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Review article

High-resolution sequence stratigraphy of clastic shelves II: Controls on sequence development

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ABSTRACT

Both allogenic and autogenic processes may contribute to the formation of sequence stratigraphic surfaces, particularly at the scale of fourth-order and lower rank cycles. This is the case with all surfaces that are associated with transgression, which include the maximum regressive surface, the transgressive ravinement surfaces and the maximum flooding surface, and, under particular circumstances, the subaerial unconformity as well. Not all autogenic processes play a role in the formation of sequence stratigraphic surfaces, but only those that can influence the direction of shoreline shift. Any changes in shoreline trajectory, whether autogenic or allogenic in origin, influence the stratal stacking patterns in the rock record which sequence stratigraphic interpretations are based upon.

The discrimination between the allogenic and autogenic processes that may control changes in shoreline trajectory is a matter of interpretation and is tentative at best in many instances. For this reason, the definition and nomenclature of units and bounding surfaces need to be based on the observation of stratal features and stacking patterns rather than the interpretation of the controlling mechanisms. In this light, we extend the concept of 'sequence' to include all cycles bounded by recurring surfaces of sequence stratigraphic significance, irrespective of the origin of these surfaces. The updated sequence concept promotes a separation between the objective observation of field criteria and the subsequent interpretation of controlling parameters, and stresses that a sequence stratigraphic unit is defined by its bounding surfaces and not by its interpreted origin. The use of high-frequency sequences eliminates the need to employ the concepts of parasequence or small-scale cycle in high-resolution studies, and simplifies the sequence stratigraphic methodology and the nomenclature.

1. Introduction

Sequence stratigraphy developed as a main and widely used method of stratigraphic analysis that can be applied to build frameworks of sequences, systems tracts and bounding surfaces at different scales of observation, depending on the purpose of the study and on the data available. The more types of data that can be integrated (e.g., geophysical, sedimentologic, petrographic, biostratigraphic, geochemical, etc.) the more detailed and reliable the sequence stratigraphic interpretation. The sequence stratigraphic methodology offers a genetic, process-based analytical approach to stratigraphic interpretation that of necessity involves conceptual depositional models (Catuneanu et al., 2011). The development of the method within the last three decades has recorded a shift in emphasis from theoretical models to field criteria, in parallel with the recognition that the stratigraphic record is far more diverse and complex than simple theoretical models can predict. It is now understood that sequences may consist of different combinations of systems tracts (e.g., see recent discussions in Csato and Catuneanu, in press; Zecchin and Catuneanu, 2012), which is why modern analyses emphasize the observation of stratal stacking patterns (i.e., proxies to systems tracts) and key bounding surfaces, rather than relying on theoretical templates.

The shift from models to field criteria marks an important step in the development of sequence stratigraphy, and provides the opportunity to revisit some of the underlying principles of the method. One of these principles relates to the nature of the controls on sequence development. A wide variety of controls may generate stratigraphic cycles in the rock record, from allogenic (eustatic, tectonic, climatic) to autogenic. The identification and separation of

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these controls is a most challenging task as they may interact with each other, may operate over overlapping temporal and spatial scales, and may generate similar field expressions. The perception of the nature of the dominant controls on sequence development has also changed over time, from eustasy-dominated models (1970s–1980s) to a wider acceptance of a variety of controls today.

Criteria for the interpretation of the various controls on sequence development have been discussed extensively (e.g., Miall, 2010), but the relative role of these co-existing controls remains essentially impossible to quantify in every case. This is the reason why concepts such as "accommodation" or "sediment supply" are critical in sequence stratigraphy as they refer to the outcome of the interplay between multiple controls, but without inferring or assuming their relative contributions. An evaluation of the nature of the controls on sequence development may be feasible in the case of large subsurface datasets (e.g., well-log and seismic data that afford the construction of isopach maps across large areas), but more difficult in the case of sparse outcrop- or core-based studies.

The generally sparse availability of outcrops and core may limit or prevent not only the ability to correlate, but in many cases also the ability to recognize the scale and the type of parameters controlling stratigraphic surfaces and depositional trends. A typical example is the distinction between allogenic processes, external to the system, and those of autogenic origin. The designation of sequences is historically tied to allocyclicity represented by changes of eustatic sea level and/or tectonic subsidence/uplift. However, the recognition of an allocyclic origin on the basis of discontinuous data sets from outcrop or cores may be difficult or impossible in many instances, and this problem is increasingly evident with a decreasing scale of observation. This gave way to an area of interpretative uncertainty between the larger scale sequences of undoubted allocyclic origin and the bed- and bedset-scale features of sedimentology. This "grey area" between stratigraphy and sedimentology is filled by parasequences or generic transgressive-regressive cycles of unspecified origin (Van Wagoner et al., 1988, 1990; Zecchin, 2007a).

Zecchin (2007a) proposed a generic, descriptive cycle concept conceived for outcrop studies, based on the occurrence of transgressions and regressions irrespective of the nature (allo- or autogenic) of their control. This implies that such cycles, referred to as "small-scale cycles", may be driven by relative sea-level changes as well as by both local and large-scale sediment supply changes leading to shoreline shifts. In contrast to the parasequence concept, small-scale cycles are bounded by surfaces of sequence stratigraphic significance and display variable architectures. This cycle concept resembles the stratigraphic sequence of Catuneanu et al. (2009) who included sediment supply in the definition of a sequence as a possible control on sequence development. However, the stratigraphic sequence concept *sensu* Catuneanu et al. (2009) provides only a generalized, scale-independent definition, and it does not explore specifically the "grey area" of the "small-scale cycles". For the larger scale of conventional sequence stratigraphy as applied to petroleum exploration, commonly referred to as of third-order, Catuneanu et al. (2009) emphasize the external factors as the main contributors to the generation of sequences and surfaces of sequence stratigraphic significance, whereas autocyclicity is considered to only affect the internal architecture of systems tracts. This paper explores more specifically the meaning of "small-scale cycles" in the context of sequence stratigraphy, and the distinction between such cycles related to shoreline shifts (i.e., transgressions and regressions) and other sedimentary cycles that form independently of shoreline shifts.

Work within the last two decades demonstrated that autogenic mechanisms such as the autoretreat or the deltaic diversions influencing adjacent open shorelines, may generate cyclic stratigraphic architectures and surfaces that are indistinguishable from those produced by allocyclic factors (Muto and Steel, 1992, 1997, 2002). Consequently, as the discrimination of processes controlling cyclicity and bounding surfaces may be impossible to resolve in many instances, the definition of sequences as units governed exclusively by external factors is too limited and potentially misleading.

This paper explores the concept of sequence as applied within the context of clastic shelves to smaller scales, particularly to the meter- to decameter-scale cycles that are prevalent in outcrop, where the effect of autocyclicity is potentially most significant.

2. Concept of sequence

The concept of 'sequence' has been gradually refined and redefined since its introduction as a stratigraphic unit in the 1940s (Longwell, 1949; Sloss et al., 1949) (Fig. 1). As with any other method of stratigraphic analysis, the trend over time was to increase the resolution of sequence stratigraphy by applying the concept of sequence to increasingly smaller scales of observation. This trend parallels technological advances in the acquisition and processing of subsurface seismic data, and also responds to the ever increasing need to improve the degree of detail of stratigraphic studies.

The original sequence was defined as a large-scale unconformity-bounded unit of significant temporal duration and lateral extent, of higher than lithostratigraphic group or supergroup rank, and meant for continental-scale mapping and correlations (Longwell, 1949; Sloss et al., 1949; Sloss, 1963). The application of

Decade	Definition	Scale
1940s	Major rock-stratigraphic unit bounded by interregional unconformities (Longwell, 1949; Sloss et al., 1949; Sloss, 1963)	2nd order
1970s	A relatively conformable succession of genetically related strata bounded by unconformities or their correlative conformities (Mitchum, 1977)	3rd order
2000s	A cycle of change in accommodation or sediment supply defined by the recurrence of the same types of sequence stratigraphic surface through geologic time (Catuneanu et al., 2009, 2011)	4th order and lower rank

Figure 1. Definitions of a 'sequence'. Changes in the definition followed a trend of gradually decreasing the scale of a 'sequence' and increasing the resolution of stratigraphic analyses. The applications of the sequence concept have changed according to the scale of the unit, from continental-scale correlations (1940s–1960s) to seismic-scale exploration (1970s) and sub-seismic scale production development (2000s). A sequence is expressed as a cycle of change in stratal stacking patterns, dividable into systems tracts and bounded by sequence stratigraphic surfaces. Sediment supply may fluctuate in response to both allogenic and autogenic factors, and may control the timing of any sequence stratigraphic surface that forms during stages of positive accommodation.

this concept led to the subdivision of the entire Phanerozoic sedimentary cover of North America into only six sequences delimited by interregional unconformities (Sloss, 1963). Given the large scale of the Sloss-type sequence, the application of this concept to petroleum exploration was not evident at the time. The concept of sequence was redefined in the 1970s as "a relatively conformable succession of genetically related strata bounded by unconformities or their correlative conformities" within the context of seismic-scale petroleum exploration (Mitchum, 1977). This time, the new definition stemmed from the industry with the purpose of providing an improved stratigraphic methodology for petroleum exploration, at scales above the resolution of the seismic data (Payton, 1977). By decreasing the scale of a sequence, from above supergroup level (1940s–1960s) essentially to formation level (1970s), the magnitude and the extent of its bounding unconformities have decreased accordingly. Following the 1970s, the trend to decrease the scale of a sequence continued, by applying this methodology to higher resolution datasets that included well logs, outcrops and cores. In doing so, the applications of sequence stratigraphy have expanded from petroleum exploration to production development, by generating stratigraphic frameworks at sub-seismic scales for the purpose of understanding issues of reservoir compartmentalization and fluid flow. Another consequence of expanding the sequence stratigraphic methodology to datasets other than seismic was the proliferation of several approaches to the application of the method, mainly because the mappability of the different types of sequence stratigraphic surface varies with the dataset. Accordingly, researchers working with different datasets proposed different sequence stratigraphic surfaces as sequence boundaries, based on the prominence of those surfaces in their preferred (or available) datasets. As a result, different types of sequence have been defined: depositional sequences (Mitchum, 1977; Haq et al., 1987; Posamentier et al., 1988; Van Wagoner et al., 1988, 1990; Christie-Blick, 1991; Hunt and Tucker, 1992; Neal and Abreu, 2009), transgressive–regressive (T–R) sequences (Johnson and Murphy, 1984; Embry and Johannessen, 1992) and genetic stratigraphic sequences (Frazier, 1974; Galloway, 1989).

The different types of sequence may overlap in terms of temporal and spatial scales, as their bounding surfaces may be part of the same stratigraphic frameworks that develop at any particular scale of observation. The co-existence of several types of sequence starting with the 1980s required a new definition of a sequence, flexible enough to accommodate and account for all types of sequence. The most recent definition designates the sequence as "a cycle of change in accommodation or sediment supply defined by the recurrence of the same types of sequence stratigraphic surface through geologic time" (Catuneanu et al., 2009, 2010, 2011) (Fig. 1).

The evolution of the sequence concept indicates that sequence stratigraphy can be applied at different scales of observation which correspond to different hierarchical levels. In retrospect, the Sloss-type sequence (1940s–1960s) is now referred to as a 'second-order' sequence; the exploration-scale sequence of the seismic stratigraphy era (1970s) is now commonly referred to as a 'third-order' sequence; and the more recent sub-seismic scale sequences are referred to as 'fourth-order' or lower rank sequences (Fig. 1). The latter high-frequency sequences define the scale and the purpose of high-resolution sequence stratigraphy. It is noteworthy that the terminology associated with the seismic-scale sequence of the 1970s designated the stratigraphic cycles below the sequence scale as 'parasequences', which correspond to cycles of 4th-order and lower hierarchical rank (Van Wagoner et al., 1988, 1990; Duval et al., 1998; Schlager, 2010). However, the concept of parasequence has significant drawbacks (Zecchin and Catuneanu, 2012), and attempts have been made to either redefine it (e.g., Spence and Tucker, 2007; Tucker and Garland, 2010) or replace it with alternative concepts (e.g., the 'small-scale cycle' of Zecchin, 2007a, 2010). The result is that cycles of 4th-order and lower rank are currently referred to as parasequences, small-scale cycles or high-frequency sequences, which brings significant nomenclatural and methodological confusion.

Sequences of second-order and lower rank are nested within first-order sequences, which correspond to entire sedimentary-basin fills related to a particular tectonic setting (Catuneanu, 2006). Irrespective of hierarchical rank, all sequences display common features, namely that (1) they are bounded by recurrent sequence stratigraphic surfaces; and (2) they can be subdivided into component systems tracts of corresponding hierarchical rank. In the downstream-controlled settings of underfilled basins, the nature and timing of systems tracts are directly related to shoreline shifts. Implicitly, the nature and timing of sequence stratigraphic surfaces (i.e., systems tract boundaries) are directly controlled by changes in the direction and/or the type of shoreline shift (e.g., forced regression, normal regression, transgression; Catuneanu et al., 2011). The shoreline is therefore a critical element for the sequence stratigraphy of underfilled sedimentary basins. A sedimentary cycle that cannot be subdivided into systems tracts is no longer a sequence, but rather a succession of bedsets that accumulates in an autocyclic manner independent of shoreline shifts.

3. Controls on sequence development

3.1. Allocyclic factors

Allocyclic (allogenic) factors are those external to the depositional system, such as eustasy, tectonics and climate (Einsele et al., 1991), which control relative sea-level changes, sediment supply, environmental energy, and ultimately the architecture of sedimentary units and bounding surfaces typically at larger scales that encompass multiple depositional systems. Early sequence stratigraphic concepts considered eustasy as the main control on sequence development (Posamentier and Vail, 1988; Posamentier et al., 1988; Vail et al., 1991), even though evidence was already emerging that tectonism can also generate sequences and sequence boundaries (e.g. Cloetingh, 1988). It is now recognized that it is the complex interplay between eustasy and tectonism that shapes the stratigraphic record, and that either control may become dominant under specific circumstances (Miall, 1997).

The typical allocyclic factors that may control high-frequency, outcrop-scale cycles are illustrated below.

3.1.1. Glacio-eustasy

Glacio-eustasy is known to be one of the most important controls on accommodation during the Quaternary as well as other periods of Earth history, generally referred to as Icehouse, but its role has been recognized during warm (Greenhouse) periods as well, although with a significantly lower magnitude (Fielding et al., 2006).

High-frequency sequences developed worldwide during Icehouse periods, that is during the late Paleozoic, Neogene and Pleistocene, and tend to display a distinct stratal architecture as compared to that exhibited by Greenhouse cycles. In particular, Icehouse sequences are relatively thin (meters to a few tens of meters), show an incomplete systems tract development, are top-truncated, vertically stacked, and are commonly dominated by transgressive deposits (Kidwell, 1997; Zecchin, 2005; Fielding et al., 2006; Di Celma and Cantalamessa, 2007) (Fig. 2). A shoreface-shelf high-frequency sequence dominated by transgressive deposits has an architecture corresponding to the *T cycle* of Zecchin (2007a) (Fig. 3). These sequences were controlled by glacio-eustatic changes with a periodicity within the Milankovitch band, in which

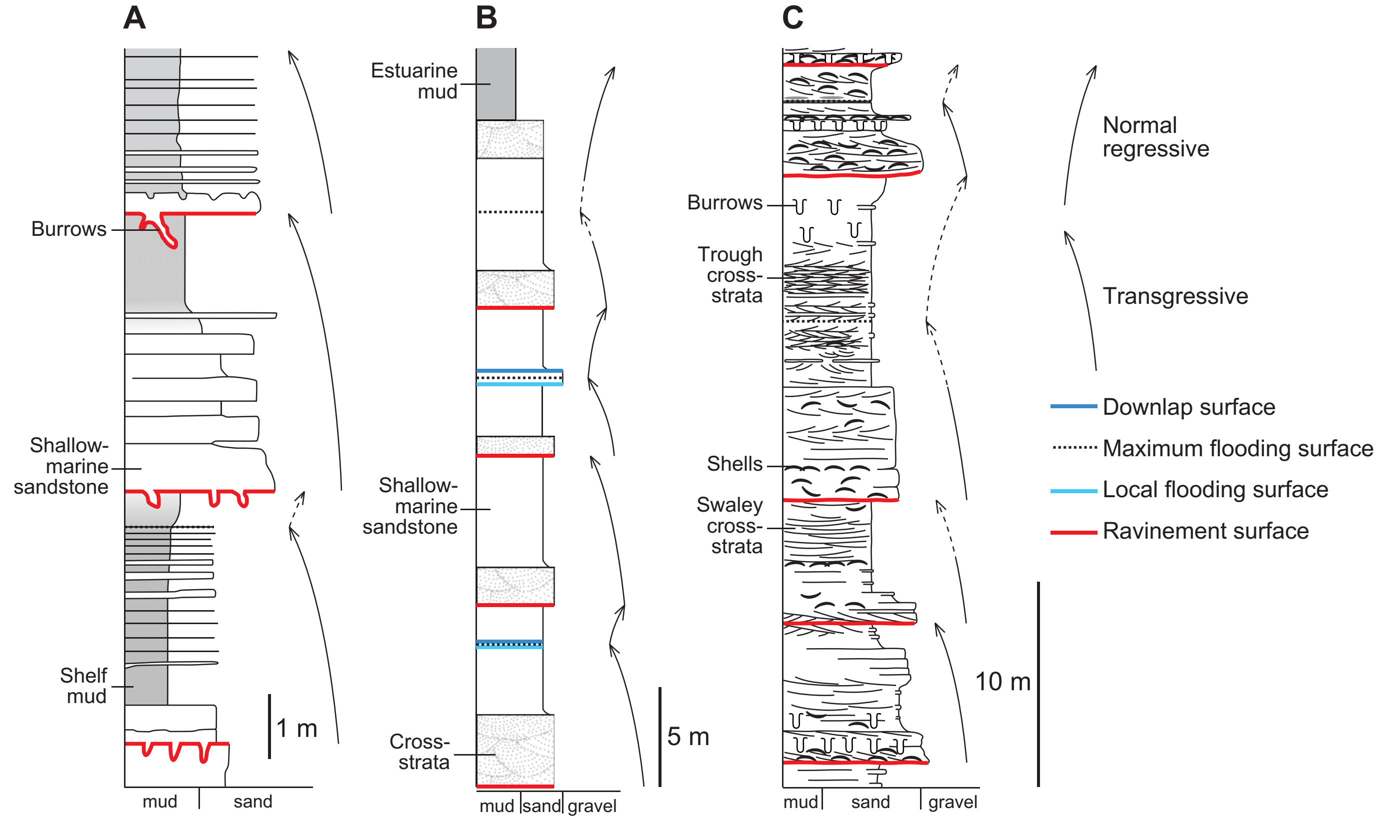

Figure 2. Examples of stacked metre-scale to decametre-scale shallow-marine cycles dominated by transgressive deposits and inferred to be related to glacio-eustasy in Icehouse periods. (A) The Miocene Calvert Cliffs succession, Maryland, USA (modified from Kidwell, 1997). (B) The Pleistocene Tablazo Formation, Canoa Basin, Ecuador (modified from Di Celma et al., 2005). (C) The lowel Pliocene Belvedere Formation, Crotone Basin, southern Italy (modified from Zecchin, 2005).

subaerial unconformities were reworked by wave-ravinement surfaces during transgressions.

High-amplitude glacio-eustatic changes are considered the major cause for the observed Icehouse sequence architecture (Fielding et al., 2006). In particular, erosional transgressions across shelves exposed during sea-level fall were able to remove part or the entire regressive interval of previously deposited units, producing *T cycles* (Di Celma and Cantalamessa, 2007; Zecchin, 2007a). Wave erosion along oceanic coasts is typically higher than that operating in closed basins, and it may be associated with the removal of tens of meters of sediment during transgression (Demarest and Kraft, 1987; Leckie, 1994). The formation of the *T cycle* architecture is also favored by a relatively high sediment supply during transgression and a relatively slow relative sea-level rise, while still maintaining the conditions required to produce transgression (i.e., accommodation outpacing sediment supply; Kidwell, 1997; Cantalamessa and Di Celma, 2004; Zecchin, 2007a). Such conditions occurred during the late Pliocene and early Pleistocene time, when the glacio-eustatic cyclicity was dominated by the 40 kyr obliquity, characterized by a relatively symmetrical shape of the sea-level curve that led to slower transgressions than those typifying the more asymmetrical late Quaternary glacio-eustatic cycles with the same periodicity (Cantalamessa and Di Celma, 2004). Moreover, the *T cycle* architecture may also form in contexts of rapid accommodation creation, such as in some normal fault-bounded basins, provided that sediment supply is high enough to create an accretionary TST (Zecchin, 2005, 2007a).

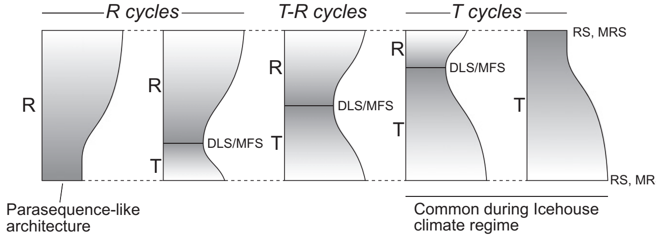

Figure 3. Schematic representation of the variable symmetry found in transgressive-regressive cycles, following Zecchin (2007a). *R cycles* and *T cycles* are dominated respectively by regressive and transgressive deposits, whereas *T–R cycles* show a symmetric architecture. Abbreviations: DLS – downlap surface; MFS – maximum flooding surface; MRS – maximum regressive surface; RS – ravinement surface; R – regressive; T – transgressive.

The analysis of late Quaternary, Mediterranean shallow-marine sequences inferred to be linked to high-amplitude glacio-eustatic changes confirmed that some features, such as reduced (up to 20 m) thickness, top truncation and incomplete systems tract development are consistent with an origin related to an Icehouse climate regime (e.g., Posamentier et al., 1992; McMurray and Gawthorpe, 2000; Nalin et al., 2007; Lucchi, 2009; Zecchin et al., 2009a,b, 2010a,b, 2011) (Fig. 4). Lowstand deposits are typically absent in inner to middle shelf settings as they accumulated close to the shelf edge at times of high-amplitude sea-level falls (Zecchin et al., 2011). The small thickness of sequences may be related to a combination of factors, including a limited time available for the deposition of transgressive and highstand deposits, marked fore-shortening during forced regression, and transgressive ravinement processes (Zecchin et al., 2010b).

In contrast to the *T cycle* model described above, late Quaternary high-frequency sequences related to the isotope substage cyclicity

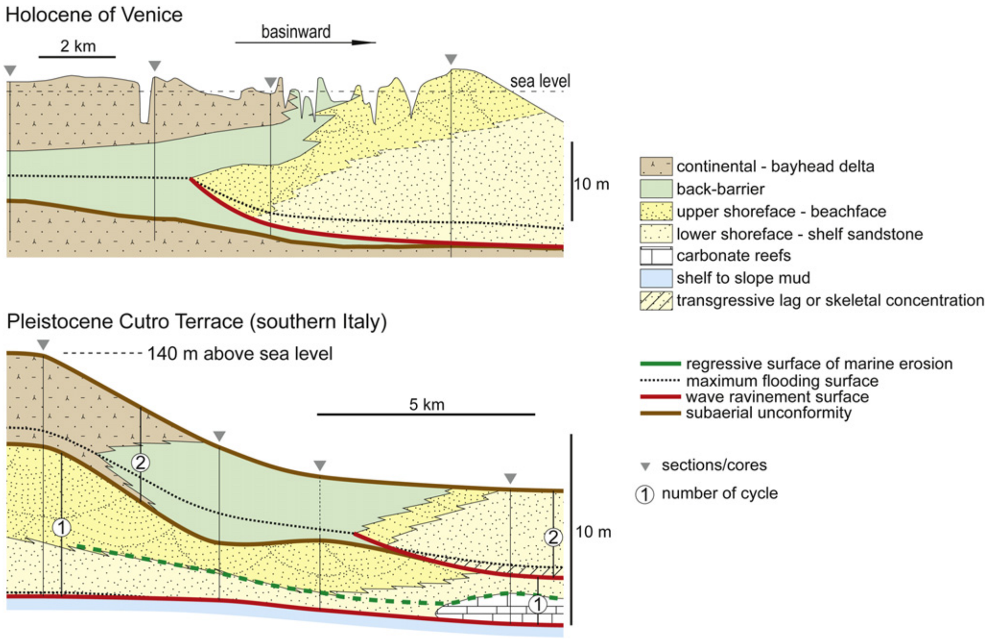

Figure 4. Facies distribution and sequence stratigraphic surfaces in proximal to distal transects showing transgressive-regressive cycles related to the marine isotope substage cyclicity during late Quaternary (modified from Zecchin et al., 2010b). The Holocene deposits of the Venice lagoon are interpreted by correlating cores, whereas the two superposed cycles of the middle Pleistocene Cutro Terrace (southern Italy) are based on outcrop data. In both cases, cycles are dominated by regressive deposits (*R-cycles*, Fig. 3).

(10^4 yr time scales) commonly show the dominance of regressive deposits over transgressive deposits (the *R cycle* of Zecchin, 2007a) (Fig. 3). This has been related to the very rapid glacio-eustatic rises characterizing the late Quaternary time, and this feature may occur irrespective of the tectonic context (Zecchin et al., 2010b).

The formation of *T cycle* versus *R cycle* architectures, therefore, is related to the shape of the relative sea-level curve and to local subsidence/uplift rates, sediment supply, physiography and environmental energy rather than to specific time scales of the glacio-eustatic cyclicity. Late Quaternary sequences recording the 100 ka eccentricity quasi-periodicity become less predictable in terms of stacking patterns, as the longer the duration of cycles the more interference can be expected from tectonism. As such, the variable architecture exhibited by larger scale sequences reflects an increased sensitivity to the tectonic context (Zecchin et al., 2010b).

Recent studies recognized a relatively low- to high-amplitude (>25 m) and high-frequency (<<1 Ma) cyclicity of glacio-eustatic origin in Late Cretaceous successions, a period characterized by a Greenhouse climate regime (Miller et al., 2003). These glacio-eustatic changes are inferred to be linked to the development of small, ephemeral ice sheets in Antarctica (Miller et al., 2003).

The metre- to decametre-scale (up to 100 m) cyclicity evidenced by several authors in the Cretaceous successions of the Western Interior Foreland Basin in the U.S.A. (Wasatch Plateau and Book Cliffs areas, Utah) (Fig. 5) and Alberta is inferred to record such a glacio-eustastic control (Plint, 1991; Hampson et al., 2011), possibly linked to Milankovitch orbital parameters (Sethi and Leithold, 1994). Some parasequences indicate deposition during forced regression, as evidenced by their sharp bases and large distances of progradation of up to 16 km (Pattison, 1995; Posamentier and Morris, 2000; Hampson et al., 2011) (Fig. 6), and this may reflect low-amplitude falls in glacio-eustatic sea level (Hampson et al., 2011). In contrast, flooding surfaces bounding the parasequences are interpreted to record stages of rapid glacio-eustatic rise. These cycles display the *R cycle* architecture of Zecchin (2007a) (Fig. 3). In comparison to the glacio-eustatic *R cycles* accumulated during Icehouse periods, such as those of the Late Quaternary, these Greenhouse analogues can be considerably thicker (up to 100 m) and less top truncated (Figs. 5 and 6). The lower amplitude of glacio-eustatic changes during the Mesozoic, as compared to those that characterized Icehouse periods, explains the higher preservation potential of Greenhouse sequences.

3.1.2. Tectonics and climate

Tectonics is commonly associated with the larger scale cyclicity in sedimentary basins (Johnson, 1971; Cloetingh, 1988); however, some outcrop–scale cycles may be generated by changes in subsidence/uplift rather than eustasy. An example is that of the Pliocene Gilbert-type deltas of the Loreto Basin (Mexico), where an earthquake clustering mechanism related to normal faulting was invoked to explain episodic delta deposition, resulting in stacked cycles (Dorsey et al., 1997). Episodic fault-controlled subsidence was also considered by Colella (1988).

Local or regional tectonics was also shown to play a role in shaping the internal architecture of sequences generated by eustatic changes. This has been observed frequently in the case of growth folding (Gawthorpe et al., 1997; Ito et al., 1999; Castelltort et al., 2003; Zecchin et al., 2003) (Fig. 7), syn-sedimentary normal faulting (Gawthorpe et al., 1994; Howell and Flint, 1996; Zecchin et al., 2006; Zecchin, 2007b), and in areas undergoing long-term uplift (Zecchin et al., 2010b, 2011). In these cases, tectonics in combination with sediment supply may control the relative development of transgressive and regressive deposits, and the aggradational vs. progradational trends of the latter. Tectonics may also lead to a marked lateral variability of the sequence architecture, depending on the type and extent of active structures.

Climate may strongly affect sediment supply, as well as the type of sediment (siliciclastic vs. carbonate), influencing the architecture of sequences and the dominant depositional trends (Cecil, 1990; Paola et al., 1992; Leeder et al., 1998; Feldman et al., 2005). For example, Roveri and Taviani (2003) related the accumulation of Plio-Pleistocene shell concentrations in the Mediterranean to climatic phases of reduced fluvial runoff and higher carbonate productivity and/or to hyperpycnal flows reworking and

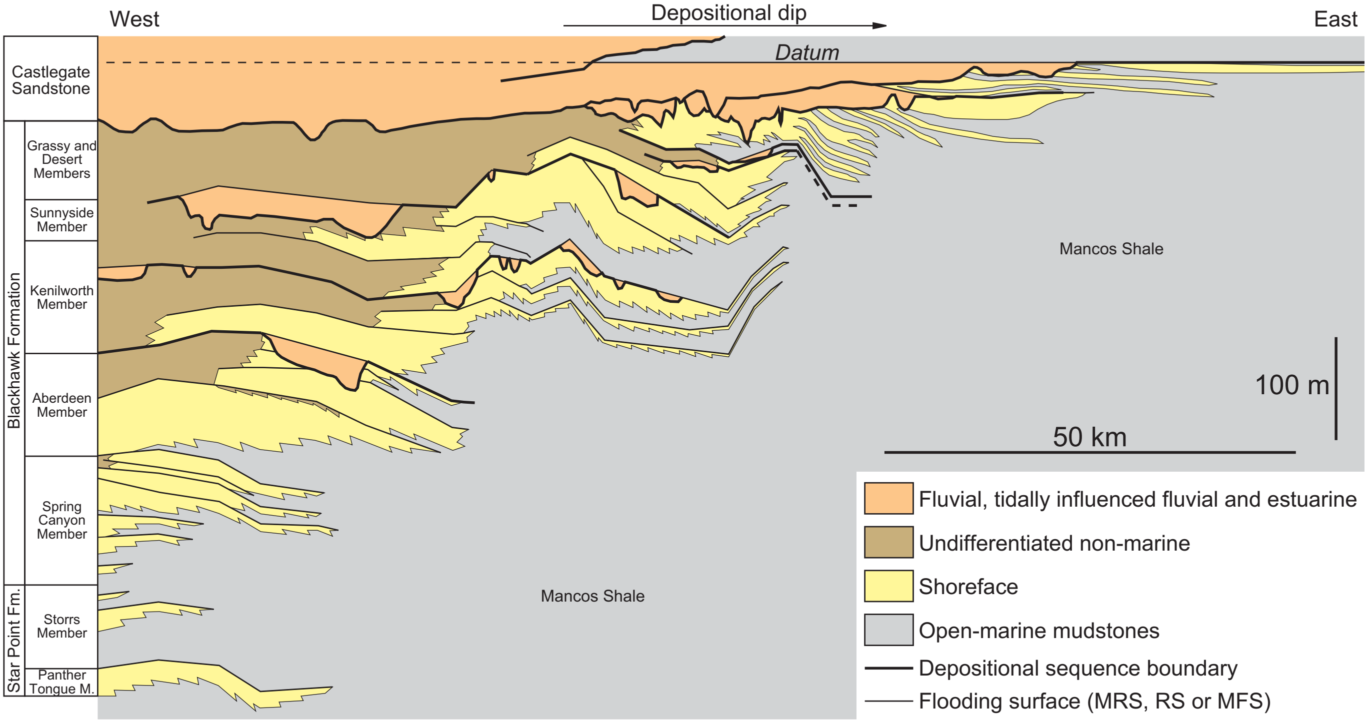

Figure 5. The Cretaceous succession of the Western Interior Foreland Basin, USA, is composed of the Star Point Formation, the Blackhawk Formation, the Castlegate Sandstone, the Mancos Shale and their members. A series of sequences and minor units were identified in the succession. Modified from Hampson et al. (2001). Abbreviations: MFS – maximum flooding surface; MRS – maximum regressive surface; RS – ravinement surface.

accumulating shell debris. Leeder et al. (1998) highlighted the strong influence of land vegetation on terrigenous supply to marine areas during late Quaternary in both south-western USA and Mediterranean areas. Similarly, Massari et al. (2007) demonstrated the role of climate-modulated sediment supply in shaping Pleistocene sequences in the Crotone Basin (Italy).

3.2. *Autocyclic factors*

Autocyclic (autogenic) factors are those internal to the depositional system, leading to responses in terms of progradation and retrogradation that are unrelated to relative sea-level changes and climate (Einsele et al., 1991). A typical example is that of delta lobe switching due to river mouth diversions during continuous relative sea-level rise (e.g., Elliott, 1975; Pulham, 1989) (Fig. 8). It is a common assumption that autogenic processes are only relevant within the confines of a depositional system. However, any changes in the pattern of sediment transport and distribution within a depositional system may have a domino effect on other depositional systems to which the sediment is supplied. For example, autocyclic shifting of deltas may also modify significantly sediment supply to the adjacent open shorelines, as the riverborne sediment

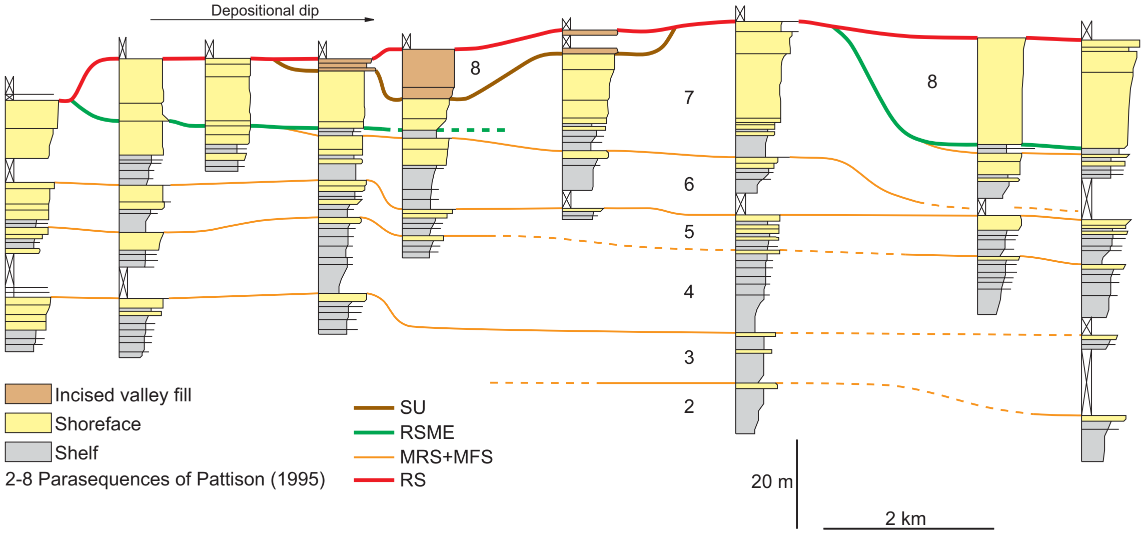

Figure 6. Cross-section showing metre-scale to decametre-scale units composing the Kenilworth Member of the Blackhawk Formation (USA) (modified from Pattison, 1995). The succession was fully described in terms of parasequences bounded by flooding surfaces, here indicated as maximum regressive surfaces merged with maximum flooding surfaces. Abbreviations: MFS – maximum flooding surface; MRS – maximum regressive surface; RS – ravinement surface; RSME – regressive surface of marine erosion; SU – subaerial unconformity.

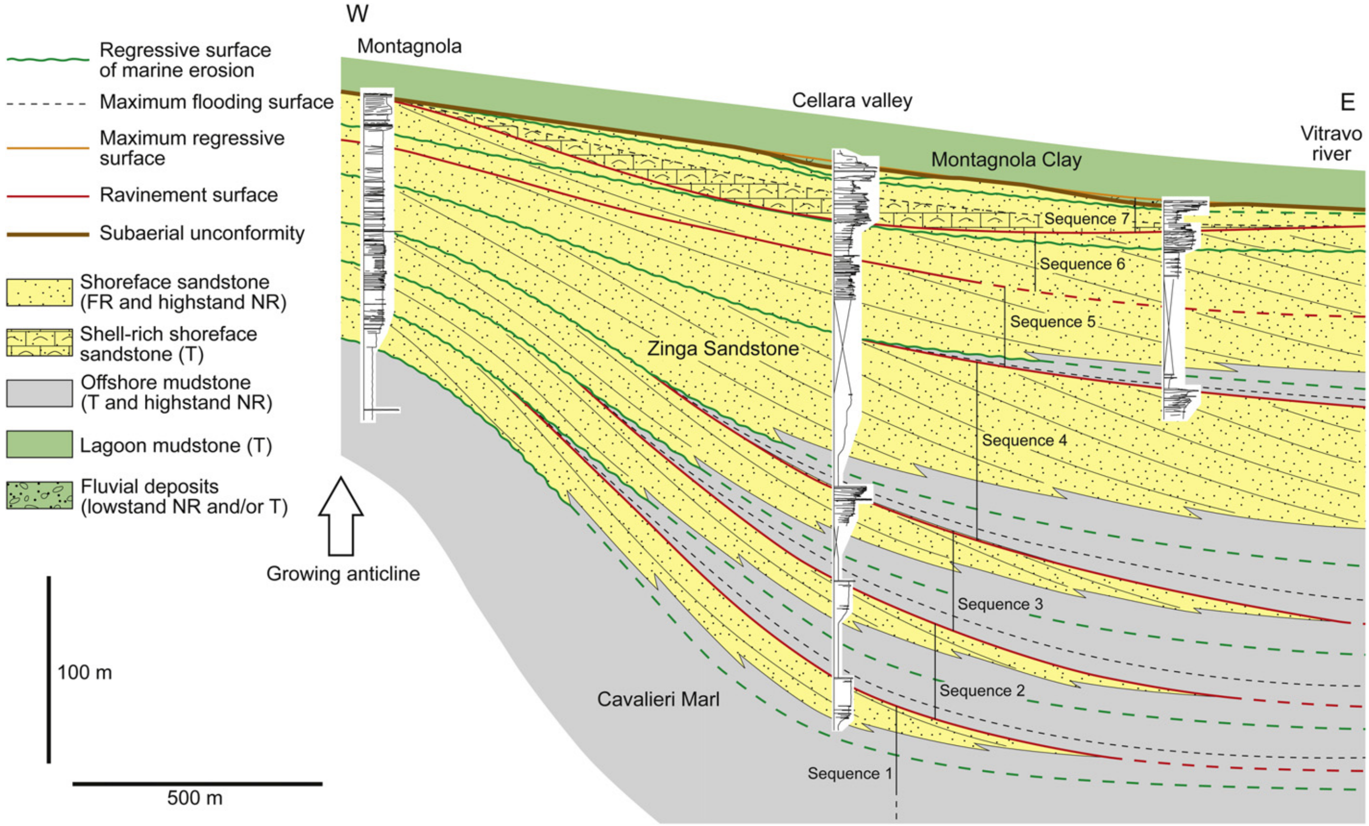

Figure 7. Example of tectonically-enhanced forced regressions in the shelf to shoreface succession forming part of the lower Pliocene Cavalieri Marl and Zinga Sandstone (Crotone Basin, southern Italy). Distal sequences 1 to 6 are *R cycles* and sequence 7 is an *R-cycle* to *T–R cycle* (Fig. 3). All sequences are amalgamated in proximal (updip) settings due to the growth of a salt-cored anticline (modified from Zecchin et al., 2003). Abbreviations: FR – forced regression; NR – normal regression; T – transgression.

is redistributed by longshore transport to feed shorefaces. Thus, autocyclic river diversions may impact depositional processes in both deltas and shorefaces, and may ultimately induce changes in the direction of shoreline shift across larger areas (from tens to hundreds of km), mimicking (and difficult to differentiate from) the effect of relative sea-level changes (Amorosi et al., 2005; Stefani and Vincenzi, 2005) (Figs. 9 and 10). In turn, shoreline shifts are fundamental to sequence stratigraphy in terms of controlling the formation and timing of systems tracts and sequence stratigraphic surfaces.

Another autogenic factor with consequences on stratigraphic architecture is the 'autoretreat' process, which predicts an inevitable landward retreat of the shoreline under conditions of constant accommodation creation (A) and sediment supply (S), due to the progressive enlargement of the depositional area during relative sea-level rise (Muto and Steel, 1992, 1997, 2002) (Fig. 11). This process highlights the inability of constant S to keep pace with A in order to maintain progradation, in contrast with the conventional sequence stratigraphic principle that changes in the direction of shoreline migration depend only on the A/S ratio. The effectiveness of the autoretreat process increases as A becomes larger and/or S becomes smaller (Muto and Steel, 1997).

The reorganization that follows the autoretreat process results in transgressive and regressive trends that are independent of changes in accommodation and/or sediment supply. Such trends affect sedimentation processes in depositional systems both landward and seaward relative to the coastline, and therefore generate systems tracts and bounding sequence stratigraphic surfaces. An added complexity is the fact that both A and S are unlikely to remain constant for any significant period of time, and therefore the autogenic process of autoretreat most likely operates in parallel with allocyclic changes in the A/S ratio. Thus, the formation of sequences or at least of some of the systems tracts may be controlled by a mix of external and internal factors whose relative contributions may be difficult or impossible to quantify. The role of relative sea-level rise in providing the necessary accommodation for sediment preservation remains important for any cycle that may form between the end members of fully allogenic and fully autogenic origin.

These considerations indicate that some surfaces of sequence stratigraphic significance, such as the maximum regressive surfaces, transgressive ravinement surfaces and maximum flooding surfaces, may originate in response to both allogenic and autogenic factors, as they are controlled by the interplay of A and S, as well as by the autoretreat and by local energy levels. Marine surfaces of forced regression (i.e., the basal surface of forced regression, the regressive surface of marine erosion, the correlative conformity) are typically controlled only by relative sea-level falls, whereas the formation of subaerial unconformities may be linked to various mechanisms, with or without a relation to the relative sea level (Zecchin and Catuneanu, 2012). Figure 12 summarizes the possible controls on the formation of different types of sequence stratigraphic surface. All sequence stratigraphic surfaces can be generated by allogenic mechanisms. In addition, all surfaces related to transgression (i.e., onset of transgression; during transgression; and end of transgression) are sensitive to sediment supply and, therefore, can be generated by autogenic mechanisms as well. This includes subaerial unconformities that may form during autoretreat-related transgressions, where the trajectory of the transgressive shoreline records a shallower angle than the topographic gradient (i.e., the case of "coastal erosion" of Catuneanu, 2006, p. 93).

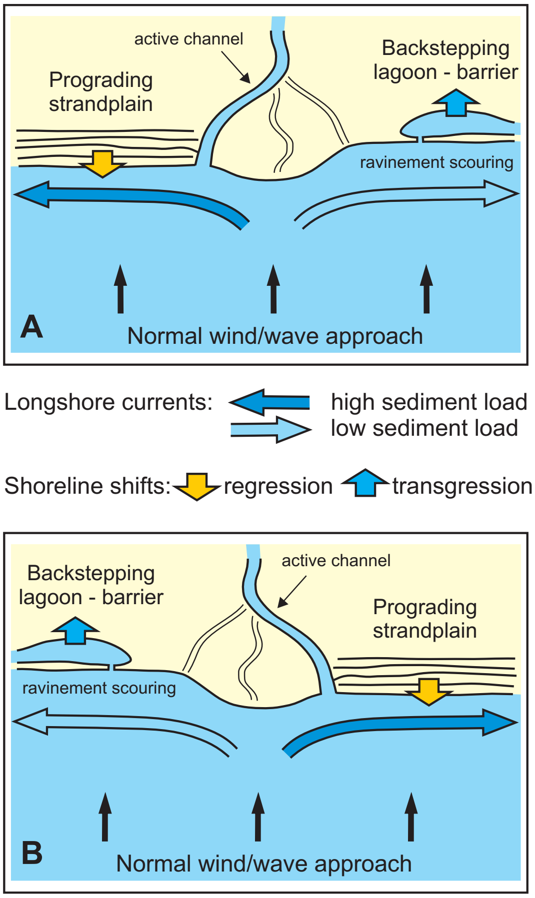

Figure 8. Shoreline shifts controlled by autocyclic river avulsion and delta lobe switching under conditions of relative sea-level rise in a shelf setting. Autocyclic shifting in the location of the main active channel of a deltaic system from time 1 (diagram A) to time 2 (diagram B) may result in changes in the sediment supply delivered to the adjacent open shorelines by longshore currents. Consequent changes in the direction of shoreline shift from time 1 to time 2 may generate maximum regressive and maximum flooding surfaces on the opposite sides of the delta.

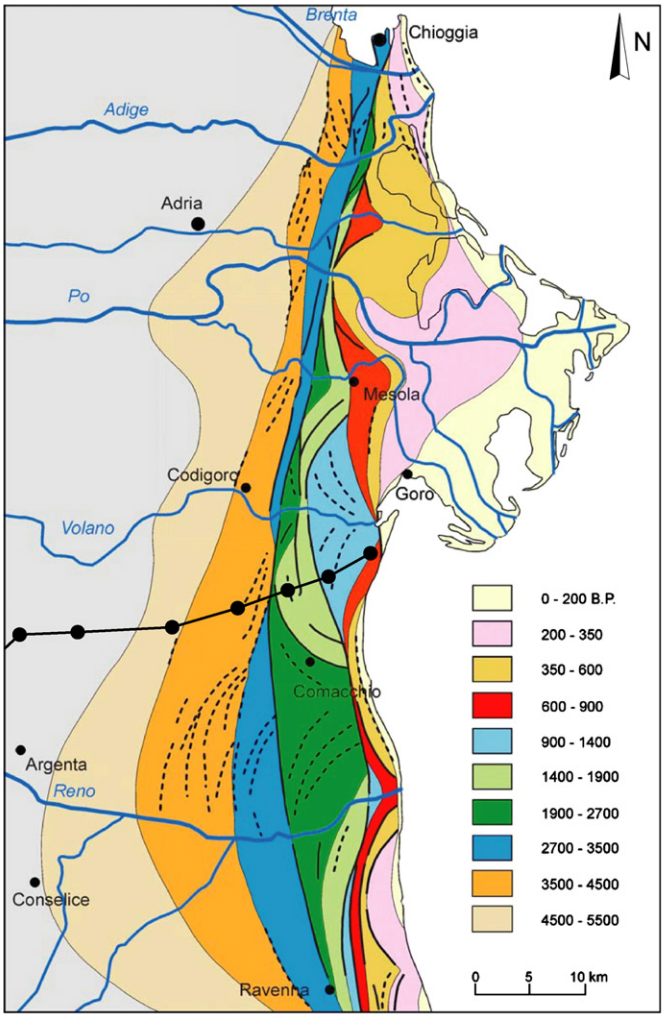

Figure 9. Map view expression of the high-frequency cycles that developed during the long-term highstand progradation of the Po delta and adjacent shoreline (from Stefani and Vincenzi, 2005). Note the good lateral extent of each cycle along strike, indicating that the autocyclic shifts of the Po delta controlled sediment supply to the adjacent shorelines as well. The transect south of the present-day Po delta indicates the location of the cross-section in Figure 10.

The link between various depositional environments as intrinsic components of a unitary sediment dispersal system indicates that autocyclicity is not necessarily 'local cyclicity', as its effects may transcend depositional-system limits and may impact stratigraphic architecture at larger scales (e.g., Muto et al., 2007). Recent research indicates that autogenic processes may affect areas as large as 10^1–10^2 km along strike and dip, over time scales of 10^3–10^5 yrs (e.g., Muto and Steel, 2002; Amorosi et al., 2005; Stefani and Vincenzi, 2005), which are comparable to, or even greater than the spatial and temporal scales associated with some allocycles. The larger the area affected by autogenic processes the more difficult it is to differentiate these processes from allocyclicity. Most studies on the origin of cycles have focused on removing the effects of smaller scale (local) autocyclicity from the larger scale stratigraphic frameworks attributed traditionally to allogenic controls.

The distinction of local cyclicity from that attributed to eustasy and/or large-scale tectonics has generally been attempted in the case of large and continuous datasets (e.g., Bhattacharya, 1993; Garrison and van den Bergh, 2004; Charvin et al., 2010). For example, Enge et al. (2010) recognized autocyclicity in the Cretaceous Panther Tongue delta (Utah, USA) (Fig. 5), represented by individual prograding mouth bars, which were referred to as bedsets, whereas the whole deltaic system was interpreted as a forced regressive unit (Posamentier and Morris, 2000). Bedsets of probable autocyclic origin were also recognized in the wave-dominated delta of the Aberdeen Member of the Blackhawk Formation (Utah, USA) (Fig. 5), in contrast to parasequences inferred to be linked to significant (>10 m) relative sea-level rises (Charvin et al., 2010).

The discrimination between external and internal controls on sedimentation becomes increasingly difficult in the case of sparse exposures or cores, when the full extent and architecture of stratigraphic units and bounding surfaces is difficult to assess. For example, the small-scale cycles in the wave-influenced deltaic system of the lower Pliocene Zinga Sandstone (Crotone Basin, southern Italy) display a coarsening- and shallowing-upward architecture, with bounding surfaces represented by maximum regressive surfaces (Zecchin et al., 2003) (Fig. 13). However, the limited availability of outcrops prevents an evaluation of the origin of these cycles and their correlation with other successions within the basin.

4. Discussion

The sequence concept was recently updated by Catuneanu et al. (2009, 2011), who designate the stratigraphic sequence as 'a cycle of change in accommodation or sediment supply', defined by 'the

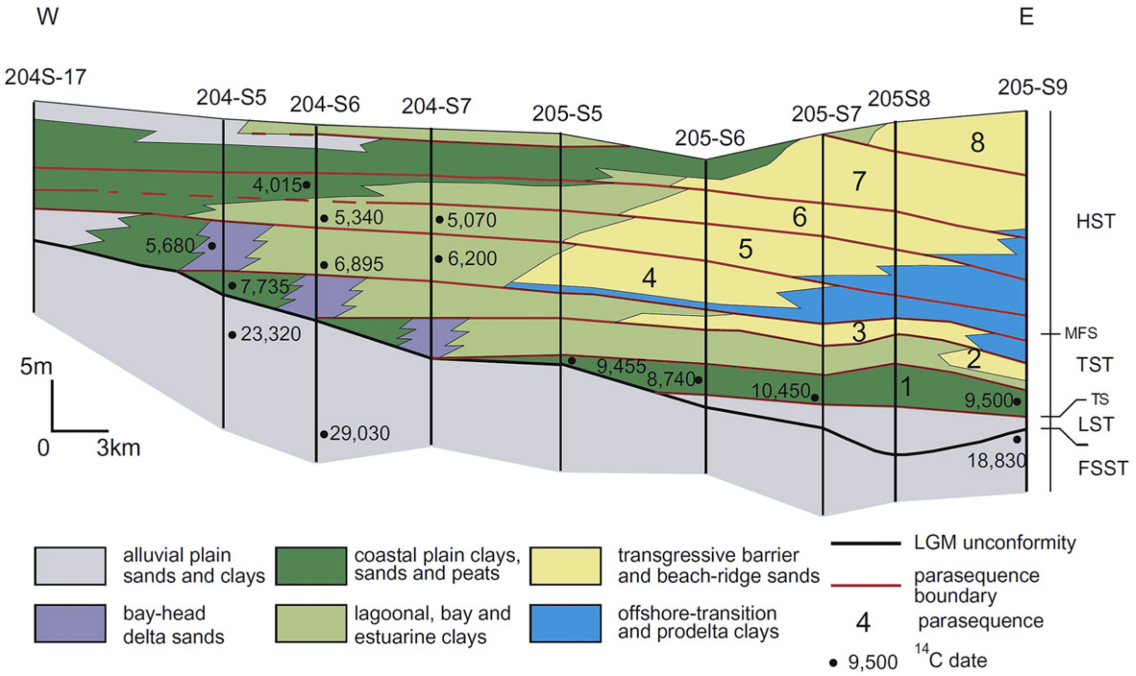

Figure 10. Stratigraphic cross-section (location in Fig. 9) showing the architecture of Holocene deposits south of the present-day Po delta (from Amorosi et al., 2005). The timing of the TST boundaries (i.e., TS and MFS) is likely controlled by the interplay of allogenic (relative sea level) and autogenic (variations in sediment supply from the Po delta) factors. The higher frequency cyclicity within the TST and HST systems tracts is most likely controlled exclusively by the autocyclic shifting of the Po delta (Amorosi et al., 2005). The terminology applied to these high-frequency cycles may range from 'parasequences' to 'small-scale cycles' and 'high-frequency sequences'. The latter term is preferred (see text for discussion). Abbreviations: FSST – falling-stage systems tract; LST – lowstand systems tract; TST – transgressive systems tract; HST – highstand systems tract; TS – transgressive surface (=maximum regressive surface); MFS – maximum flooding surface; LGM – Last Glacial Maximum.

recurrence of the same types of sequence stratigraphic surface through geologic time' (Catuneanu et al., 2011) (Fig. 1). The revised definition of a sequence places emphasis on observation (i.e., sequence stratigraphic surfaces that can be mapped in the rock record), and not on the interpreted origin of cycles. The importance of both accommodation and sediment supply in the development of sequences was also recognized previously (e.g., Schlager, 1993). Changes in accommodation are typically of allogenic origin (i.e., eustasy and tectonics, although additional space can also be created by compaction and sediment loading), whereas changes in sediment supply can be either of allogenic (e.g., climatic) or autogenic (e.g., fluvial channel avulsion, delta lobe switching and abandonment, efficiency of longshore sediment transport) origin.

The stratigraphic sequence concept recognizes not only cycles of relative sea-level change but also cycles generated by variations in the rates of sediment supply and/or creation of accommodation during continuous relative sea-level rise (Catuneanu et al., 2009, 2011). This is particularly relevant in the case of sequences bounded by surfaces that do not require relative sea-level fall to form (e.g., the maximum flooding surface in light of the genetic stratigraphic sequence approach, or the maximum regressive surface in light of the T–R sequence approach). The recurrence of such sequence boundaries in a succession defines sequences, even within intervals that accumulated during continuous relative sea-level rise. Both

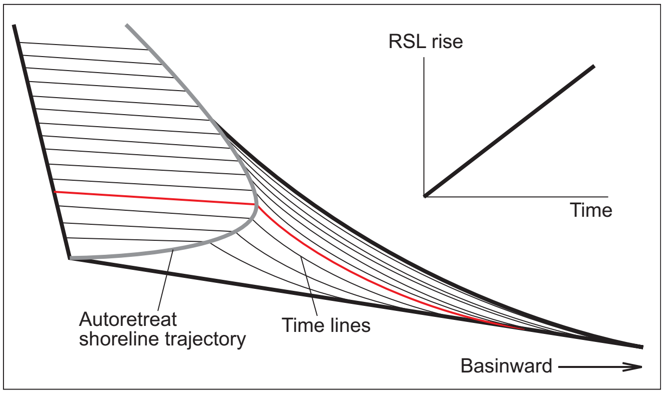

Figure 11. The autoretreat concept illustrated by an autogenic change in the direction of shoreline shift (modified from Muto and Steel, 1997, 2002). If the rates of relative sea-level (RSL) rise and sediment supply are kept constant, the shoreline undergoes an inevitable retreat after a period of progradation, due to the progressive increase of the surface area of the deltaic clinoform as the delta progrades into deeper water. The red line indicates the position of the maximum regressive surface, which marks a change from progradational to retrogradational stratal stacking patterns.

Sequence stratigraphic surface	Control	
	Allogenic	Autogenic
Subaerial unconformity	√	√
Maximum regressive surface	√	√
Maximum flooding surface	√	√
Transgressive ravinement surface	√	√
Basal surface of forced regression	√	
Regressive surface of marine erosion	√	
Correlative conformity	√	

Figure 12. Controls on the development of sequence stratigraphic surfaces. With the exception of the three subaqueous surfaces that form specifically in relation to forced regression, all other sequence stratigraphic surfaces may have an autogenic origin (see text for details).

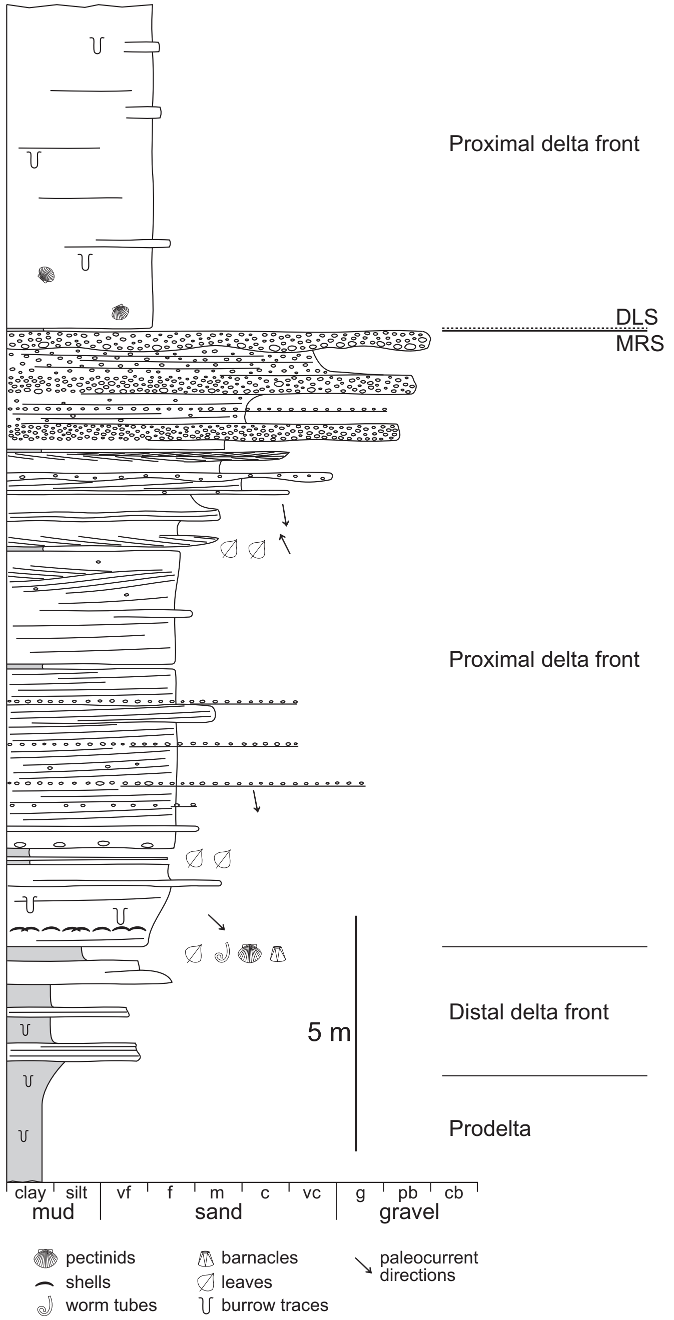

Figure 13. A shallowing-upward unit bounded at the top by a maximum regressive surface (MRS), composing part of a wave-influenced deltaic system in the lower Pliocene Zinga Sandstone (Crotone Basin, southern Italy). A condensed mud blanket separates the MRS from the downlap surface (DLS), which marks the base of the overlying prograding unit (modified from Zecchin et al., 2003).

accommodation and sediment supply play a role in the formation of these sequence boundaries, and their origin may be related to allogenic processes, autogenic processes, or a combination of both.

This sequence concept is suitable to classify cycles of any scale. At third-order seismic exploration scale, the external factors are typically highlighted as the main controls on the generation of sequences and surfaces of sequence stratigraphic significance, whereas autocyclicity is considered to only affect the internal architecture of systems tracts (Catuneanu et al., 2009, 2011). However, the role of autocyclicity as a control on the sequence stratigraphic framework becomes increasingly important at smaller scales of observation (e.g., in the case of fourth-order and lower rank cycles), where changes in shoreline trajectory may have a stronger autogenic component. This is the realm of the "small-scale cycles" of Zecchin (2007a), whose origin may be linked to both allogenic and autogenic processes. We extend the concept of sequence of Catuneanu et al. (2009, 2011) to include the small-scale cycles of Zecchin (2007a), as long as stratal stacking patterns can be linked to corresponding shoreline trajectories.

The updated sequence concept promotes a separation between the objective observation of stratal stacking patterns and bounding surfaces, and the subsequent interpretation of controlling parameters. Since the interpretation of controlling parameters may be subjective, debatable, and in some cases impossible to clarify, this aspect should not be considered in the definition of a sequence. Therefore, the concept of sequence should only be based on the observation of stratal features and stacking patterns, irrespective of forcing parameters. In this light, the small-scale cycle of Zecchin (2007a) corresponds to a high-frequency sequence (i.e., T–R or genetic stratigraphic), as it is based on the recognition of transgressive and regressive trends.

Although the exclusive allocyclic control on sequence development is usually assumed by sequence stratigraphers, this condition was never included in the definition of a sequence. By highlighting the importance of sediment supply, the possibility that autogenic processes may generate surfaces of sequence stratigraphic significance is in fact implicit in the definition of a stratigraphic sequence. Rather than assuming that 'a sequence is an allocycle', we stress that a sequence stratigraphic unit, whether systems tract, sequence or parasequence, is defined by its bounding surfaces. In turn, the definition of bounding surfaces needs to be based on consistent field criteria (i.e., observation of stratal features and stacking patterns; see Fig. 4.9 in Catuneanu, 2006, p. 113), irrespective of the interpreted origin of the surface. It is also important to note that not every autogenic process may result in the formation of a surface of sequence stratigraphic significance, but only those that can modify shoreline trajectories. In coastal to shelf settings, the recognition of shoreline shifts associated with the sequence bounding surfaces allows one to differentiate sequences from bedsets, which are unrelated to transgressive and regressive events.

The issue of nomenclature is important to consider in the definition of stratigraphic units and surfaces. If autocyclicity is dismissed as a potential control on the formation of sequence stratigraphic surfaces and units, then alternative terms should be used for 'autostratigraphic' surfaces and units that otherwise may display the same physical appearance as their allogenic counterparts. However, using different sets of terms for allo- versus autocyclic units and bounding surfaces that otherwise satisfy the same field criteria may create considerable confusion, especially when the interpretation of the origin of cycles is subject to debate. For example, the field expression of a maximum regressive surface in a shallow-water system is marked by a change from progradational to retrogradational stacking patterns, whether the turnaround from regression to transgression is caused by an increase in the rate of creation of accommodation (allogenic) or by an autoretreat process (autogenic). In both cases, the same physical processes are involved in the dispersal of sediment from river mouths to shoreface and shelf environments, and therefore the field expression of the resulting facies and stratigraphic architecture are also the same. Moreover, a maximum regressive surface is likely to be a composite surface with both allogenic and autogenic segments, particularly in the case of fourth-order and lower rank sequences (R.J. Steel, pers. comm.). Irrespective of its origin, the surface marking the change from progradation to retrogradation in a shallow-water setting can be labeled as a maximum regressive surface and mapped as a systems tract boundary or even a sequence boundary in the case

Sedimentary cycles	Origin of cycles	Subdivisions	Bounding surfaces
Stratigraphic: sequences	Allocycles or autocycles, related to shoreline shifts	Systems tracts	Sequence stratigraphic
Sedimentologic: bedsets	Autocycles, independent of shoreline shifts	Beds, bedsets	Facies contacts

Figure 14. Classification of sedimentary cycles into (1) stratigraphic, with applications for correlation, and (2) sedimentologic, with applications for facies analysis. Sequences are defined by the recurrence of the same types of sequence stratigraphic surface in the geological record, irrespective of the origin (i.e., allo- versus autogenic) of these surfaces. Sequence stratigraphic surfaces are systems tract boundaries, which are linked to shoreline shifts in underfilled basins. The definition of sequences as cycles of change in stratal stacking patterns, with the emphasis on field criteria as opposed to their interpreted origin, eliminates the need to employ other concepts (e.g., 'parasequence', 'small-scale cycle') in the classification of stratigraphic cycles.

of T–R sequences. It is therefore recommended that the nomenclature of units and surfaces be independent of interpretation and solely based on the observation of field data. A methodology based on field criteria is also most practical, since the field expression of autoretreat is indistinguishable from that of an allogenic transgression. As all sequence stratigraphic surfaces that form in relation to shoreline transgression can have dual or mixed origins (Fig. 12), we concur with the conclusion of Muto and Steel (2002) that sequence stratigraphy needs to incorporate the autoretreat concept, as well as any other autogenic process that can influence shoreline shifts.

The emphasis on the recognition of shoreline-related stratal stacking patterns, rather than their causes, also raises the possibility of human-induced sequences generated at the present time and in the recent millennia, due for example to artificial river diversions and sediment supply changes to river mouths affecting large coastal areas (e.g., Stefani and Vincenzi, 2005; Zecchin et al., 2009a).

The principles discussed in this paper apply to underfilled basins and the related downstream-controlled fluvial settings, where shoreline trajectories are fundamental in determining the timing of formation of conventional systems tracts and bounding sequence stratigraphic surfaces. Sequences that form independently of shoreline shifts, such as those composed of low- and high-accommodation systems tracts in overfilled basins or upstream-controlled fluvial settings, are thought to remain controlled by allogenic forces related to climate and source area tectonism. Changes in the degree of amalgamation of fluvial channels, which define low- and high-accommodation systems tracts, are most evident at the third-order level of cyclicity; at such 'seismic' scales, allogenic factors are known to dominate the behavior of fluvial systems (e.g., Shanley and McCabe, 1994; Miall, 1996; Blum and Tornqvist, 2000; Holbrook, 2001). The sequence stratigraphy of overfilled basins or of upstream-controlled fluvial settings is still tentative at fourth-order or lower rank scales, and more research is needed to document the role, if any, of autocyclic processes in the development of high-resolution fully fluvial sequences.

5. Conclusions

The development of sequences is controlled by a combination of allogenic and autogenic processes. The geographic extent of sequences and component systems tracts is highly variable, and depends on the size of the areas which the controlling factors operate upon. In the case of sequences controlled by glacio-eustasy, prevalent during Icehouse climatic regimes, sequences may have a global extent. In all other cases, the development of sequence stratigraphic units is restricted to individual sedimentary basins or portions thereof defined by structural elements (e.g., tectonic subbasins) or by the patterns of sediment distribution (e.g., areas dominated by particular sediment dispersal systems and supply). Typically, the lower the hierarchical rank of sequences and systems tracts the smaller their area of development, although exceptions are known especially in the case of eustatic cycles related to orbital forcing.

The shoreline is the fundamental element that controls the formation and timing of sequence stratigraphic surfaces and systems tracts in underfilled basins, from the downstream-controlled fluvial systems to the deep-water systems. Any changes in shoreline trajectory, whether auto- or allogenic in origin, influence the stratal stacking patterns that can be observed in the rock record and which sequence stratigraphic interpretations are based upon.

Forced regressions are always driven by allogenic controls, and therefore all marine surfaces associated with stages of relative sea-level fall (i.e., the regressive surface of marine erosion, the basal surface of forced regression and the correlative conformity) are of allocyclic origin. In contrast, changes in the direction of shoreline shift during stages of relative sea-level rise are sensitive not only to the rates of creation of accommodation but also to variations in sediment supply. Therefore, both allogenic and autogenic processes may contribute to the formation of sequence stratigraphic surfaces during stages of relative sea-level rise. This is the case with all surfaces that are associated with transgression (i.e., the maximum regressive surface, the transgressive ravinement surfaces and the maximum flooding surface). The subaerial unconformity typically forms during forced regression, in which case it has an allogenic origin, but it may also form during transgression, in which case an autogenic origin is possible.

Not all autogenic processes play a role in the formation of sequence stratigraphic surfaces and systems tracts, but only those that can influence the direction of shoreline shift. In the latter case, autocyclicity is no longer 'local cyclicity', but its effects transcend depositional system boundaries and impact stratigraphic architecture across areas as large as 10^1–10^2 km along strike and dip, over 10^3–10^5 yrs time scales. These spatial and temporal scales are comparable to, or even greater than the scales associated with some allocyclic processes, particularly at the 4th-order and lower rank hierarchical levels.

The discrimination between allo- and autogenic processes in the rock record is a matter of interpretation and is tentative at best in many instances. The larger the area affected by autogenic processes the more difficult it is to differentiate these processes from allocyclicity. This task is even harder when shoreline shifts and the associated sequence stratigraphic surfaces are controlled by a mix of external and internal factors. Irrespective of the relative contributions of these factors, the resulting field expression and stacking patterns in the rock record are the same, as the same physical processes are involved in the dispersal of sediment from fluvial to coastal and marine environments. For this reason, the definition and nomenclature of units and bounding surfaces need to be based on the observation of stratal features and stacking patterns rather than the interpretation of the controlling mechanisms. In this light, we extend the sequence concept of Catuneanu et al. (2009, 2011) to include all cycles bounded by recurring surfaces of sequence stratigraphic significance, irrespective of the origin of these surfaces.

Stratigraphic cycles can be classified into (1) sequences, which include all allocycles as well as autocycles linked to shoreline shifts and bounded by sequence stratigraphic surfaces, and (2) bedsets, which include autocycles unrelated to shoreline shifts and bounded by within-systems tract facies contacts (Fig. 14). In contrast to bedsets, sequences can be subdivided further into systems tracts. The recognition of the role of autocyclicity in the formation of sequence stratigraphic surfaces eliminates the need to employ 'parasequences' and 'small-scale cycles' in high-resolution stratigraphic analyses, which can be effectively replaced by high-frequency sequences.

The updated sequence concept promotes a separation between the objective observation of field criteria and the subsequent interpretation of controlling parameters, and stresses that a sequence stratigraphic unit is defined by its bounding surfaces and not by its interpreted origin. This approach helps to keep the nomenclature simple and objective, and the methodology independent of models and interpretations. Subsequent interpretations of the origin of units and bounding surfaces help to rationalize the observed architecture of the sequence stratigraphic framework.

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