systems tracts that form during positive accommodation).

The formation of genetic stratigraphic sequences depends on the development of maximum flooding surfaces, which form during times of positive accommodation. A genetic stratigraphic sequence may form during a full cycle of change in accommodation, as in the case of a depositional sequence, but it may also form during periods of positive accommodation in response to fluctuations in the rates of accommodation creation and/or sediment supply. Consequently, a genetic stratigraphic sequence may or may not include an internal subaerial unconformity, depending on whether or not the corresponding cycle includes a stage of negative accommodation. Maximum flooding surfaces may include unconformable portions expressed as 'hiatal surfaces preserved as marine unconformities' (Galloway, 1989). Such unconformities may develop on the shelf and slope because of sediment starvation, shelf-edge instability and erosion during transgression. Where present, unconformable maximum flooding surfaces are included within but do not constitute the bounding surfaces defining depositional sequences and T-R sequences.

The original T-R sequence of Johnson and Murphy (1984) depends on the development of maximum regressive surfaces, which form during times of positive accommodation. As in the case of genetic stratigraphic sequences, this type of sequence may form during a full cycle of change in accommodation, but it may also form during periods of positive accommodation as a result of fluctuations in the rates of accommodation and/or sediment supply. By contrast, the T-R sequence of Embry and Johannessen (1992) is dependent on negative accommodation, as it requires a subaerial unconformity at the sequence boundary. As the maximum regressive surface is younger than the subaerial unconformity, the marine portion of the maximum regressive surface may or may not meet with the basinward termination of the subaerial unconformity (Embry and Johannessen, 1992). The temporal and spatial offset between the two portions of the sequence boundary is increasingly evident at larger scales of observation (Catuneanu et al., 2009).

Mitchum's (1977) definition of a sequence, which depends on recognition of unconformities, poses two problems. Firstly, every type of sequence may include unconformities *within* the sequence: depositional sequences and T-R sequences can include marine surfaces of non-deposition or erosion that can form during times of maximum shoreline transgression (i.e., unconformable maximum flooding surfaces); genetic stratigraphic sequences can contain surfaces that record stages of subaerial hiatus and erosion (i.e., subaerial unconformities). Strata in juxtaposition across such internal unconformities may not be genetically related. Secondly, the potential presence of unconformities within a sequence also indicates that the succession of strata cannot always be described as relatively conformable. For these reasons, the concept of sequence was redefined as 'a succession of strata deposited during a full cycle of change in accommodation or sediment supply' (Catuneanu et al., 2009). This definition is generic, model-independent, and embraces all types of sequence that may develop at any spatial or temporal scale. It is flexible in that one can choose to start and end an accommodation or sediment flux cycle at any point; however, internal consistency of approach is required.

Larger scale (lower frequency) sequences consist of stacked smaller scale (higher frequency) sequences. The pattern of stacking of high frequency sequences defines the systems tracts of larger scale sequences.

Systems tracts

A systems tract is 'a linkage of contemporaneous depositional systems, forming the subdivision of a sequence' (Brown and Fisher, 1977). The definition of a systems tract is independent of spatial and temporal scales. The internal architecture of a systems tract may vary greatly with the scale of observation, from a succession of facies (e.g., in the case of high frequency sequences driven by orbital forcing) to a parasequence set (see the definition of a parasequence below) or a set of higher frequency sequences.

A systems tract consists of a relatively conformable succession of genetically related strata bounded by conformable or unconformable sequence stratigraphic surfaces. As discussed by Catuneanu et al. (2009), the original definition of a sequence provided by Mitchum (1977) is more applicable to the concept of systems tracts than it is to the concept of sequence. This is because sequences may include internal unconformities, whereas such unconformities, where present, are always placed at the boundary between systems tracts. This discussion considers sequences, systems tracts and bounding surfaces that develop at the same hierarchical level: discontinuities of a higher frequency can occur within a sequence or systems tract without violating the above definitions.

Systems tracts are interpreted on the basis of stratal stacking patterns, position within the sequence, and types of bounding surface (Van Wagoner et al., 1987, 1990; Posamentier et al., 1988; Van Wagoner, 1995; Posamentier and Allen, 1999). Systems tracts may be either shoreline-associated, where their origin can be related to particular types of shoreline trajectory, or shoreline-independent, where a genetic link to coeval shoreline shifts cannot be determined. In both cases, however, the formation of systems tracts reflects the interplay of the same two fundamental variables, namely accommodation (whether marine or fluvial) and sediment supply. Therefore, all systems tracts are conceptually related, regardless of where they occur.

Shoreline-associated systems tracts consist of packages of strata that correspond to particular types of shoreline trajectory (i.e., forced regressive, normal regressive, transgressive; Figure 3). These types of shoreline trajectory may be observed at different scales, and are defined by distinct stratal stacking patterns (e.g., Helland-Hansen and Martinsen, 1996).

Forced regression is characterized by a combination of progradational and downstepping stacking patterns (Figures 3, 4, 5, and 6). This type of shoreline trajectory is interpreted as the result of negative accommodation at the shoreline (Posamentier et al., 1992b). Sediment supply can only modify the rate of forced regression: the higher the sediment influx the greater the rates of basinward shoreline shift. The systems tract nomenclature applied to forced regressive deposits includes 'early lowstand', 'late highstand', 'forced-regressive wedge', and 'falling-stage' (Figure 2).

Normal regression is characterized by a combination of progradational and aggradational stacking patterns (Figures 3, 4, and 6). This type of shoreline trajectory is interpreted as the result of positive accommodation, where sedimentation outpaces the creation of accommodation at the shoreline. In the case of stratigraphic cycles that include a stage of negative accommodation, as well as a stage of transgression, normal regressions can occur during both lowstands and highstands of relative sea level and consequently may be classified as 'lowstand' and 'highstand' (Figure 6). The systems tract nomenclature applied to lowstand normal regressive deposits includes 'late lowstand' and 'lowstand' (Figure 2). Highstand normal regressive deposits are designated as 'highstand' or 'early highstand' systems tracts (Figure 2).

Transgression is characterized by a retrogradational stacking pattern (Figures 3, 4, and 7). This type of shoreline trajectory is interpreted as the result of positive accommodation, whereby the creation of accommodation at the shoreline outpaces sedimentation. By definition, transgressive deposits comprise the transgressive systems tract (Figure 2). Transgressive systems tracts may be condensed or absent on shelves that are starved because sediment is trapped in fluvial and coastal systems during the landward shift of the shoreline (Loutit et al., 1988). Under certain circumstances, such as where coastline backstepping occurs as a result of beach erosion caused by high wave energy, transgression can be independent of the interplay between accommodation and sediment supply (Leckie, 1994). In this special instance, erosion and bypass, rather than aggradation, characterizes the transgressive systems tract.

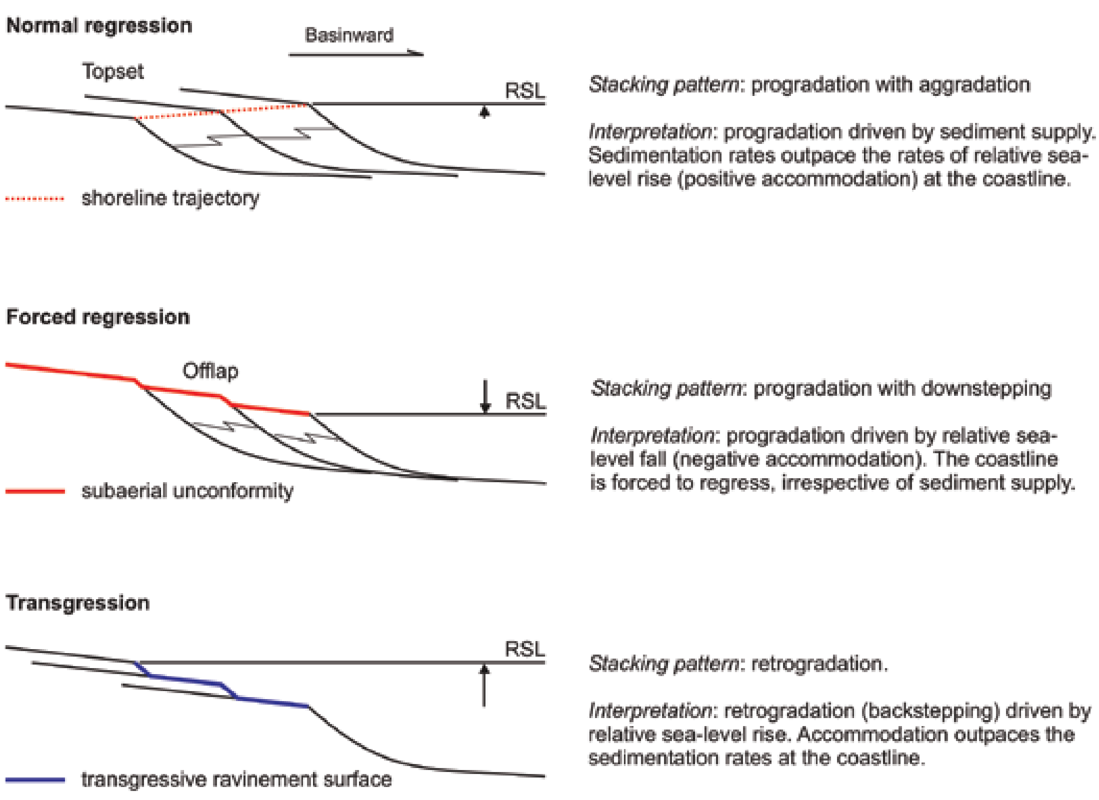

Figure 3 *Stratal stacking patterns that define the genetic types of deposit which are the fundamental building blocks of the sequence stratigraphic framework: normal regressive, forced regressive and transgressive. Zigzag lines indicate lateral changes of facies within individual sedimentary bodies. The diagram shows the possible types of shoreline trajectory during changes (rise or fall) in relative sea level. During a stillstand of relative sea level (not shown), the shoreline may undergo sediment-driven progradation (normal regression, where the topset is replaced by toplap), erosional transgression, or no movement at all. However, due to the complexity of independent variables that interplay to control relative sea level change, it is unlikely to maintain stillstand conditions for any extended period of time. RSL – relative sea level.*

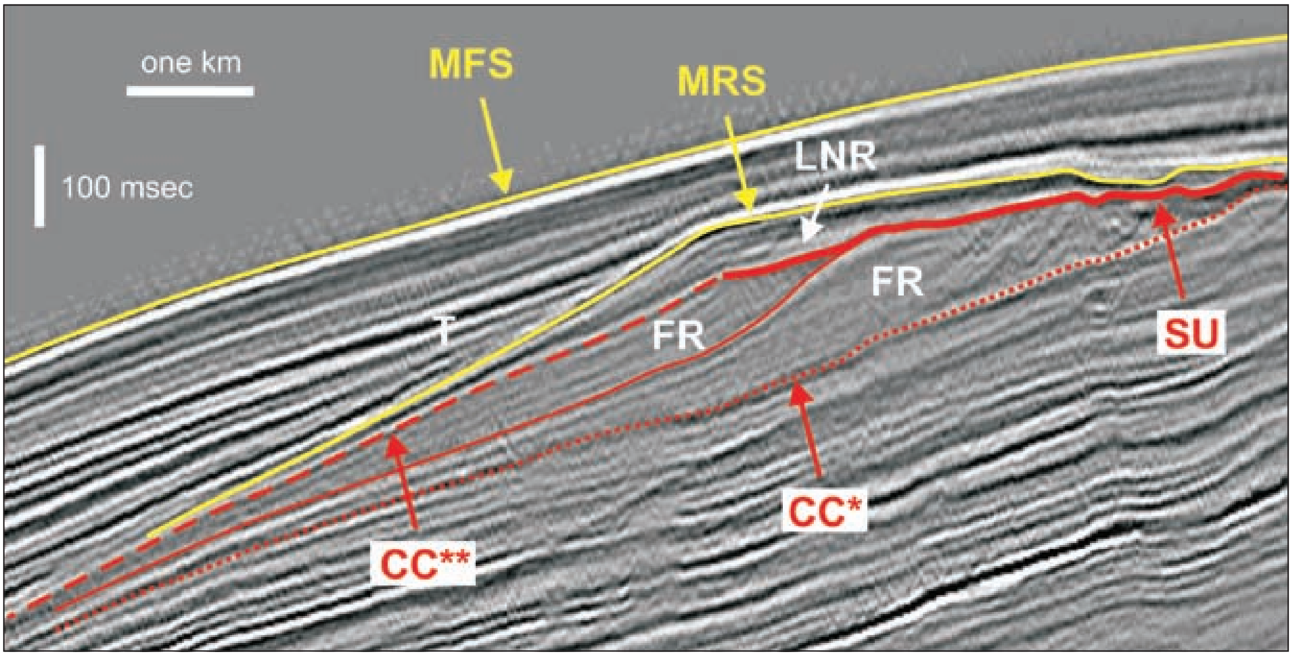

Figure 4 *Seismic line in the Gulf of Mexico showing different genetic types of deposit (forced regressive, normal regressive, transgressive) and sequence stratigraphic surfaces. FR – forced regressive; LNR – lowstand normal regressive; T – transgressive; SU – subaerial unconformity; CC* – correlative conformity in the sense of Posamentier and Allen (1999) (= basal surface of forced regression); CC** – correlative conformity in the sense of Hunt and Tucker (1992); MRS – maximum regressive surface; MFS – maximum flooding surface. Modified from Posamentier and Kolla (2003).*

Figure 5 *Modern forced regressive delta (Svalbard) showing a stratal stacking pattern defined by a combination of progradation and downstepping (photograph courtesy of Jean-Loup Rubino). In this case, the fall in relative sea level is driven by post-glacial isostatic rebound at a rate that exceeds the rate of eustatic sea level rise.*

Not all systems tracts in each sequence are necessarily preserved everywhere because of local subsequent erosion. Moreover, not all systems tracts are necessarily deposited everywhere because syn-sedimentary conditions may not allow one or more systems tracts to form. Where stratigraphic units cannot be tied directly to changes in shoreline trajectory, shoreline-independent systems tracts may be defined based on changes in depositional style that can be recognized and correlated regionally. Processes in an upstream-controlled fluvial setting may be unrelated to changes in accommodation at the shoreline, but fluvial accommodation may change and create sequences and systems tracts (Posamentier and

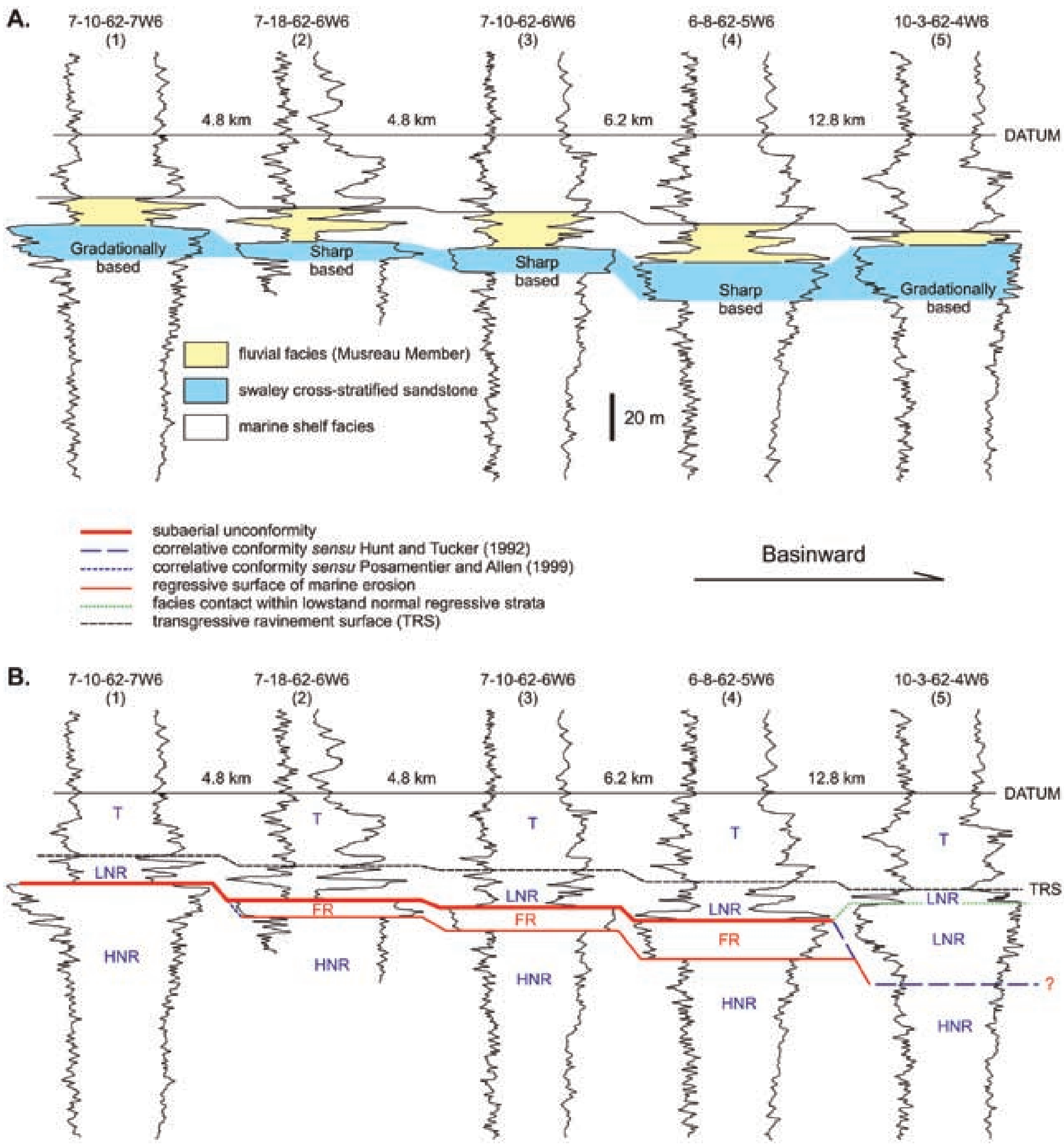

***Figure 6** Sequence stratigraphic interpretation of the swaley cross-stratified sandstone of the Kakwa Member (Cardium Formation), and adjacent units. The datum is represented by a flooding surface within the Muskiki marine shale. A. Sedimentary facies. B. Sequence stratigraphic interpretation. The interpretation is based on the following observations: 1. the shoreface displays coarsening-upward trends in all five wells; 2. the shoreface is gradationally based in wells (1) and (5), and it is sharp-based in wells (2), (3) and (4); 3. the top of the shoreface downsteps from well (1) to well (4), and upsteps from well (4) to well (5); 4. the sharp-based shoreface thins out toward the basin margin; and 5. the shoreface is overlain by non-marine facies in all five wells. The gradationally-based shoreface indicates normal regression (highstand to the left; lowstand to the right), whereas sharp-based shoreface is diagnostic for forced regression. These criteria afford the separation of normal from forced regressive deposits in the absence of seismic data. FR – forced regressive; HNR – highstand normal regressive; LNR – lowstand normal regressive; T – transgressive. Modified after Plint (1988).*

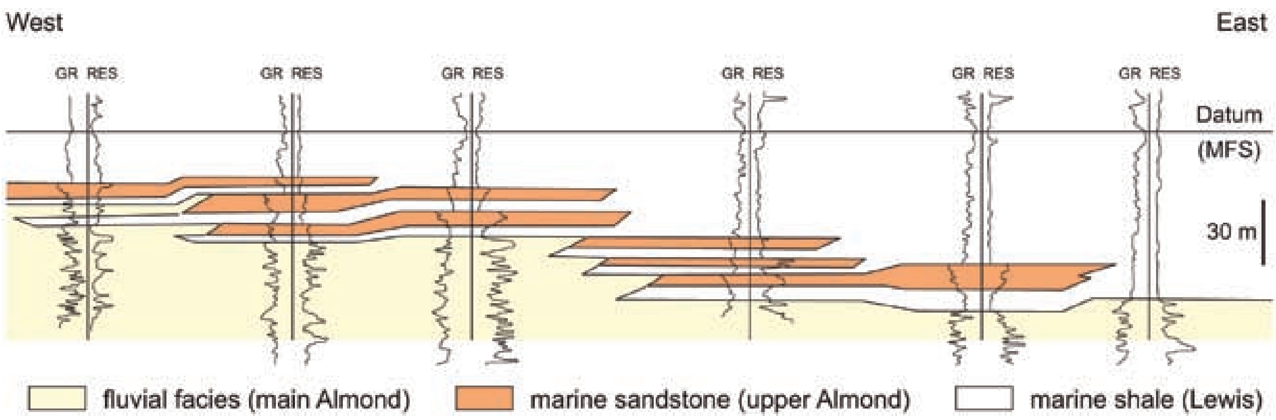

Figure 7 *Regional well log cross-section of the Almond Formation in the Washakie Basin, Wyoming. The backstepping stacking pattern of parasequences records the westward transgression of the Western Interior Seaway during the Campanian. The cross-section is approximately 65 km long. Well logs shown: gamma ray (GR) and resistivity (RES). Modified from Weimer (1966), Martinsen and Christensen (1992), and C. Bartberger (pers. comm.).*

Allen, 1999). In such inland settings, fluvial systems tracts may be defined based on changes in the degree of amalgamation of channel deposits (e.g., Shanley and McCabe, 1994; Boyd et al., 2000). Similarly, offshore sub-basin tectonism may generate sequences in a manner that is independent of changes in accommodation at the shoreline (e.g., Fiduk et al., 1999). In such deep-water settings, systems tract boundaries can be placed at the contact between weakly confined channel deposits (e.g., a splay-dominated succession) and overlying leveed channel-dominated deposits (Posamentier and Kolla, 2003; Posamentier and Walker, 2006).

Parasequences

A parasequence is an upward-shallowing succession of facies bounded by marine flooding surfaces (Van Wagoner et al., 1988, 1990). Parasequences can form and prograde during periods of overall positive accommodation (i.e., normal regression or transgression) or overall negative accommodation (i.e., forced regression) (Posamentier and Allen, 1999); however, negative accommodation does not occur during the time of formation of the parasequence boundary. The concept was originally defined, and it is commonly applied, within the context of siliciclastic coastal to shallow water settings, where parasequences correspond to individual prograding sediment bodies. In carbonate settings, a parasequence corresponds to a succession of facies that reflects a cycle of increase and decrease in the rate of carbonate production; commonly, a shallowing-upward peritidal cycle.

Parasequences are commonly nested within sequences and systems tracts; however, scale and hierarchical relationships are not the criteria that differentiate parasequences from sequences. There are high frequency sequences controlled by orbital forcing which may develop at scales comparable to, or even smaller than, those of many parasequences (e.g., Bartek et al., 1991, 1997; Naish and Kamp, 1997; Strasser et al., 1999; Fielding et al., 2000, 2001, 2006, 2008; Naish et al., 2001; Figure 8). Some of these high frequency sequences, particularly those developed in carbonate settings, may consist only of a succession of facies rather than sets of parasequences.

In contrast to sequences and systems tracts, which may potentially be mapped across an entire sedimentary basin from fluvial into the deep water setting, parasequences are geographically restricted to the coastal to shallow water areas where marine flooding surfaces may form. Parasequences cannot be mapped in fully fluvial and deep water settings, where the concept of flooding surface does not apply (Posamentier and Allen, 1999).

The mappability of parasequences depends on the development of their bounding surfaces. A marine flooding surface is a lithological discontinuity across which there is an abrupt shift of facies that commonly indicates an abrupt increase in water depth (Van Wagoner et al., 1988, 1990). However, not all parasequence-type successions include lithological discontinuities that define flooding surfaces. Whether or not flooding surfaces can be identified, high frequency maximum flooding and maximum regressive surfaces are always present to define *cycles of change in depositional trend* (i.e., progradation–retrogradation cycles; Figure 9). In such cases, the concepts of high frequency genetic stratigraphic sequence or T-R cycle may be more readily applicable to define mappable units (e.g., Spence and Tucker, 2007). The wider applicability of high-frequency genetic stratigraphic sequences and T-R cycles over parasequences is also evident in the case of facies successions dominated by the deepening-, rather than the shallowing-upward, portion of the cycle (e.g., Catuneanu et al., 1999).

Parasequences consist of the same genetic types of deposit (i.e., normal regressive, transgressive, forced regressive) as any other type of sequence stratigraphic unit. Parasequences may be stacked in an upstepping succession, in which case they consist of normal regressive and transgressive deposits that accumulate during a period of positive accommodation in response to variations in the rates of accommodation and/or sediment supply (Figure 9). Parasequences may also be stacked in a downstepping succession, in which case they

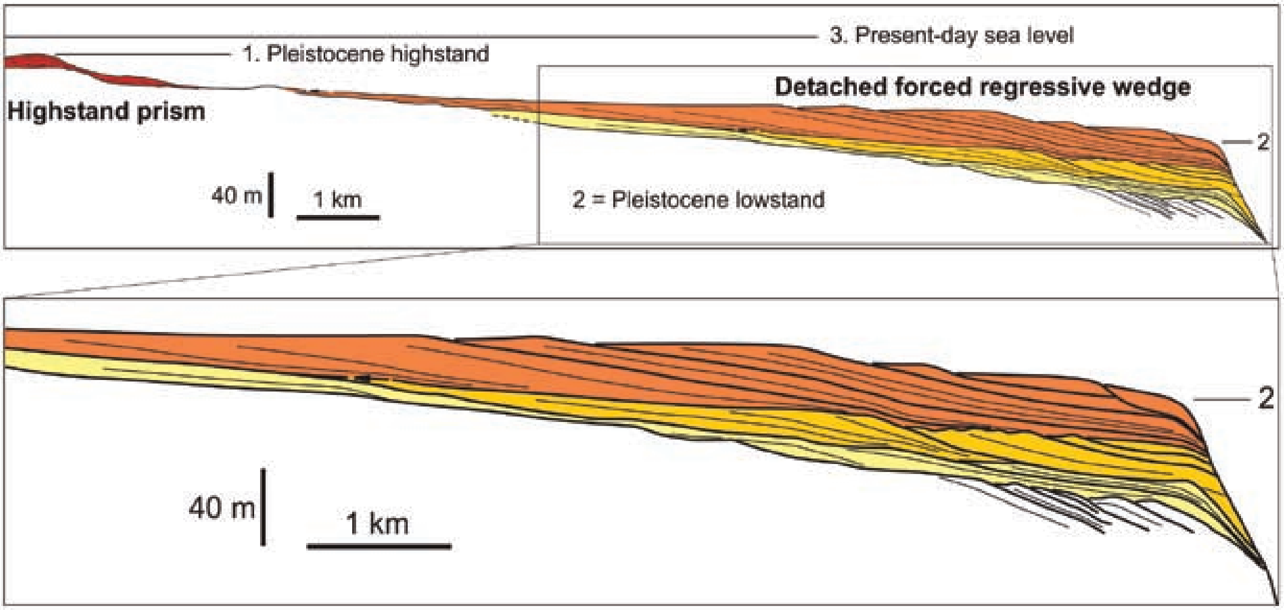

Figure 8 *Cross-section through Pleistocene deposits of the Rhône shelf (offshore southeastern France), based on a regional seismic line. The three unconformity-bounded depositional sequences correspond to high frequency glacial-interglacial cycles. Each sequence consists primarily of forced regressive deposits, which show a lateral stacking of downstepping parasequences. Modified from Posamentier et al. (1992b).*

consist primarily of forced regressive deposits that accumulate during a period of overall negative accommodation (Figure 8). This process results in 'foreshortened' successions wherein the compaction-corrected thickness of the parasequence is significantly less than the water depth change from the deepest palaeo water depth within the parasequence to that at the top of the parasequence (Posamentier and Allen, 1999, Figure 4.49). The pattern of stacking of parasequences defines longer term normal regressive, forced regressive or transgressive shoreline trajectories (Figure 3).

Sequence stratigraphic surfaces

Sequence stratigraphic surfaces are surfaces that can serve, at least in part, as systems tract boundaries. Seven sequence stratigraphic surfaces (Figures 4 and 6) have been defined and are currently in use:

- subaerial unconformity;
- correlative conformity in the sense of Posamentier et al. (1988);
- correlative conformity in the sense of Hunt and Tucker (1992);
- maximum flooding surface;
- maximum regressive surface;
- transgressive ravinement surface; and
- regressive surface of marine erosion.

A full discussion concerning the timing of formation of these surfaces, the processes involved in their formation, and the criteria that can be used to recognize them in the rock record, is provided by Catuneanu et al. (2009).

All sequence stratigraphic surfaces are to some extent diachronous (e.g., Martinsen and Helland-Hansen, 1995; Catuneanu et al., 1998; Catuneanu, 2006; Martin et al., 2009). This may make it difficult to correlate sequences and systems tracts, particularly along strike, as they may overlap partially in time (e.g., Posamentier and Allen, 1999; Anderson, 2005). Therefore, the interpretation of sequence stratigraphic units and bounding surfaces within a sedimentary basin, or sub-basin, cannot be based on time correlations with cycle charts constructed on the basis of data derived from other sedimentary basins, or even other areas within the same sedimentary basin. Any curves that describe changes in accommodation through time may only have local significance.

The degree of diachroneity associated with various types of sequence boundary depends on changes in tectonic regimes and sediment supply between different areas of sediment accumulation. In a relative sense the larger the scale of the sequence the less the significance of the diachroneity of bounding surfaces, even though the actual diachroneity of surfaces can increase as the scale of observation increases. For example, break-up unconformities that mark the end of supercontinent cycles can be highly diachronous, in a range of millions of years, but this diachroneity may be regarded as minimal compared with the duration of the sequence. At the opposite end of the spectrum, small scale sequences (e.g., related to Milankovitch cycles) may be bounded by surfaces the diachroneity of which may be undetectable relative to the resolution of any available age dating technique. Therefore, a general correlation between the degree of diachroneity of a bounding surface and the scale or the duration of a sequence may be inferred.

Not all kinds of sequence stratigraphic surface form in every depositional setting. Surfaces that involve marine

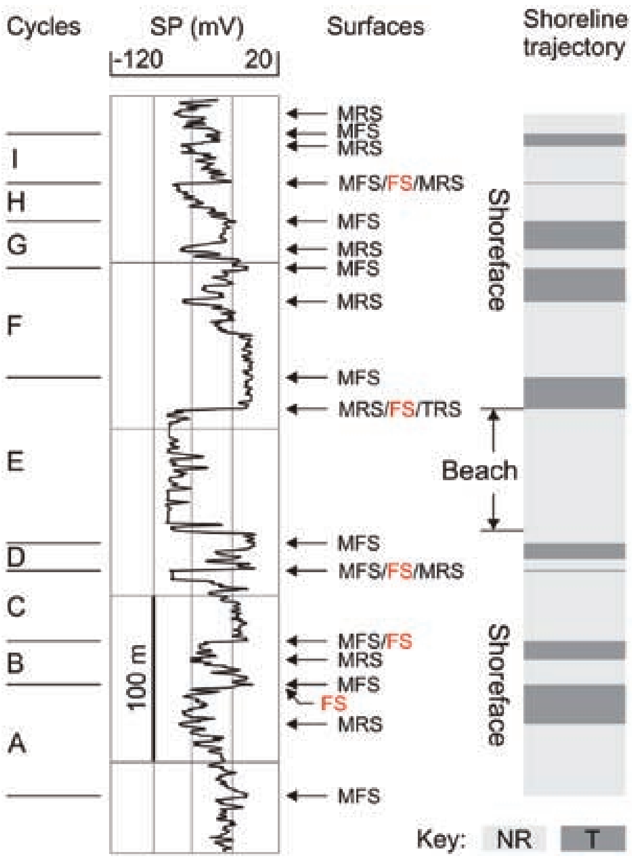

***Figure 9** Vertical stacking of parasequences in an upstepping succession (Gulf of Mexico; well log courtesy of PEMEX). In an aggrading (upstepping) succession, parasequences consist of normal regressive and transgressive types of deposit. The cycles that can be observed on this log may be described using the concepts of parasequence (i.e., bounded by flooding surfaces), high frequency genetic stratigraphic sequence (i.e., bounded by high frequency maximum flooding surfaces), or T-R cycle (i.e., bounded by maximum regressive surfaces). Whether or not flooding surfaces can be identified, high frequency maximum flooding and maximum regressive surfaces are always present to define cycles of change in depositional trend (i.e., progradation–retrogradation cycles). For this reason, the concepts of high frequency genetic stratigraphic sequence and T-R cycle are more widely applicable to define mappable units. SP – spontaneous potential log; MFS – maximum flooding surface; FS – flooding surface; MRS – maximum regressive surface; TRS – transgressive ravinement surface; NR – normal regression; T – transgression.*

processes, such as correlative conformities, the transgressive ravinement surface, and the regressive surface of marine erosion, are absent in a fully non-marine setting. Similarly, surfaces that involve subaerial erosion (i.e., the subaerial unconformity) or scouring in a shallow water setting (i.e., the transgressive ravinement surface or the regressive surface of marine erosion) are absent in the deep water setting. Only the area of transition between the downstream-controlled portion of the fluvial system and the shallow water setting offers the opportunity for the formation of all seven types of surface, and even then they seldom, if ever, all occur together within the same stratigraphic section.

Sequence stratigraphy places emphasis on subaerial unconformities and surfaces that form in relation to changes in shoreline trajectory. However, submarine unconformities in the deep marine record are also present, and they have been generally overlooked within the sequence stratigraphic paradigm. These, like surfaces in the upstream-controlled fluvial realm, may be shoreline independent, but carry the same sequence-stratigraphic significance. They are often the most prominent and regionally mappable surfaces in the deep water setting, and can serve as sequence boundaries. Like the subaerial unconformities, submarine unconformities also represent negative accommodation, only expressed differently. They have many causative agencies such as shifts of currents due to climatic and tectonic changes, widespread gravity flows triggered by tectonic tilt or sediment loading on the slope, or chemical unconformities due to a change in the ocean bottom water chemistry. The deep sea drilling project and ocean drilling programmes have recorded numerous examples of basin-wide submarine unconformities with significant chronostratigraphic gaps (Surlyk et al., 2008).

Submarine unconformities can have a clear expression on seismic sections, being associated with stratal terminations that indicate truncation below and onlap above. More effort is required in the future to tie regional submarine unconformities with sequence stratigraphic frameworks traditionally constructed for the non-marine to shallow water portions of a sedimentary basin. Tying shoreline-independent sediment bodies, either fully fluvial or deep water, to shoreline-associated sequence stratigraphic units and surfaces is similarly difficult but equally important for basin-scale 'source-to-sink' studies.

Hierarchy of sequences

An empirical classification of stratigraphic sequences using rank order designations, based on their duration, was devised by Vail et al. (1977). This classification is widely known, but has become increasingly unsatisfactory as more has been learned about sequences and their generating mechanisms. The quantitative study of the duration and thickness of stratigraphic sequences carried out by Drummond and Wilkinson (1996) concluded that 'discrimination of stratigraphic hierarchies and their designation as n^{th}-order cycles may constitute little more than the arbitrary subdivision of an uninterrupted stratigraphic continuum.' Schlager (2004) demonstrated that sequences are self-similar at a wide range of scales. He (2004, p. 185) stated: 'Orders of stratigraphic sequences are being used loosely and with widely varying definitions. The orders seem to be subdivisions of convenience rather than an indication of natural structure.' The scale-independent, fractal-like nature of stratigraphic cycles has also been demonstrated by means of laboratory experiments and modelling (e.g., Martin et al., 2009).

The conclusions of Drummond and Wilkinson (1996), Schlager (2004), and Martin et al. (2009) are particularly true for tectonically generated sequences. However, Milankovitch cycles may give discrete modes in the frequency distribution of sequence durations, albeit with slight change over geologic time, if they do not interfere with other sequence forming mechanisms that may operate within a similar range of temporal scales. Indeed, it is difficult to isolate the effects of any particular control on sequence development, since several independent sequence forming mechanisms commonly interact and contribute to the architecture of the preserved stratigraphic record (Miall, 1997).

With respect to high frequency sequences, if it can be demonstrated that the hierarchy in the stacking of sequences was induced by orbital cycles, then the potential for the creation of a high-resolution time scale is given (Strasser et al., 2006). Recent work also suggests that sub-Milankovitch millennial-scale cycles may be attributed to changes in the level of solar irradiance (Mawson and Tucker, 2009). In such instances, allogenic stratigraphic cycles may develop at centimetre to decimetre scale. Irrespective of the causal mechanism, it has become increasingly evident that the scale of stratigraphic cycles in the rock record varies across a broad continuum of thickness and time. As such, any boundaries between cycles attributed to different hierarchical levels are potentially artificial and misleading as to the duration of the cycle and the causative process.

It is useful, therefore, to refer to sequences in a descriptive and relative sense as being of lower versus higher frequency, or to make reference to their periodicity or episodicity in terms of the order of magnitude of the cycle frequency, e.g., 10^7-year episodicity for the six North American sequences defined by Sloss (1963). This is a flexible approach which implies no pre-judgments about sequence-generating mechanisms. Given that it is now recognized that there is a range of generating mechanisms (e.g., Miall, 1995; 1997), many of which operate across overlapping time scales, it is clearly desirable to retain a descriptive nomenclature.

In terms of efforts to assign approximate durations to sequences, progress has been made in quantifying the time required for shorelines to cross the shelf and to reach the shelf edge. These 'transit times' vary with a variety of shelf parameters, including shelf width and shelf processes, but generally fall within a range of 10^5 years (Burgess and Hovius, 1998; Muto and Steel, 2002). This helps to constrain the duration of sequences the formation of which involves full cross-shelf transits within the tectonic setting of a divergent continental margin (Figure 8). Such sequences can then be used as a reference for building a relative hierarchy that includes higher frequency sequences related to smaller magnitude changes in accommodation and sediment supply that result in partial cross-shelf transits, as well as lower frequency sequences within which the reference full cross-shelf transit sequences are nested.

Other hierarchical systems may be established starting from the sedimentary basin fill as the reference sequence, and defining higher frequency sequences as the basic subdivisions of lower frequency sequences (e.g., Catuneanu, 2006); or, alternatively, starting with the highest frequency cycle discernible as a reference unit and building the hierarchy up at increasingly larger scales of observation (e.g., Mitchum and Van Wagoner, 1991). The interplay of competing sequence-forming mechanisms makes the definition of discrete cutoffs (or modes) within the continuum of temporal and scalar measures of sequences difficult. As a result, hierarchical subdivisions often remain arbitrary and defined by common agreement amongst the users at the outset of each study. Therefore, any working model for a hierarchical system may be basin specific. This approach provides a flexible and empirical solution to a problem for which there is no universally applicable and accepted methodology for the definition of a hierarchy.

Conclusions: toward a common methodology

The existence of seemingly competing approaches has prevented the inclusion of sequence stratigraphy in stratigraphic codes or guides. The various approaches differ in terms of (1) the nomenclature of systems tracts and sequence stratigraphic surfaces, and (2) the selection of surfaces that should be elevated to the rank of sequence boundary (Figure 2). Despite the strength of the views for and against the various approaches, neither of these aspects impacts the successful application of the sequence stratigraphic method. Best practice requires the identification in a stratigraphic succession of all potential sequence stratigraphic surfaces and the genetic types of deposit that are bounded by them (Figure 10). This model independent methodology provides the practitioner with the greatest number of tools to build a sequence stratigraphic framework in a manner that is independent of any particular approach. The definition of a common ground methodology not only eliminates unnecessary confusion and debate, but also facilitates the formal inclusion of sequence stratigraphy in stratigraphic codes and guides.

The recognition of stratal stacking patterns that define normal regressive, forced regressive and transgressive types of deposit is the common denominator and essential first step for any sequence stratigraphic study in which the stratigraphic architecture can be related to changes in shoreline trajectory. These genetic types of deposit represent the building blocks of a sequence stratigraphic framework, which, at various scales of observation, combine to form

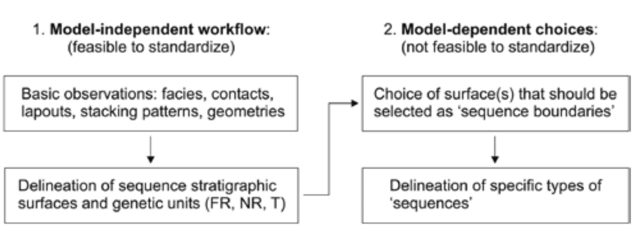

Figure 10 *Model-independent workflow versus model-dependent choices in sequence stratigraphy. The model-independent workflow leads to the subdivision of the stratigraphy into a succession of genetic units separated by sequence stratigraphic surfaces. After this sequence stratigraphic framework is built, the geoscientist may make model-dependent choices with respect to the selection of surfaces that should be elevated to the status of sequence boundary. This selection is commonly guided by how well the various surfaces are expressed with the available data in a given succession. FR – forced regressive; NR – normal regressive; T – transgressive. From Catuneanu et al. (2009).*

any type of sequence stratigraphic unit, from parasequence to systems tract and sequence. The realization that the identification of these building blocks is more important than the choice of where sequence boundaries are placed is a basic requirement to reaching a consensus in sequence stratigraphy. This is because, in practice, the particular depositional setting commonly dictates the prominence (or obscurity) of any particular surface, whereas the data available typically dictate which of these surfaces are most readily observed and thus hold the greatest utility for defining sequence boundaries. As a result, flexibility is required.

Sequences in the rock record may develop over a wide range of temporal and spatial scales, from a scale comparable to that of a parasequence or less (e.g., Posamentier et al., 1992a; Krapez, 1996; Strasser et al., 1999; Figure 8) to the scale of sedimentary basin fills. Smaller sequences are nested within larger sequences in a fractal manner across a continuum of thickness and time. The original unconformity-bounded sequence of Sloss et al. (1949) applies to large scales of observation, and accounts only for the most significant unconformities in the rock record, with the largest stratigraphic hiatus and regional extent. As the frequency of stratigraphic cycle increases, the hiatus associated with the sequence-bounding unconformities may decrease to the point where unconformities become diastems. As the scale of sequences increases, their internal architecture becomes increasingly complex.

The portrayal of sequence stratigraphic units in a chronostratigraphic framework does much to help clarify the scale of the events that are being interpreted. Wheelerian transforms are a useful component of any stratigraphic study (Wheeler, 1964). One of the common pitfalls in a sequence stratigraphic analysis is the lack of quantitative measures of rates of deposition and rates of erosion, as well as a depiction of the distribution and magnitude of stratigraphic hiatuses in a Wheeler domain. This kind of transformation makes the interpretation much more dynamic and requires the analyst to think more deeply about the processes that are involved in the formation of the sequence stratigraphic framework under analysis.

In spite of the immense variability of the stratigraphic record, a common theme emerges between all sequence stratigraphic approaches: at any scale of observation, sequence stratigraphic units of any type are always the product of changes in accommodation (whether marine or fluvial) and/or sediment supply, and their internal architecture is described by a combination of the same stratal stacking patterns and depositional trends (Figures 3 and 10). These patterns of sedimentation define genetic types of deposit that build sequences, systems tracts and parasequences. The identification of these genetic types of deposit, without trying to fulfill the predictions of any particular model, provides the key to the universal application of sequence stratigraphy.

Acknowledgments

This paper benefited from the constructive reviews provided by Rutger Gras, David Smith and Cedric Griffiths.

References

Anderson, J. [2005] Diachronous development of late Quaternary shelf-margin deltas in the Northwestern Gulf of Mexico: implications for sequence stratigraphy and deep water reservoir occurrence. In: Giosan, L. and Bhattacharya, J.P. (Eds.) *River Deltas: Concepts, Models and Examples*. Society for Sedimentary Geology (SEPM), Special Publication **83**, 257-276.

Bartek, L.R., Vail, P.R., Anderson, J.B., Emmet, P.A. and Wu, S. [1991] Effect of Cenozoic ice sheet fluctuations in Antarctica on the stratigraphic signature of the Neogene. *Journal of Geophysical Research*, **96**, 6753-6778.

Bartek, L.R., Andersen, J.L.R. and Oneacre, T.A. [1997] Substrate control on distribution of subglacial and glaciomarine seismic facies based on stochastic models of glacial seismic facies deposition on the Ross Sea continental margin, Antarctica. *Marine Geology*, **143**, 223-262.

Boyd, R., Diessel, C.F.K., Wadsworth, J., Leckie, D. and Zaitlin, B.A. [2000] Organization of non marine stratigraphy. In: Boyd, R., Diessel, C.F.K. and Francis, S. (Eds.) *Advances in the Study of the Sydney Basin*. Proceedings of the 34th Newcastle Symposium, University of Newcastle, Callaghan, New South Wales, Australia, 1-14.

Brown, L.F., Jr. and Fisher, W.L. [1977] Seismic stratigraphic interpretation of depositional systems: examples from Brazilian rift and pull apart basins. In: Payton, C.E. (Ed.) *Seismic Stratigraphy - Applications to Hydrocarbon Exploration*. AAPG Memoir **26**, 213-248.

Burgess, P.M. and Hovius, N. [1998] Rates of delta progradation during highstands; consequences for timing of deposition in deep-marine systems. *Journal of the Geological Society, London*, **155**, 217-222.

Catuneanu, O. [2006] *Principles of Sequence Stratigraphy*. Elsevier, Amsterdam.

Catuneanu, O., Sweet, A.R. and Miall, A.D. [1999] Concept and styles of reciprocal stratigraphies: Western Canada foreland system. *Terra Nova*, **11**, 1-8.

Catuneanu, O., Willis, A.J. and Miall, A.D. [1998] Temporal significance of sequence boundaries. *Sedimentary Geology*, **121**, 157-178.

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

Christie-Blick, N. [1991] Onlap, offlap, and the origin of unconformity-bounded depositional sequences. *Marine Geology*, **97**, 35-56.

Drummond, C.N. and Wilkinson, B.H. [1996] Stratal thickness frequencies and the prevalence of orderedness in stratigraphic sequences. *Journal of Geology*, **104**, 1-18.

Embry, A.F. and Johannessen, E.P. [1992] T-R sequence stratigraphy, facies analysis and reservoir distribution in the uppermost Triassic-Lower Jurassic succession, western Sverdrup Basin, Arctic Canada. In: Vorren, T.O., Bergsager, E., Dahl-Stamnes, O.A., Holter, E., Johansen, B., Lie, E. and Lund, T.B. (Eds.) *Arctic Geology and Petroleum Potential*. Norwegian Petroleum Society, Special Publication **2**, 121-146.

Fiduk, J.C., Weimer, P., Trudgill, B.D., Rowan, M.G., Gale, P.E., Phair, R.L., Korn, B.E., Roberts, G.R., Gafford, W.T., Lowe, R.S. and Queffelec, T.A. [1999] The Perdido Fold Belt, northwestern deep Gulf of Mexico, Part 2: Seismic stratigraphy and petroleum systems. *AAPG Bulletin*, **83**, 578-612.

Fielding, C.R., Naish, T.R., Woolfe, K.J. and Lavelle, M.A. [2000] Facies analysis and sequence stratigraphy of CRP-2/2A, Victoria Land Basin, Antarctica. *Terra Antartica*, **7**, 323-338.

Fielding, C.R., Naish, T.R. and Woolfe, K.J. [2001] Facies architecture of the CRP-3 drillhole, Victoria Land Basin, Antarctica. *Terra Antartica*, **8**, 217-224.

Fielding, C.R., Bann, K.L., MacEachern, J.A., Tye, S.C. and Jones, B.G. [2006] Cyclicity in the nearshore marine to coastal, Lower Permian, Pebbley Beach Formation, southern Sydney Basin, Australia: a record of relative sea-level fluctuations at the close of the Late Palaeozoic Gondwanan ice age. *Sedimentology*, **53**, 435-463.

Fielding, C.R., Frank, T.D., Birgenheier, L.P., Rygel, M.C., Jones, A.T. and Roberts, J. [2008] Stratigraphic record and facies associations of the late Paleozoic ice age in eastern Australia (New South Wales and Queensland). In: Fielding, C.R., Frank, T.D. and Isbell, J.L. (Eds.) *Resolving the Late Paleozoic Ice Age in Time and Space*. Geological Society of America, Special Paper **441**, 41-57.

Frazier, D.E. [1974] Depositional episodes: their relationship to the Quaternary stratigraphic framework in the northwestern portion of the Gulf Basin. *University of Texas at Austin, Bureau of Economic Geology, Geological Circular*, **4**(1).

Galloway, W.E. [1989] Genetic stratigraphic sequences in basin analysis, I. Architecture and genesis of flooding-surface bounded depositional units. *AAPG Bulletin*, **73**, 125-142.

Haq, B.U., Hardenbol, J. and Vail, P.R. [1987] Chronology of fluctuating sea levels since the Triassic (250 million years ago to present). *Science*, **235**, 1156-1166.

Helland-Hansen, W. and Gjelberg, J.G. [1994] Conceptual basis and variability in sequence stratigraphy: a different perspective. *Sedimentary Geology*, **92**, 31-52.

Helland-Hansen, W. and Martinsen, O.J. [1996] Shoreline trajectories and sequences: description of variable depositional-dip scenarios. *Journal of Sedimentary Research*, **66**, 670-688.

Holbrook, J.M., Scott, R.W. and Oboh-Ikuenobe, F.E. [2006] Base-level buffers and buttresses: a model for upstream versus downstream control on fluvial geometry and architecture within sequences. *Journal of Sedimentary Research*, **76**, 162-174.

Hunt, D. and Tucker, M.E. [1992] Stranded parasequences and the forced regressive wedge systems tract: deposition during base-level fall. *Sedimentary Geology*, **81**, 1-9.

Hunt, D. and Tucker, M.E. [1995] Stranded parasequences and the forced regressive wedge systems tract: deposition during base-level fall – reply. *Sedimentary Geology*, **95**, 147-160.

Jervey, M.T. [1988] Quantitative geological modeling of siliciclastic rock sequences and their seismic expression. In: Wilgus, C.K., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H.W., Ross C.A. and Van Wagoner, J.C. (Eds.) *Sea Level Changes – An Integrated Approach*. Society of Economic Paleontologists and Mineralogists (SEPM), Special Publication **42**, 47-69.

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

Johnson, J.G., Klapper, G. and Sandberg, C.A. [1985] Devonian eustatic fluctuations in Euramerica. *Geological Society of America Bulletin*, **96**, 567-587.

Krapez, B. [1996] Sequence-stratigraphic concepts applied to the identification of basin-filling rhythms in Precambrian successions. *Australian Journal of Earth Sciences*, **43**, 355-380.

Leckie, D.A. [1994] Canterbury Plains, New Zealand - implications for sequence stratigraphic models. *AAPG Bulletin*, **78**, 1240-1256.

Loutit, T.S., Hardenbol, J., Vail, P.R. and Baum, G.R. [1988] Condensed sections: the key to age-dating and correlation of continental margin sequences. In: Wilgus, C.K., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H.W., Ross C.A. and Van Wagoner, J.C. (Eds.) *Sea Level Changes – An Integrated Approach*. Society of Economic Paleontologists and Mineralogists (SEPM), Special Publication **42**, 183-213.

Martin, J., Paola, C., Abreu, V., Neal, J. and Sheets, B. [2009] Sequence stratigraphy of experimental strata under known conditions of differential subsidence and variable base level. *AAPG Bulletin*, **93**, 503-533.

Martinsen, O.J. and Helland-Hansen, W. [1995] Strike variability of clastic depositional systems: does it matter for sequence stratigraphic analysis? *Geology*, **23**, 439-442.

Martinsen, R.S. and Christensen, G. [1992] A stratigraphic and environmental study of the Almond Formation, Mesaverde Group, Greater Green River Basin, Wyoming. *Wyoming Geological Association Guidebook, Forty-third Field Conference*, 171-190.

Mawson, M. and Tucker, M. [2009]. High-frequency cyclicity (Milankovitch and millennial-scale) in slope-apron carbonates: Zechstein (Upper Permian), north-east England. *Sedimentology*, **56**, 1905-1936.

Miall, A.D. [1995] Whither stratigraphy? *Sedimentary Geology*, **100**, 5-20.

Miall, A.D. [1997] *The Geology of Stratigraphic Sequences*. Springer, Berlin.

Mitchum, R.J. [1977] Glossary of seismic stratigraphy. In: Payton, C.E. (Ed.) *Seismic Stratigraphy – Applications to Hydrocarbon Exploration*. AAPG Memoir **26**, 205-212.

Mitchum, R.M. and Van Wagoner, J.C. [1991] High-frequency sequences and their stacking patterns; sequence-stratigraphic evidence of high-frequency eustatic cycles. *Sedimentary Geology*, **70**, 131-160.

Mitchum, R.M., Jr., Vail, P.R. and Thompson, S., III [1977] Seismic stratigraphy and global changes of sea-level, part 2: the depositional sequence as a basic unit for stratigraphic analysis. In: Peyton, C.E. (Ed.) *Seismic Stratigraphy – Applications to Hydrocarbon Exploration*. AAPG Memoir **26**, 53-62.

Muto, T. and Steel, R.J. [2002] In defense of shelf-edge delta development during falling and lowstand of relative sea level. *Journal of Geology*, **110**, 421-436.

Naish, T. and Kamp, P.J.J. [1997] Sequence stratigraphy of sixth-order (41 k.y.) Pliocene-Pleistocene cyclothems, Wanganui Basin, New Zealand: a case for the regressive systems tract. *Geological Society of America Bulletin*, **109**, 978-999.

Naish, T.R., Woolfe, K.J., Barrett, P.J., Wilson, G.S., Atkins, C., Bohaty, S.M., Bucker, C.J., Claps, M., Davey, F.J., Dunbar, G.B., Dunn, A.G., Fielding, C.R., Florindo, F., Hannah, M.J., Harwood, D.M., Henrys, S.A., Krissek, L.A., Lavelle, M.A., van der Meer, J., McIntosh, W.C., Niessen, F., Passchier, S., Powell, R.D., Roberts, A.P., Sagnotti, L., Scherer, R.P., Strong, C.P., Talarico, F., Verosub, K.L., Villa, G., Watkins, D.K., Webb, P.-N. and Wonik, T. [2001] Orbitally induced oscillations in the East Antarctic ice sheet at the Oligocene/Miocene boundary. *Nature*, **413**, 719-723.

Neil, J. and Abreu, V. [2009] Sequence stratigraphy hierarchy and the accommodation succession method. *Geology*, **37**, 779-782.

Plint, A.G. [1988] Sharp-based shoreface sequences and "offshore bars" in the Cardium Formation of Alberta; their relationship to relative changes in sea level. In: Wilgus, C.K., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H.W., Ross C.A. and Van Wagoner, J.C. (Eds.) *Sea Level Changes – An Integrated Approach*. Society of Economic Paleontologists and Mineralogists (SEPM), Special Publication **42**, 357-370.

Plint, A.G. and Nummedal, D. [2000] The falling stage systems tract: recognition and importance in sequence stratigraphic analysis. In: Hunt, D. and Gawthorpe, R.L. (Eds.) *Sedimentary Response to Forced Regression*. Geological Society, London, Special Publication **172**, 1-17.

Posamentier, H.W. and Allen, G.P. [1999] *Siliciclastic Sequence Stratigraphy: Concepts and Applications*. Society of Economic Paleontologists and Mineralogists (SEPM), Concepts in Sedimentology and Paleontology #7.

Posamentier, H.W. and Kolla, V. [2003] Seismic geomorphology and stratigraphy of depositional elements in deep-water settings. *Journal of Sedimentary Research*, **73**, 367-388.

Posamentier, H.W. and Walker, R.G. [2006] Deep-water turbidites and submarine fans. In: Posamentier, H.W. and Walker, R.G. (Eds.) *Facies Models Revisited*. Society for Sedimentary Geology (SEPM), Special Publication **84**, 397-520.

Posamentier, H.W., Allen, G.P. and James, D.P. [1992a] High resolution sequence stratigraphy – the East Coulee Delta, Alberta. *Journal of Sedimentary Petrology*, **62**, 310-317.

Posamentier, H.W., Allen, G.P., James, D.P. and Tesson, M. [1992b] Forced regressions in a sequence stratigraphic framework: concepts, examples, and exploration significance. *AAPG Bulletin*, **76**, 1687-1709.

Posamentier, H.W., Jervey, M.T. and Vail, P.R. [1988] Eustatic controls on clastic deposition I – conceptual framework. In: Wilgus, C.K., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H.W., Ross C.A. and Van Wagoner, J.C. (Eds.) *Sea Level Changes – An Integrated Approach*. Society of Economic Paleontologists and Mineralogists (SEPM), Special Publication **42**, 110-124.

Schlager, W. [2004] Fractal nature of stratigraphic sequences. *Geology*, **32**, 185-188.

Schlager, W. [2005] *Carbonate Sedimentology and Sequence Stratigraphy*. Society of Economic Paleontologists and Mineralogists (SEPM), Concepts in Sedimentology and Paleontology #8.

Shanley, K.W. and McCabe, P.J. [1994] Perspectives on the sequence stratigraphy of continental strata. *AAPG Bulletin*, **78**, 544-568.

Sloss, L.L. [1963] Sequences in the cratonic interior of North America. *Geological Society of America Bulletin*, **74**, 93-113.

Sloss, L.L., Krumbein, W.C. and Dapples, E.C. [1949] Integrated facies analysis. In: Longwell, C.R. (Ed.) *Sedimentary Facies in Geologic History*. Geological Society of America, Memoir **39**, 91-124.

Spence, G.H. and Tucker, M.E. [2007] A proposed integrated multi-signature model for peritidal cycles in carbonates. *Journal of Sedimentary Research*, **77**, 797-808.

Strasser, A., Pittet, B., Hillgartner, H. and Pasquier, J.-B. [1999] Depositional sequences in shallow carbonate-dominated sedimentary systems: concepts for a high-resolution analysis. *Sedimentary Geology*, **128**, 201-221.

Strasser, A., Hilgen, F.J. and Heckel, P.H. [2006] Cyclostratigraphy – concepts, definitions, and applications. *Newsletters Stratigraphy*, **42**, 75–114.

Surlyk, F., Jensen, S.K. and Engkilde, M. [2008] Deep channels in the Cenomanian-Danian Chalk Group of the German North Sea sector; evidence of strong constructional and erosional bottom currents and effect on reservoir quality distribution. *AAPG Bulletin*, **92**, 1565-1586.

Vail, P.R., Mitchum, R.M., Jr. and Thompson, S., III [1977] Seismic stratigraphy and global changes of sea level, part 3: relative changes of sea level from coastal onlap. In: Payton, C.E. (Ed.) *Seismic Stratigraphy – Applications to Hydrocarbon Exploration*. AAPG Memoir **26**, 63-81.

Van Wagoner, J.C. [1995] Overview of sequence stratigraphy of foreland basin deposits: terminology, summary of papers, and glossary of sequence stratigraphy. In: Van Wagoner, J.C. and Bertram, G.T. (Eds.) *Sequence Stratigraphy of Foreland Basin Deposits: Outcrop and Subsurface Examples from the Cretaceous of North America*. AAPG Memoir **64**, ix-xxi.

Van Wagoner, J.C., Mitchum, R.M., Posamentier, H.W. and Vail, P.R. [1987] An overview of sequence stratigraphy and key definitions. In: A.W. Bally (Ed.) *Atlas of Seismic Stratigraphy*, volume 1. AAPG Studies in Geology **27**, 11-14.

Van Wagoner, J.C., Posamentier, H.W., Mitchum, R.M., Vail, P.R., Sarg, J.F., Loutit, T.S., and Hardenbol, J. [1988] An overview of sequence stratigraphy and key definitions. In: Wilgus, C.K., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H.W., Ross C.A. and Van Wagoner, J.C. (Eds.) *Sea Level Changes – An Integrated Approach*. Society of Economic Paleontologists and Mineralogists (SEPM), Special Publication **42,** 39-45.

Van Wagoner, J.C., Mitchum, R.M., Jr., Campion, K.M. and Rahmanian, V.D. [1990] *Siliciclastic Sequence Stratigraphy in Well Logs, Core, and Outcrops: Concepts for High-Resolution Correlation of Time and Facies*. AAPG Methods in Exploration Series **7**.

Weimer, R.J. [1966] Time-stratigraphic analysis and petroleum accumulations, Patrick Draw field, Sweetwater County, Wyoming. *AAPG Bulletin*, **50**, 2150-2175.

Wheeler, H.E. [1964] Baselevel, lithosphere surface, and time-stratigraphy. *Geological Society of America Bulletin*, **75**, 599-610.

Received 14 June 2009; accepted 29 August 2009.