



Review article

High-resolution sequence stratigraphy of clastic shelves I: Units and bounding surfaces

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ARTICLE INFO

Article history:

Received 24 April 2012

Received in revised form

30 August 2012

Accepted 31 August 2012

Available online 13 September 2012

Keywords:

High-resolution sequence stratigraphy

Clastic shelves

Stratigraphic units

Stratigraphic surfaces

ABSTRACT

The high-resolution sequence stratigraphy tackles scales of observation that typically fall below the resolution of seismic exploration methods, commonly referred to as of 4th-order or lower rank. Outcrop- and core-based studies are aimed at recognizing features at these scales, and represent the basis for high-resolution sequence stratigraphy. Such studies adopt the most practical ways to subdivide the stratigraphic record, and take into account stratigraphic surfaces with physical attributes that may only be detectable at outcrop scale. The resolution offered by exposed strata typically allows the identification of a wider array of surfaces as compared to those recognizable at the seismic scale, which permits an accurate and more detailed description of cyclic successions in the rock record. These surfaces can be classified as 'sequence stratigraphic', if they serve as systems tract boundaries, or as facies contacts, if they develop within systems tracts. Both sequence stratigraphic surfaces and facies contacts are important in high-resolution studies; however, the workflow of sequence stratigraphic analysis requires the identification of sequence stratigraphic surfaces first, followed by the placement of facies contacts within the framework of systems tracts and bounding sequence stratigraphic surfaces.

Several types of stratigraphic units may be defined, from architectural units bounded by the two nearest non-cryptic stratigraphic surfaces to systems tracts and sequences. The need for other types of stratigraphic units in high-resolution studies, such as parasequences and small-scale cycles, may be replaced by the usage of high-frequency sequences. The sequence boundaries that may be employed in high-resolution sequence stratigraphy are represented by the same types of surfaces that are used traditionally in larger scale studies, but at a correspondingly lower hierarchical level.

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1. Introduction

Sequence stratigraphic methodology and terminology developed gradually since the inception of sequence stratigraphy (Payton, 1977; Wilgus et al., 1988), largely without formal guidelines from the international stratigraphic commissions, and this resulted in the co-existence of several schools of thought that advocate different approaches to the application of the method. At the same time, the nature of the controls that govern sedimentary cyclicity in the rock record, such as eustasy vs. tectonics, climate and sediment supply, was also the subject of much debate (e.g., Miall, 1997).

The lack of formal guidance in the development of sequence stratigraphy, coupled with the great variability exhibited by sedimentary successions, resulted in the proliferation of unnecessarily

complex and sometimes conflicting terminology, leading to redundancies and ultimately to confusion. Catuneanu et al. (2009) initiated an international effort to identify a common platform in sequence stratigraphy, and highlighted the model-independent and the model-dependent aspects of the method. The former deal with all the objective features of sequences, such as the observation of stratal stacking patterns and changes thereof, whereas the latter referred to the nomenclature of surfaces and systems tracts, and to the selection of the sequence boundary.

The adoption of a standard workflow based on model-independent principles free of any model-oriented personal preference has been endorsed recently by the International Subcommission on Stratigraphic Classification as the recommended approach to describe the cyclicity in sedimentary successions (Catuneanu et al., 2011). The adopted terminology should also follow a unified scheme derived from large consensus, and should be applicable to a wide range of scales, from seismic to high-resolution outcrop and core studies. However, while a standard workflow can be defined as a unified platform, the actual approach that is most applicable to

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a particular case study depends on a number of variables, including the types of data available for analysis, as well as the depositional and tectonic settings (Catuneanu et al., 2009, 2010, 2011).

High-resolution sequence stratigraphic analysis is a very effective tool for outcrop research as well as for studies based on closely spaced well-logs and cores. Recent developments in the acquisition of seismic data have improved the resolution of seismic imaging to a level that rivals the resolution of outcrop studies, especially in the case of Chirp or Boomer data (e.g., Liu et al., 2004; Ridente and Trincardi, 2005; Zecchin et al., 2009a, 2011a). However, the degree of detail concerning the physical attributes of surfaces and sediment packages offered by outcrops and cores is irreplaceable and essential for the full understanding of sedimentary processes and the definition of process-based high-resolution sequence stratigraphic frameworks. Additional insights, such as those afforded by chemostratigraphy, may further improve the degree of stratigraphic detail.

Traditional sequence stratigraphy was developed for the purpose of petroleum exploration at scales above the seismic resolution, commonly referred to as of third order (Payton, 1977). For this reason, all the elements of a sequence stratigraphic framework, from depositional systems to systems tracts and sequences, were defined originally relative to this scale of observation. Subsequent developments in sequence stratigraphy followed two trends: 1. the methodology was applied to datasets other than seismic, including well logs, core and outcrop; and 2. the methodology was applied to increasingly smaller (sub-seismic) scales of observation to resolve, for example, issues of reservoir characterization and fluid flow at stages of petroleum production development. These trends resulted in a significant increase in the level of stratigraphic detail that can be resolved, defining what is known today as high-resolution sequence stratigraphy.

The high-resolution sequence stratigraphy tackles scales of observation that typically fall below the resolution of seismic data, within the realm of 4th-order or lower rank stratigraphic frameworks. Outcrop and core data provide unique opportunities to

observe the physical attributes of various types of sediment bodies and bounding surfaces at these scales, and allow the identification of a wider array of surfaces as compared to those recognizable at the seismic scale (Fig. 1). Some of these surfaces hold a sequence stratigraphic significance, others are simply facies contacts within the sequence stratigraphic frameworks (Fig. 1). However, all types of surfaces that can be observed at outcrop scale are important to consider in high-resolution stratigraphic studies, and their origins and roles in defining stratigraphic frameworks are discussed in this paper.

This work also reviews the various types of units that can be defined in high-resolution studies in clastic shallow-water settings, and discusses the strengths and limitations of the different approaches to the classification of high-frequency stratigraphic cycles. Competing approaches to the definition of cycles at outcrop scale originated in part from the lack of formal guidance in the development of sequence stratigraphy. These approaches can now be re-evaluated for a streamlined methodology and nomenclature in sequence stratigraphy.

2. Sequence stratigraphic surfaces

Surfaces suitable for high-resolution sequence stratigraphic studies are stratigraphic contacts that serve as boundaries between sequences, as well as for the subdivision of sequences into systems tracts (genetic units *sensu* Catuneanu et al., 2009) that are linked to specific shoreline trajectories (Fig. 1).

2.1. Subaerial unconformity (SU) and correlative conformity (CC)

The SU (Sloss et al., 1949) forms under subaerial conditions, is typically associated with erosion of variable degree, non-deposition or pedogenesis, and therefore it is typified by temporal hiatus (Figs. 1–3). This surface usually forms and progressively expands basinward during relative sea-level fall; however, its development may continue during subsequent lowstand normal regression and transgression (Milana and Tietze, 2007; Swenson and Muto, 2007),

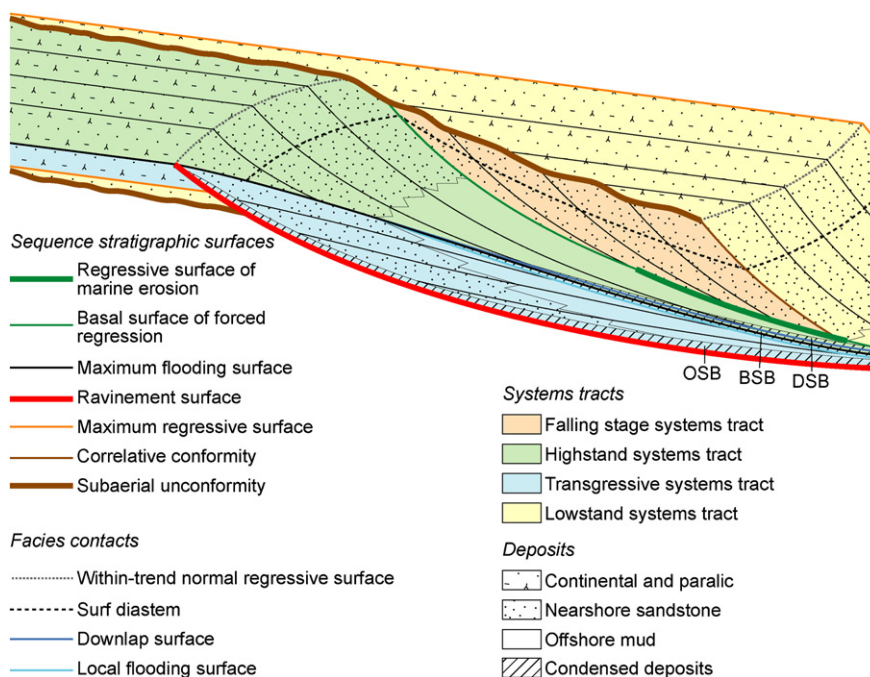


Figure 1. Sequence stratigraphic surfaces, facies contacts, systems tracts and condensed shell beds developed during a full cycle of relative sea-level change in a clastic shelf/ramp setting. Continental to offshore deposits are considered. Abbreviations: BSB – backlap shell bed; DSB – downlap shell bed; OSB – onlap shell bed.

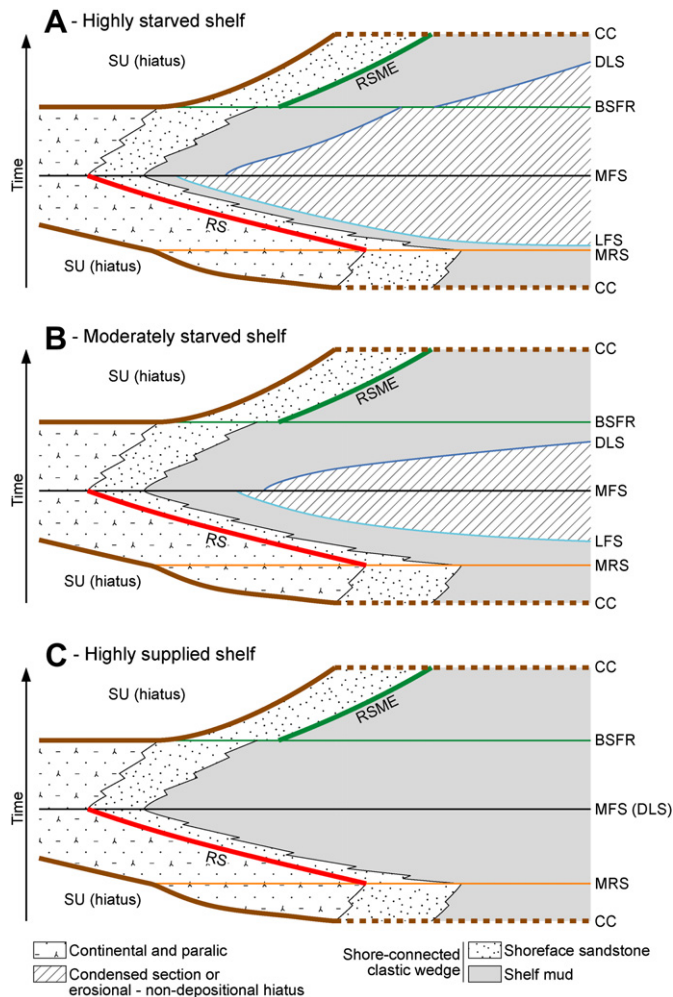


Figure 2. Wheeler diagrams showing the framework of sequence stratigraphic surfaces and facies contacts in the case of (A) highly starved shelf; (B) moderately starved shelf; and (C) highly supplied shelf. Note the offset between the MFS, the DLS and the LFS under increasingly starved conditions. Abbreviations: BSFR – basal surface of forced regression; CC – correlative conformity; DLS – downlap surface; LFS – local flooding surface; MFS – maximum flooding surface; MRS – maximum regressive surface; RS – ravinement surface; RSME – regressive surface of marine erosion; SU – subaerial unconformity.

or may be triggered by climatic and tectonic factors irrespective of relative sea-level changes in upstream-controlled areas or in overfilled basins (Blum, 1994; Catuneanu and Elango, 2001). In cases of autoretreat, and 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), the formation of the subaerial unconformity may be autocyclic.

The SU commonly is well defined in the field. It may be associated with sharp channelized truncations of the underlying units by fluvial erosion (Figs. 4–6), or with variably developed paleosols in interfluvial areas (Aitken and Flint, 1996; McCarthy and Flint, 1998) (Fig. 3). The sedimentary facies underlying the SU can be of any origin, while those accumulated above range commonly between continental and paralic (Figs. 1, 4–7). Transgressive erosional surfaces may also rework the SU, and in such cases the resulting composite unconformity is onlapped by fully marine transgressive “healing-phase” facies (Figs. 1, 4 and 7). The SU passes into a correlative conformity (CC) in the marine realm, which represents the paleo-seafloor at the end of forced regression (Catuneanu, 2002, 2006) (Figs. 1 and 2). The CC was originally defined on the basis of reflection stacking patterns on seismic lines,

but field criteria for its recognition in outcrop have also started to be defined in recent years (MacNeil and Jones, 2006; Bover-Arnal et al., 2009; Catuneanu et al., 2011).

2.2. Maximum regressive surface (MRS)

The MRS (Helland-Hansen and Martinsen, 1996), also known as the ‘transgressive surface’ (Posamentier and Vail, 1988), separates regressive deposits below from transgressive deposits above (Figs. 1 and 2). In marine settings, the MRS is commonly marked by a conformable shift from a progradational stacking pattern (commonly, a coarsening- and shallowing-upward succession) to a retrogradational stacking pattern (commonly, a fining- and deepening-upward succession) (Fig. 8). However, care is recommended in the interpretation of coarsening- and fining-upward trends in terms of water shallowing and deepening, respectively, both in siliciclastic and carbonate systems. An accurate facies analysis, accompanied by the analysis of the geometry of the sedimentary succession, is needed to recognize true turnarounds from regression to transgression. A significant degree of diachroneity may be associated with this surface along depositional strike, depending on lateral variations in sediment supply and subsidence (Catuneanu et al., 2009).

The MRS includes a non-marine portion, landward from the shoreline at the end of regression, and a marine portion, seaward from the shoreline at the end of regression (Figs. 1 and 2). The distal part of the fluvial portion of the MRS is typically reworked by the transgressive ravinement surface (Figs. 1 and 4), and the landward extent of this reworking depends on a number of factors including the gradient of the landscape and the trajectory of the transgressive shoreline. Where preserved, the fluvial MRS onlaps the SU in an updrift direction, at the point where the lowstand fluvial topset wedges out (Figs. 1 and 2). The non-marine portion of the MRS typically sits at the boundary between amalgamated fluvial channels below and floodplain-dominated deposits above (Amorosi and Colalongo, 2005), or at the base of the earliest estuarine deposits (e.g. Amorosi et al., 1999; Olsen et al., 1999; Allen and Johnson, 2011) (Fig. 4). The marine portion of the MRS may merge with the maximum flooding surface in a downdip direction, if the transgressive deposits do not accumulate or are removed by erosional processes.

2.3. Ravinement surface (RS)

The RS is a diachronous erosional surface cut during transgression by waves in shallow-marine settings (wave-ravinement surface, WRS; Swift, 1968; Demarest and Kraft, 1987; Nummedal and Swift, 1987) or by tidal currents in estuarine settings (tidal-ravinement surface, TRS; Allen and Posamentier, 1993) (Figs. 1 and 2). The erosion associated with this surface is variable, typically in a range of meters to few tens of meters, and in some cases it may rework the SU (Figs. 1, 4 and 7). For a review of the factors governing the development of the RS see Cattaneo and Steel (2003) and Zecchin (2007).

The WRS climbs toward the basin margin (Fig. 1), and is commonly paved by coarser grained sediment reworked from the substrate (i.e., a transgressive lag, Figs. 4, 5 and 9) or by condensed shell beds that concentrate on top of the WRS (“onlap shell beds”, OSB, Figs. 1, 5, 6, and 9–13) (Kidwell, 1991; Naish and Kamp, 1997; Kondo et al., 1998), and are onlapped by the transgressive healing-phase shallow-water facies. OSBs result from low net deposition due to sediment bypass (Kidwell, 1991), and they may accumulate after repeating storm reworking in high energy settings or by the concentration of organisms in life or near life position in sheltered settings (Di Celma et al., 2005), or may represent the final result of

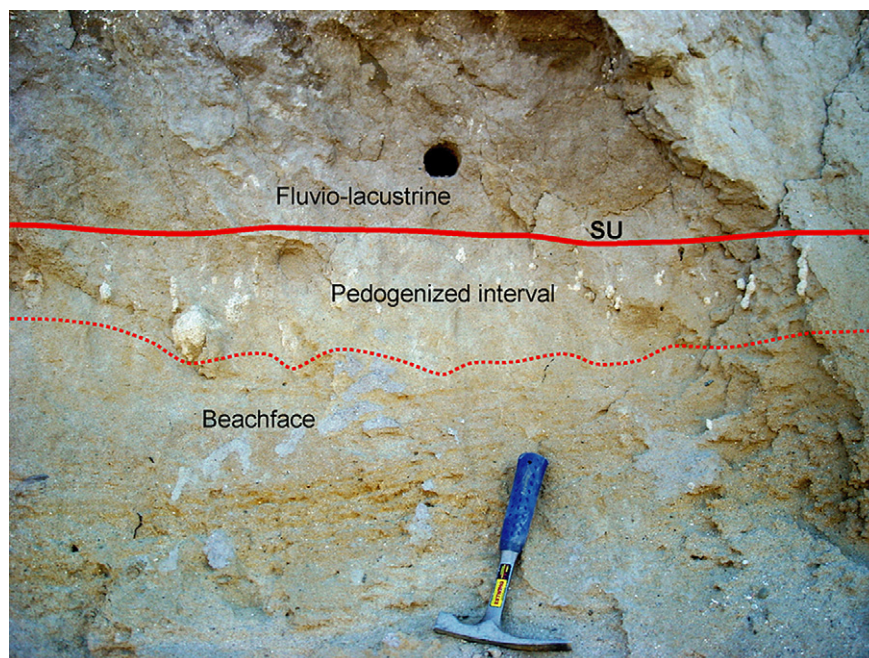


Figure 3. Subaerial unconformity (SU) marked by a calcrete interval, separating upper beachface sandstones from fluvio-lacustrine deposits. Middle Pleistocene Cutro terrace, southern Italy (modified from Zecchin et al., 2011b).

concentration by infaunal organisms (Carnevale et al., 2011). The WRS is also frequently marked by substrate-related ichnofossils belonging to the *Glossifungites* ichnofacies, including *Thalassinoides*, *Skolithos*, *Diplocraterion* and *Arenicolites* (Pemberton et al., 1992) (Figs. 9, 11 and 12), or to the *Trypanites* ichnofacies where a lithified substrate is exhumed (Pemberton et al., 1992; Cantalamessa et al., 2007). *Gastrochaenolites*, *Entobia* or other borings belonging to the *Trypanites* ichnofacies can also affect the clasts composing transgressive lags (Siggerud et al., 2000).

Although the RS is commonly a relatively flat surface, the evidence from post-glacial transgressed shelves shows locally high-relief, stepped or irregular RSs (Goff et al., 2005; Zecchin et al., 2011a). Due to its very good appearance in the field (Fig. 9), the RS is one of the most suitable surfaces to subdivide shallow-marine successions into cycles (Zecchin, 2007).

2.4. Maximum flooding surface (MFS)

The maximum flooding surface (MFS, Posamentier et al., 1988; Van Wagoner et al., 1988) corresponds to the seafloor at the time of maximum shoreline transgression, and marks a change between transgressive and normal regressive shoreline trajectories (Helland-Hansen and Martinsen, 1996; Catuneanu, 2006) (Figs. 1 and 2). While on seismic lines the MFS is generally equated to the downlap surface marking the base of the highstand prograding clinoforms, high-resolution outcrop and core studies indicate that the MFS and the downlap surface may be separated by a condensed section and, therefore, they may not necessarily coincide (see Section 3.2) (Figs. 1, 5, 11A,B and 12). The MFS, therefore, may correspond to a cryptic 'conceptual' horizon within condensed deposits accumulated around the time of maximum transgression, without necessarily having a clear physical expression (Carter et al., 1998) (Figs. 11–14). In the case of starved shelves, the MFS may be represented by omission surfaces; in the case of condensed sections, the MFS is commonly taken at the point of highest Bioturbation Index, interpreted to indicate the change from transgression to highstand normal regression (Figs. 11 and 14).

The MFS may be associated to a significant degree of diachroneity along depositional strike, whereas it approximates a timeline along dip (Catuneanu et al., 2009) (Fig. 2).

2.5. Basal surface of forced regression (BSFR)

The BSFR (Hunt and Tucker, 1992) coincides with the seafloor at the onset of forced regression and marks the base of all marine forced regressive deposits (Catuneanu, 2002, 2006) (Figs. 1 and 2). This surface was originally defined on the basis of seismic data (Catuneanu, 2006), but there is increasing evidence that the BSFR has a lithological expression in outcrop and core as well (MacEachern et al., 1999; MacNeil and Jones, 2006; Bover-Arnal et al., 2009). As sediment supply to the marine environment increases with the start of relative sea-level fall, both in terms of volume and sediment caliber, an increase in the dip angle of clinoforms may occur at the onset of forced regression in a prograding wedge, producing a downlap surface at the top of the youngest highstand marine sediment (Fig. 15). If the base of the forced regressive wedge lies below wave base and/or the gradient of the forced regressive clinoforms is high (i.e., steeper than the wave equilibrium profile), then a regressive surface of marine erosion (see below) may not form; in this case, the downlap surface that separates highstand from forced regressive sediments is preserved as the BSFR, as it is not reworked by waves during forced regression. A field example illustrating this situation is provided by Pomar and Tropeano (2001) (Fig. 15).

2.6. Regressive surface of marine erosion (RSME)

The RSME (Plint, 1988; Plint and Nummedal, 2000) is a diachronous surface produced by wave erosion in the lower shoreface during relative sea-level fall, and it marks the base of forced-regressive shorefaces (Figs. 1, 2, 7 and 16). This surface is commonly recognizable by a sharp contact between fine-grained shelf sediments below and sandy to gravely shoreface sediments above (Fig. 16); however, this contact may be cryptic where the amount of scouring is less and the caliber of the sediment below and

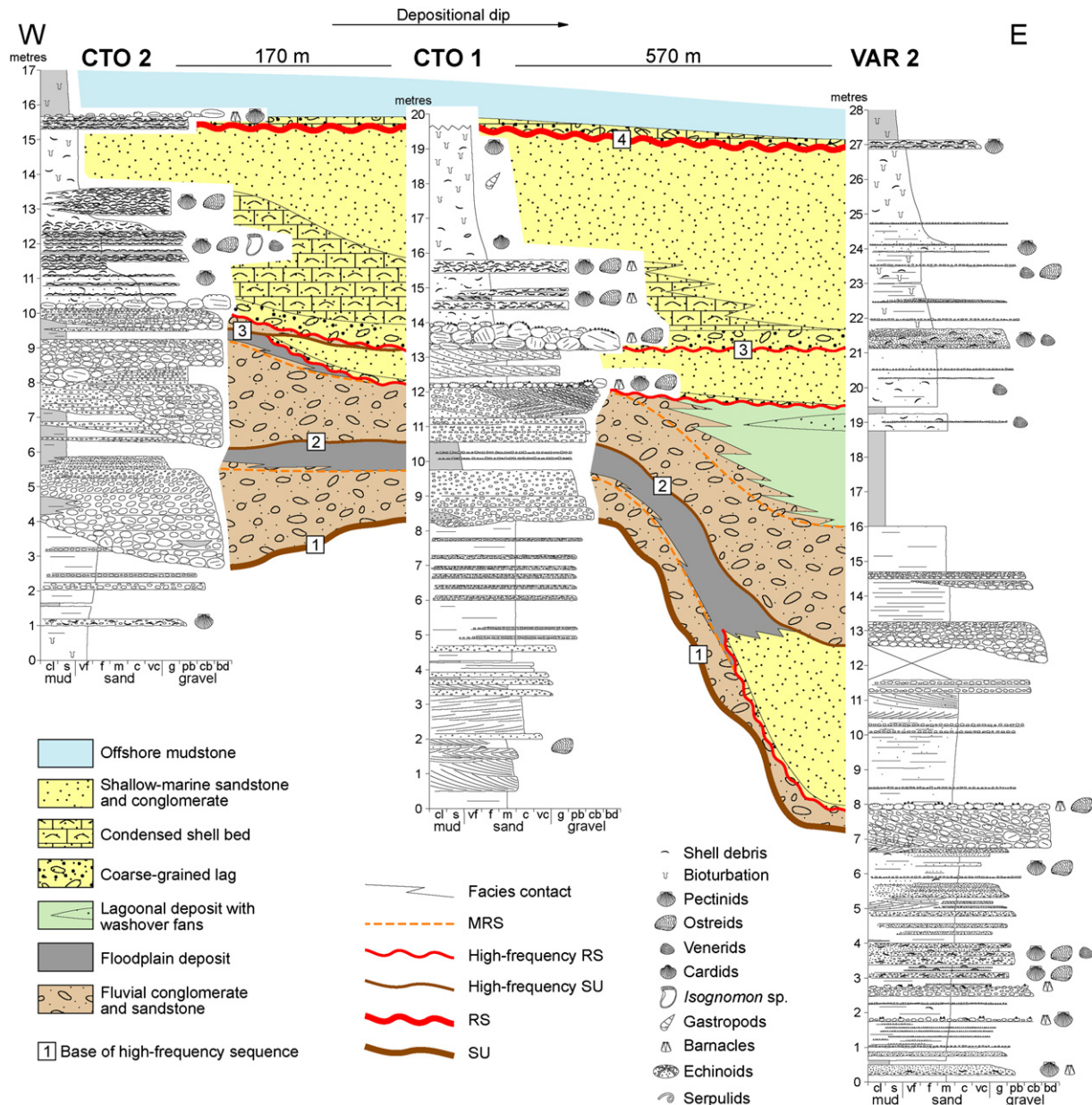


Figure 4. Hierarchical organization of cycles, with three high-frequency sequences composing a larger transgressive, deepening-upward trend, in the continental to marine Pliocene succession of the Croton Basin, southern Italy (modified from Zecchin et al., 2006). Individual RSs, marked by coarse-grained lags, rework MRSs and SUs locally. MRSs are cryptic and inferred to lie at the transition between amalgamated fluvial channel and floodplain deposits. Abbreviations: MRS – maximum regressive surface; RS – ravinement surface; SU – subaerial unconformity.

above is similar (e.g. Zecchin et al., 2009b, 2011b) (Fig. 7). This surface may also not form during forced regression, particularly in front of river-dominated deltas where seafloor gradients are steeper than the wave equilibrium profile (Catuneanu, 2006). The RSME may be associated with lags (Pattison, 1995), gutter casts (Plint and Nummedal, 2000) and *Glossifungites* ichnofacies (Pemberton et al., 1992). For a review of the factors governing the development of the RSME see Plint and Nummedal (2000) and Zecchin (2007).

2.7. The significance of sequence stratigraphic surfaces for correlation

2.7.1. The choice of a datum

Because of the sparse occurrence of outcrops, the choice of an appropriate datum to correlate exposed stratigraphic sections and

cores may be difficult, and therefore the correct recognition of surfaces of sequence stratigraphic significance is essential. The arbitrary choice of lithologic boundaries or inclined clinoform surfaces as datum invariably leads to highly distorted architectures of sedimentary bodies on cross sections (see examples in Bhattacharya, 2011).

In principle, surfaces that are relatively flat at syn-depositional time, such as MFSs lying within fine-grained marine successions, make better datums, but they are often difficult to pick precisely within condensed sections (Fig. 14). Wave scouring during transgression may result in relatively flat and regular WRSSs, as compared to other surfaces, which can form extensive and well recognizable wave-cut platforms. However, they may exhibit a variable seaward inclination which needs to be accounted for in the construction of cross sections. Similarly, the portion of the MRS that develops in

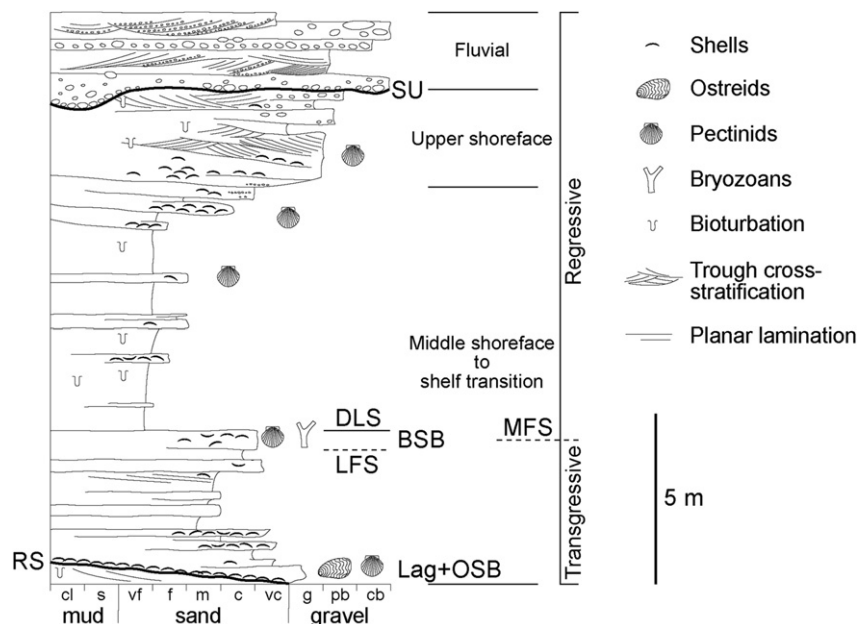


Figure 5. Example of transgressive–regressive unit from the lower Pliocene Zinga Sandstone, Crotone Basin, southern Italy (modified from Zecchin et al., 2004). The lower part of the transgressive interval consists of packed shell concentrations (OSB) mixed at the base with material reworked from the substrate (transgressive lag) and overlying a transgressive erosional surface (RS). The transition between transgressive and regressive deposits consists of condensed shell beds (BSB) accumulated under conditions of sediment starvation (see text for details). The regressive succession is dominated by shoreface–shelf deposits separated from the overlying fluvial strata by a subaerial unconformity. The MFS is cryptic and inferred to lie between the LFS and the DLS. Abbreviations: BSB – backlap shell bed; DLS – downlap surface; LFS – local flooding surface; MFS – maximum flooding surface; OSB – onlap shell bed; RS – ravinement surface; SU – subaerial unconformity.

shallow-water systems may also dip basinward, as representing the clinoform surface at the end of regression (Fig. 1). WRSs were used as datum in several cases, for example in the study of shoreface tongues (e.g., Hampson, 2000) or of marine terrace deposits (Zecchin et al., 2009b, 2011b) (Fig. 7).

2.7.2. Correlation based on sparse datasets

The correlation of sparse outcrop sections or cores and the consequent 3D reconstruction of facies and stratigraphic architecture of sedimentary units can be made following a careful facies analysis and the recognition of surfaces of sequence stratigraphic

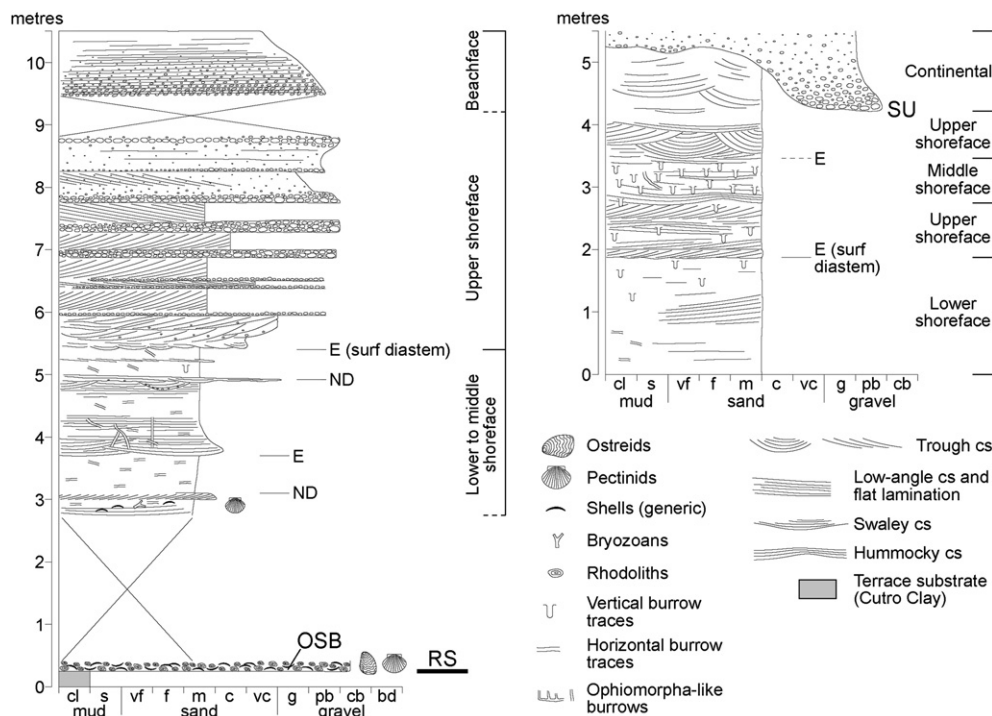


Figure 6. Sections illustrating the middle Pleistocene Cutro terrace deposits, southern Italy (modified from Zecchin et al., 2011b). The terrace is marked at the base by an RS overlain by a rhodolith-bearing OSB, whereas the larger part of the succession is represented by regressive shoreface to continental deposits. The erosional surf diastem separates the middle shoreface from the upper shoreface sandstones and conglomerates. Minor discontinuity surfaces define smaller-scale units that can be referred to as bedsets. Abbreviations: cs – cross-stratification; E – erosional discontinuity; OSB – onlap shell bed; ND – non-depositional discontinuity; RS – ravinement surface; SU – subaerial unconformity.

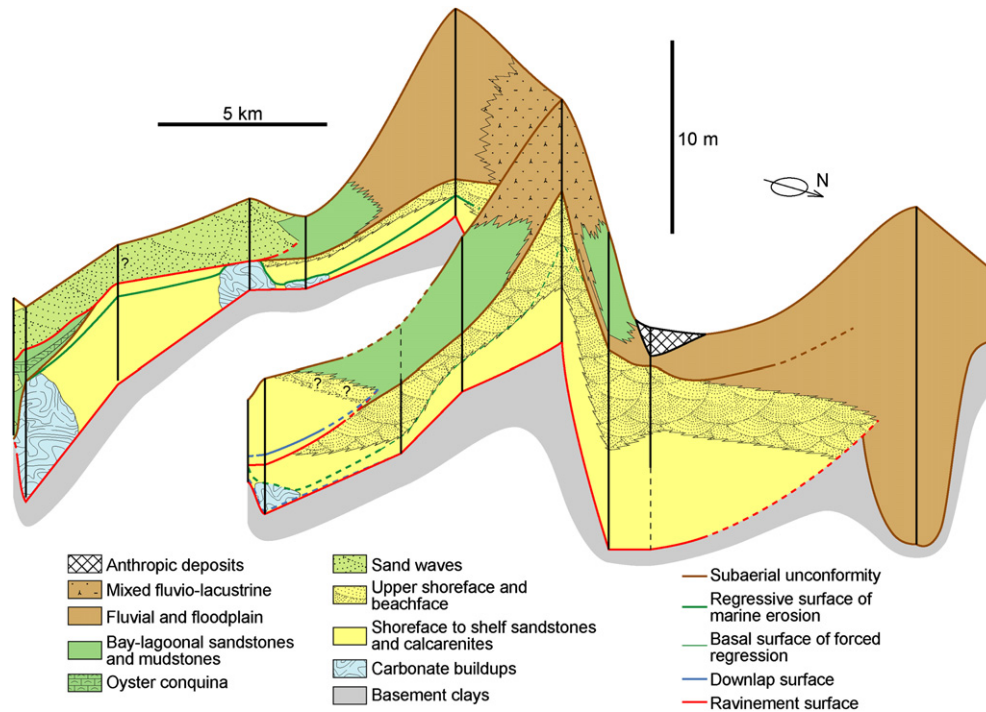


Figure 7. Fence panel showing facies and stratal surfaces recognized in the middle Pleistocene Cutro terrace, southern Italy (modified from Zecchin et al., 2011b). The unit is composed of two cycles marked by the basal ravinement surface (first cycle) and by another ravinement surface partially reworking a subaerial unconformity in the middle of the deposit (second cycle). The terrace consists of a mix of continental, paralic, shoreface and shelf deposits. Forced regressive deposits underlain by a regressive surface of marine erosion form part of the lower cycle.

significance. This integrated approach affords prediction of lateral and vertical facies changes within a sequence stratigraphic framework of units and bounding surfaces, even where the elements of this framework cannot be walked in a continuous section, provided

that data are not so scattered to obscure the lateral continuity among depositional systems.

Several studies based on core, well-log and field data successfully adopted such a process-based methodology that of necessity



Figure 8. Conformable maximum regressive surface (arrow) separating coarsening-upward (below) from fining-upward (above) shallow-water facies in the Panther Tongue Formation, Utah (from Catuneanu, 2006).

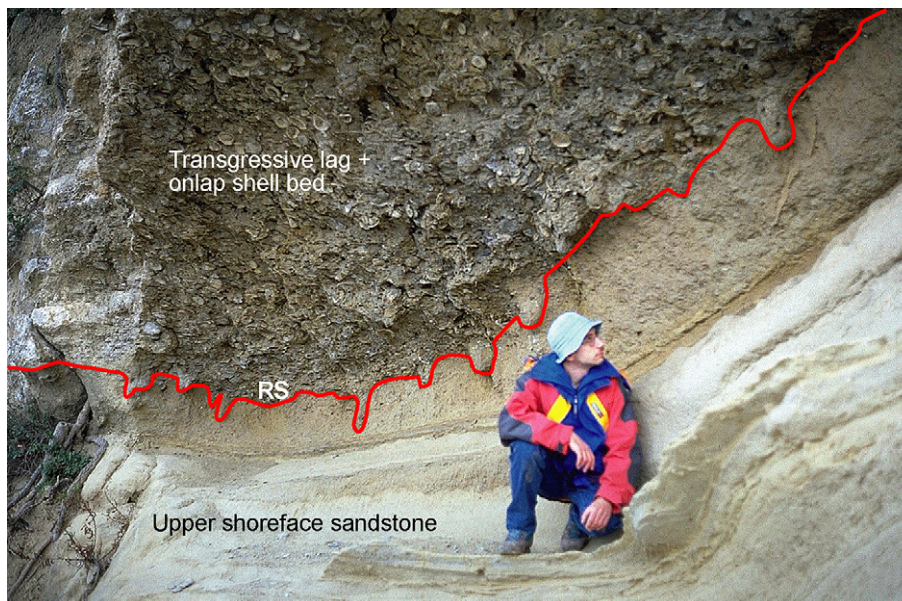


Figure 9. Prominent ravinement surface (RS) marked by large burrows, from the lower Pliocene Zinga Sandstone, Crotone Basin, southern Italy (modified from Zecchin et al., 2003). The surface is paved by material reworked from the substrate (transgressive lag) and by a thick accumulation of large oyster shells concentrated as an “onlap shell bed”.

involves a certain degree of interpretation of the nature of surfaces and their large-scale architecture. An example based on well-logs is provided by [Plint \(2000\)](#) in the Cenomanian Dunvegan Formation (Alberta). [Amorosi et al. \(1999, 2005\)](#) adopted a sequence stratigraphic approach to correlate sparse cores in the Late Quaternary succession of the Po Plain (Italy), making a 3D reconstruction of facies architecture. A 3D facies and stratal architecture, based on sparse measured sections, was provided by [Zecchin et al. \(2011b\)](#) in the Late Pleistocene Cutro terrace deposits (southern Italy) (Fig. 7). The degree of interpretation is minimized where continuous exposures are available, such as in the case of the Cretaceous succession of Book Cliffs (Utah) or the Eocene section of Spitsbergen (Norway), where all elements of a sequence stratigraphic framework, including key bounding surfaces and stratal terminations can be observed in near seismic-scale outcrops (e.g., [Pattison, 1995](#); [Hampson, 2000](#); [Plink-Björklund and Steel, 2005](#)).

3. Facies contacts in high-resolution stratigraphic analyses

Facies contacts are typically diachronous surfaces that develop within (rather than at the boundary between) systems tracts, but have good physical expression in outcrop or cores, bound sediment bodies with distinct lithologies, and have the potential to refine the internal architecture of systems tracts.

3.1. Flooding surface (FS)

The term FS was originally defined as the parasequence boundary, and interpreted to correspond to ‘a surface across which there is evidence of an abrupt increase of water depth’ ([Van Wagoner et al., 1988](#)). More recently, it has been recognized that lithological discontinuities that are typically interpreted as FSs do not necessarily form as a result of abrupt increases in water depth, which would involve allogenic controls, but may also form in response to autocyclic processes such as delta lobe switching and abandonment (Fig. 17A). The term FS is also equivocal to some extent, as, under specific circumstances, a number of different types of stratigraphic contacts (some sequence stratigraphic surfaces, some not) may satisfy the definition of a flooding surface ([Catuneanu, 2002, 2006](#)) (Fig. 17). For this reason, on a case-by-case basis, the term FS can be effectively replaced with more specific terminology that indicates particular sequence stratigraphic surfaces (e.g., MRS, MFS, RS, Fig. 17B) or facies contacts within transgressive systems tracts. For the latter situation, specific terms such as “local FS” (LFS; [Abbott and Carter, 1994](#)) or “within-trend FS” (WTFS; [Catuneanu, 2006](#)) have been proposed.

The LFS (Figs. 1, 2, 5 and 11–13) is produced distally on the shelf due to marked sediment starvation and variable degree of erosion during transgression. Where the transgressive sediments are missing entirely, the LFS becomes an MFS, which also reworks the

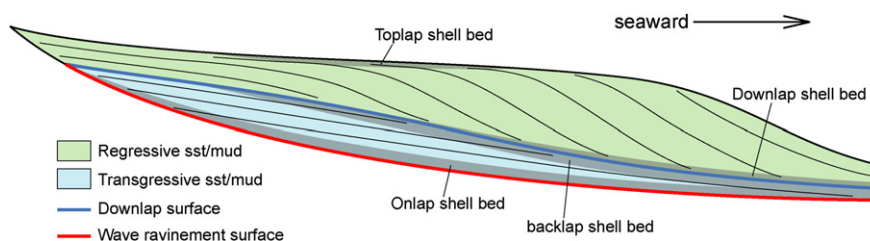


Figure 10. Types of shell beds within the down-dip sequence stratigraphic framework of a clastic shelf (modified from Zecchin, 2007). Shell beds indicate stages of low sediment supply, and accumulate commonly during transgressions or highstands when the shelf is largely submerged, providing favorable conditions for the growth and concentration of coquinas. Condensed shell beds are typically described at the base and at the top of transgressive deposits (onlap and backlap shell beds, respectively), and at the base and at the top of highstand normal regressive deposits (downlap and toplap shell beds, respectively).

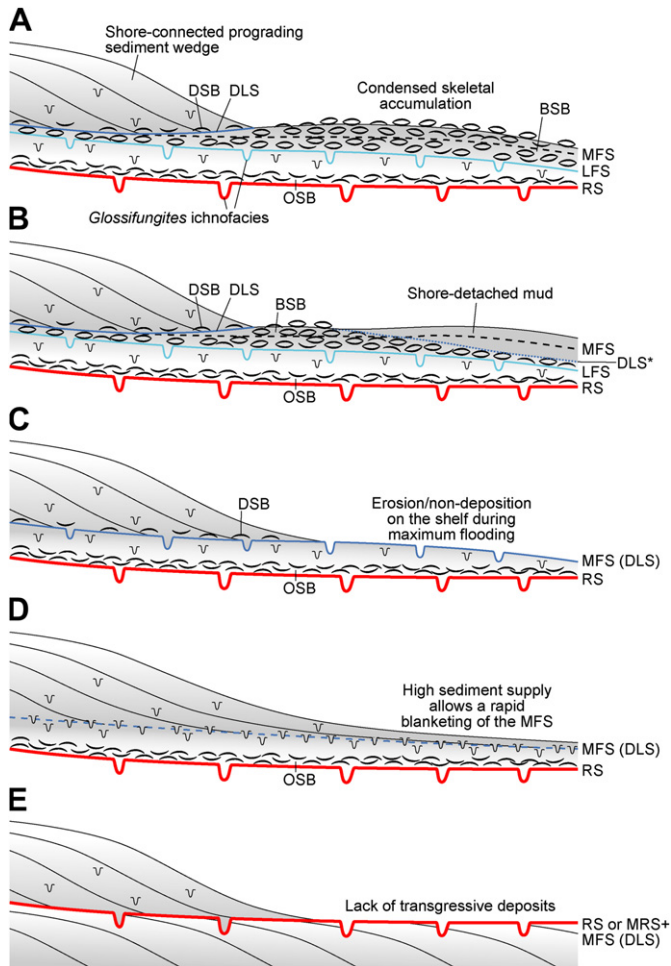


Figure 11. Different scenarios of surfaces and shell beds forming during transgression to early highstand normal regression. (A) The OSB paves the RS during early transgression, whereas sediment starvation during late transgression may lead to the formation of the LFS at the base of the condensed BSB which may contain faunas in life or near life position. The progradation of the shore-connected prograding sediment wedge progressively stops the development of the BSB, which thickens in a distal direction. The BSB and the shore-connected prograding sediment wedge are separated by the DLS. A DSB may lie at the base of the regressive sediment body. Note the offset between the cryptic MFS, corresponding to the seafloor at the time of maximum shoreline retreat, and both the LFS and the DLS. (B) In this case, the accumulation of shore-detached muds during late transgression and early highstand stops the development of the BSB distally and promotes the development of a mud-rich condensed section that may contain the MFS. The base of the shore-detached mud may be misinterpreted as a DLS. The MFS and the DLS coincide where erosion, non-deposition or high sediment supply prevent the development of the condensed section (cases C and D), or where the transgressive deposits do not accumulate (case E). Abbreviations: BSB – backlap shell bed; DLS – downlap surface; DLS* – apparent downlap surface; DSB – downlap shell bed; LFS – local flooding surface; MFS – maximum flooding surface; OSB – onlap shell bed; RS – ravinement surface.

underlying MRS (Fig. 11E). The LFS may be characterized by intense burrowing (*Glossifungites* ichnofacies), and generally marks the base of condensed skeletal accumulations which typically consist of epifauna-dominated community concentrations occasionally swept by major storm waves and shelf currents (the “backlap shell beds”, BSB, of Kidwell, 1991, Figs. 1, 5 and 10–13). The BSBs preserve faunas in life or near life position, due to the low environmental energy, which lived in deeper water relative to those forming OSBs (Kidwell, 1991; Naish and Kamp, 1997; Kondo et al., 1998; Di Celma et al., 2005). Backlap refers to the termination of beds at the distal edge of a retrogradational body, as a result of sediment starvation and condensation, where stratal surfaces converge asymptotically

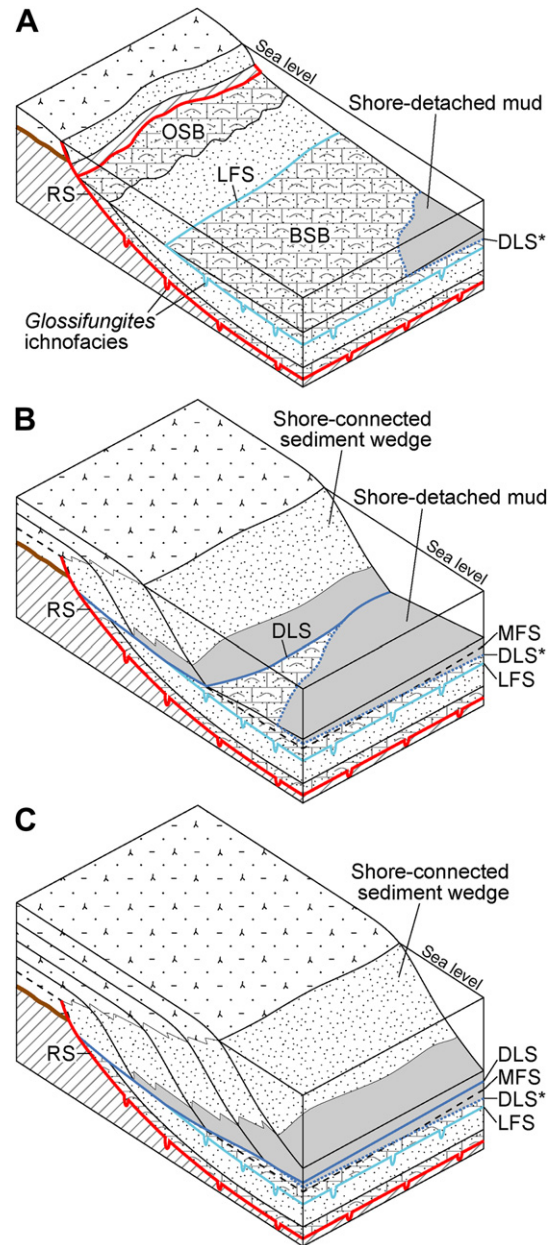


Figure 12. Development of stratigraphic surfaces and condensed shell beds during transgression and highstand normal regression. (A) RS, OSB, LFS and BSB form during shoreline transgression. At the end of transgression, the BSB still continues to accumulate, although its development is locally interrupted by an expanding shore-detached mud wedge accumulated from suspension (see Fig. 11B). The seafloor at this time of maximum shoreline retreat represents the MFS (modified from Abbott, 2000). (B) The BSB continues its development until its blanketing by the shore-detached mud and by the prograding shore-connected sediment wedge. (C) The superposition of the shore-connected sediment wedge on the shore-detached mud may obscure the recognition of the distal part of the DLS in the field, which becomes a cryptic contact within the lower part of the fine-grained succession. On the shelf, the MFS is a cryptic surface that may lie in part within the BSB and in part within the shore-detached mud. Abbreviations: BSB – backlap shell bed; DLS – downlap surface; DLS* – apparent downlap surface; LFS – local flooding surface; MFS – maximum flooding surface; OSB – onlap shell bed; RS – ravinement surface.

(Kidwell, 1991) (Fig. 10). Condensed sections may be marked by an increase in the abundance of microfossils, marine hardgrounds, authigenic minerals and organic matter (Loutit et al., 1988).

The LFS corresponds to the ‘offshore marine erosion diastem’ of Nummedal and Swift (1987), and is characterized by a variable degree of diachroneity (Carter et al., 1998) (Fig. 2). In some cases,

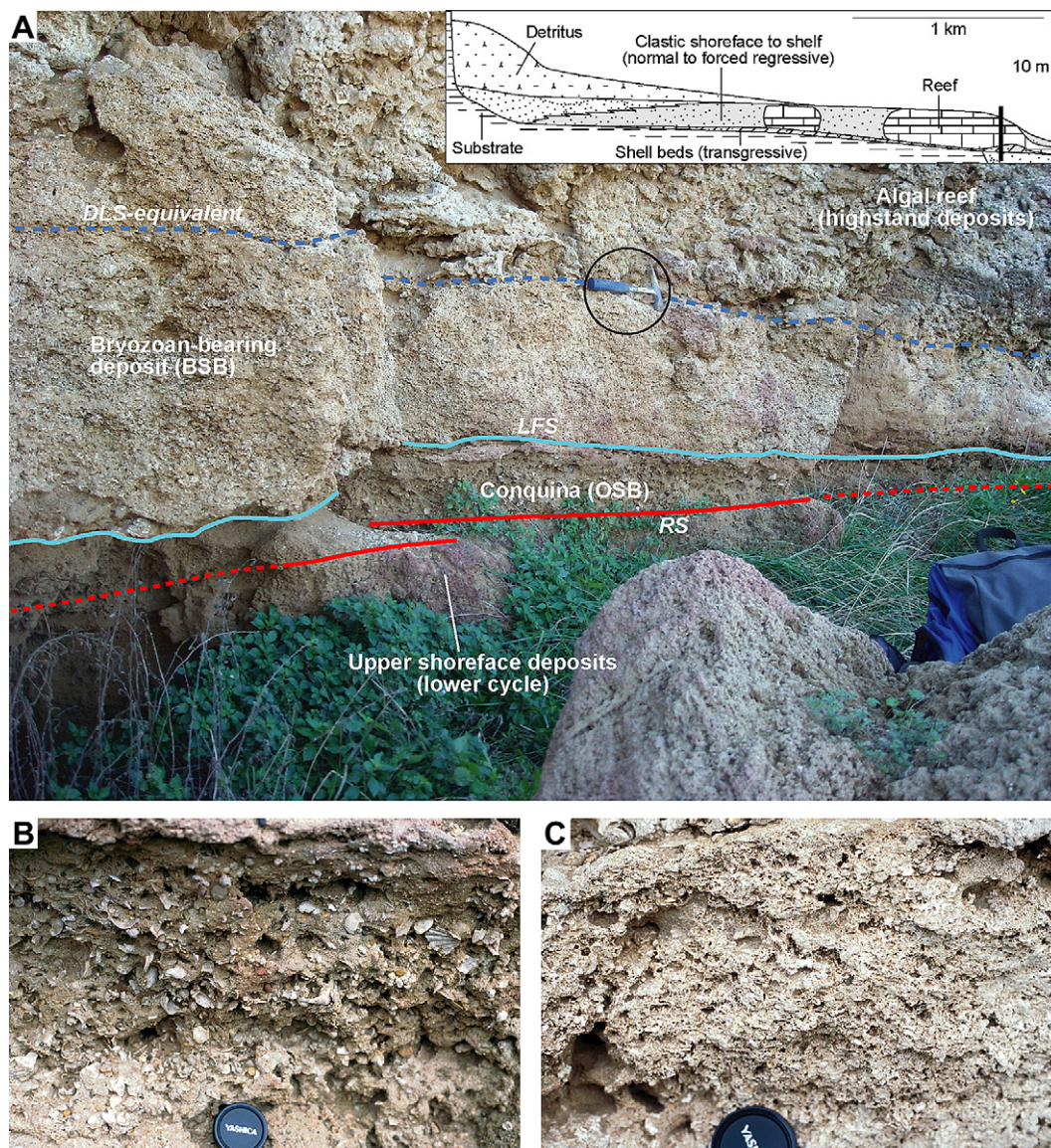


Figure 13. Example of shell beds and stratigraphic surfaces in the late Pleistocene Capo Colonna terrace, southern Italy. (A) Transgressive interval composed in its lower part of a mollusc-rich assemblage (OSB) overlying an RS, and in its upper part of a bryozoan-bearing accumulation (BSB) placed between a sharp LFS and a lateral equivalent of the DLS (see the vertical thick line for location in the inset dip section of the terrace). The highstand deposits are here represented by coralline algal patch reefs that pass laterally into both calcarenites and mixed bioclastic–siliciclastic sandstones (modified from Zecchin and Caffau, 2011). (B) and (C) show respectively the OSB and the BSB visible in (A) (modified from Zecchin et al., 2009b). Abbreviations: BSB – backlap shell bed; DLS – downlap surface; LFS – local flooding surface; OSB – onlap shell bed; RS – ravinement surface.

the LFS is absent and the base of BSBs is gradual because of relatively high sediment supply and/or reduced wave energy (Kidwell, 1991; Di Celma et al., 2005). Where the transgressive marine deposits are poorly represented, BSBs (accumulated on the shelf) and OSBs (accumulated within the shoreface) may be superposed or amalgamated as a result of backstepping (Naish and Kamp, 1997; Kondo et al., 1998; Di Celma et al., 2002) (Fig. 10).

3.2. Downlap surface (DLS)

The DLS typically develops as a distinct surface on starved shelves, where it sits at the sharp contact between the riverborne sediment of prograding clastic wedges and the underlying hemipelagic condensed sections that accumulate below the storm wave base (Figs. 1, 2, 5, 10–12, 17 and 18). As such, the succession overlying the DLS includes clinoforms and grades upward into progressively more proximal facies that indicate accelerating sedimentation (Kidwell, 1991; Kondo et al., 1998) (Fig. 18). The DLS

may be overlain by less condensed shell beds that concentrate due to sediment starvation at the basinward termination of the prograding wedge (the “downlap shell beds”, DSB, of Kidwell, 1991, Figs. 1, 10 and 11A–C). DSBs tend to be more common in sand-rich basins than in mud-rich basins (Kondo et al., 1998).

The DLS does not necessarily correspond to the seafloor at the time of maximum shoreline transgression, which is the MFS (Fig. 2), although they were commonly considered as equivalent (Baum and Vail, 1988). In fact, the MFS is generally cryptic in the field and may lie anywhere between the LFS and the DLS, within the condensed section (Figs. 11–13), depending on local sediment supply and location in the shoreface–shelf system (see Abbott and Carter, 1994; Carter et al., 1998). In particular, the DLS and the MFS diverge in a downdip direction on starved shelves characterized by the formation of condensed sections (Figs. 2A,B and 11A,B). Where erosion prevails and condensed deposits do not accumulate, the DLS will merge with both the MFS and the LFS (Fig. 11C), and such a composite surface may be associated with significant hiatus. If the

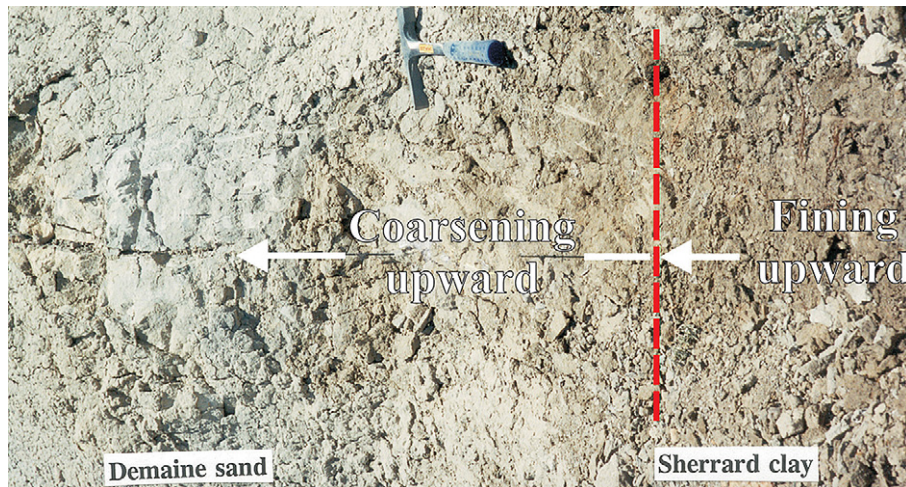


Figure 14. Conformable maximum flooding surface separating fining-upward shelf clays from overlying shoreface facies in the Late Campanian Bearpaw Formation, Canada (from Catuneanu, 2006). This surface is cryptic, without lithological contrast, and is placed at the peak of finest sediment.

transgressive deposits are missing entirely, the coincident DLS and MFS will also merge with the MRS or the RS (Fig. 11E). In highly supplied shelves, where abundant sediment is efficiently transported downdip, transgressive deposits may pass gradually into regressive deposits without significant sediment starvation (Figs. 2C and 11D). The package representing such a transition was called the 'maximum flooding zone' (e.g., Siggerud and Steel, 1999; Cantalamessa and Di Celma, 2004; Di Celma and Cantalamessa, 2007) (Fig. 19), and it may be characterized by higher bioturbation index. The DLS, in this case approximating the cryptic MFS, lies within this interval and is generally placed where the bioturbation index is highest (Fig. 11D).

In the case of starved shelves, LFSs and their associated BSBs are typically overlain by hemipelagic condensed sections consisting in part of mud detached from the nearshore wedge and transported offshore as hypopycnal plumes during late transgression and/or early highstand (Figs. 11B and 12). Where such condensed sections are present, the base of the shore-connected highstand prograding wedge (i.e., the DLS) does not coincide with the top of the BSB (i.e., the DLS and the LFS are separated by the condensed section; Fig. 12). In contrast, Abbott (2000) considered the facies contact between shore-detached hemipelagic condensed sections and the BSBs as the DLS, placing, by implication, the mud-rich condensed section and the MFS within the highstand systems tract (Fig. 12). However, the base of the shore-detached condensed section is only an apparent DLS, whereas the true DLS marking base of the shore-connected prograding wedge lies at the top of the condensed section (Figs. 11B and 12).

A significant degree of diachroneity may be associated with the DLS along both depositional dip and strike, depending on lateral variations of sediment supply and subsidence (Carter et al., 1998), and generally it becomes younger basinward (Fig. 2). On highly

starved shelves, the DLS may even become distally younger than the BSFR (Fig. 2A), implying that the time involved in the accumulation of the condensed section may approach the entire duration of the accommodation cycle.

3.3. Within-trend forced regressive surface (WTFRS)

The WTFRS represents the relatively abrupt facies contact between the delta front (foreset) and the prodelta (bottomset) deposits in forced regressive river-dominated deltaic settings, where the RSME does not form (Catuneanu, 2006) (Fig. 20). In the case of highly starved shelves, the formation of the WTFRS may be accompanied by the concomitant formation of a DLS downdip, at the contact between the riverborne sediment of the bottomset and the hemipelagic condensed section. Both the WTFRS and the DLS record the same degree of diachroneity, which matches the rate of forced regression. As forced regressions are faster than normal regressions, the WTFRS is less diachronous than the downlap surfaces that develop during normal regressions. The degree of diachroneity of a normal regressive downlap surface matches the diachroneity of the within-trend normal regressive surface (see Section 3.4) that forms within the same systems tract.

3.4. Within-trend normal regressive surface (WTNRS)

This is the contact between topset and underlying foreset facies in a normal regressive systems tract (lowstand or highstand; Catuneanu, 2006) (Fig. 1). It is typically highly diachronous, with a diachroneity rate that matches the rate of normal regression. The WTNRS is placed at the contact between delta front and delta plain facies in a river-mouth setting (Fig. 21A), or at the contact between beach and coastal plain facies in an open coastline setting (Fig. 21B).

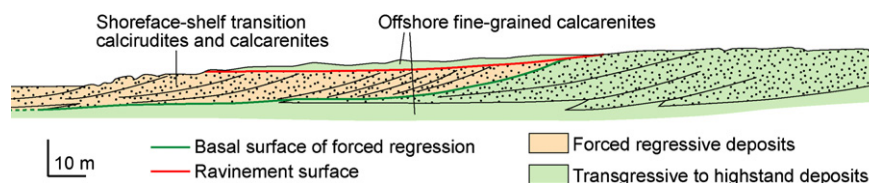


Figure 15. Sketch of the large exposures of the Pliocene "Calcarene di Gravina" in Matera, southern Italy (modified from Pomar and Tropeano, 2001). A downlap surface within the coarse-grained prograding body is inferred to be the result of the onset of relative sea-level fall, which marks an increase in sediment supply and a steepening of the prograding clinoforms, and is interpreted as a basal surface of forced regression.

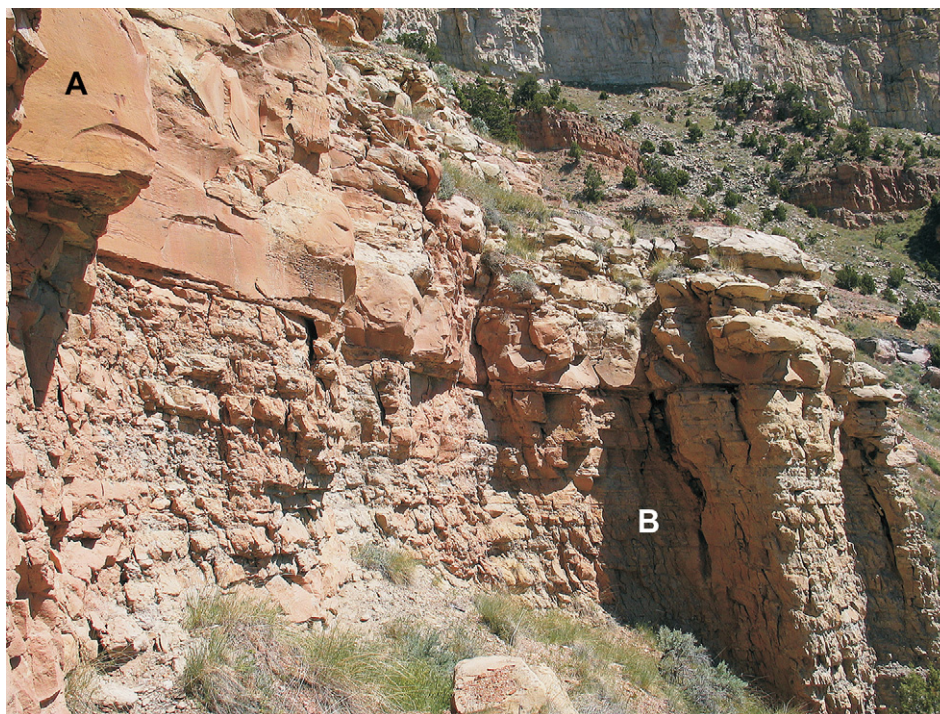


Figure 16. Regressive surface of marine erosion (RSME) abruptly separating inner shelf sands and muds (B) from wave-dominated shoreface sands (A) in the Blackhawk Formation, Utah (modified from Catuneanu, 2006). The exposed section below the RSME is about 2 m thick.

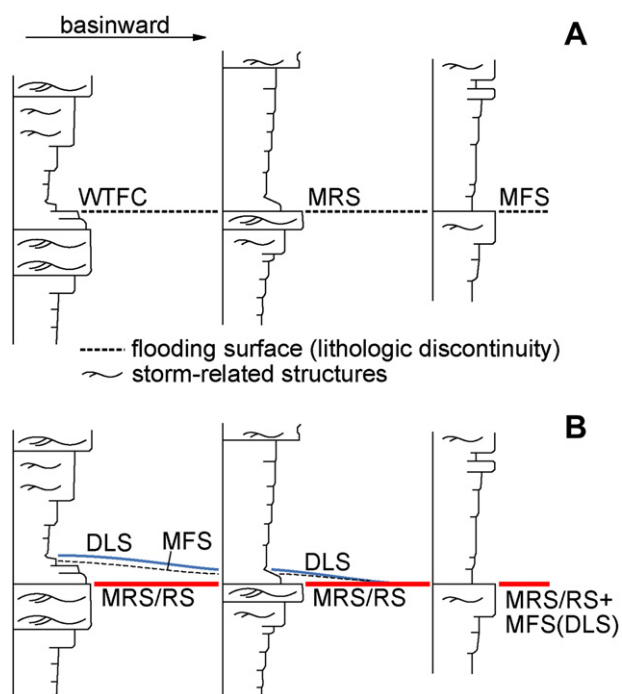


Figure 17. (A) The variable significance of the flooding surface defined as a lithologic discontinuity (modified from Catuneanu, 2002). Depending on the location along depositional dip, the FS may coincide with an MFS, an MRS or a WTFC that is unrelated to any surface of sequence stratigraphic significance. (B) The same succession can be interpreted using sequence stratigraphic surfaces (MFS, MRS and RS) and facies contacts (DLS), which merge basinward becoming a composite surface. Note that the MFS may be a cryptic surface lying between the MRS/RS and the DLS. Abbreviations: DLS – downlap surface; FS – flooding surface; MFS – maximum flooding surface; MRS – maximum regressive surface; RS – ravinement surface; WTFC – within-trend facies contact.

3.5. Surf diastem (SD)

The SD is a facies contact generated by the seaward migration of longshore troughs and rip channels during coastal progradation, and separates lower shoreface to shoreface–shelf transition deposits below from trough cross-bedded upper shoreface deposits above (Zhang et al., 1997; Swift et al., 2003; Clifton, 2006) (Figs. 1, 6 and 22).

The SD should not be confused with the RSME, as the former develops independently of relative sea-level changes, during both forced and normal regressions (Clifton, 2006) (Fig. 1). Where upper shoreface deposits erosionally overlie shelf sediments during a forced-regressive phase, without the interposition of lower shoreface deposits, then the SD coincides with the RSME.

3.6. Turbidite shelf entrenchment surface (tSES)

The turbidite shelf entrenchment surface (tSES) is a zone of sediment bypass across the shelf, consisting of a channelized feature carved during transgression by sediment-laden turbidite currents (Di Celma et al., 2010). The development of tSESs is associated to headward erosion of shore-connected shelf channels. The tSES separates shelf sediments below from turbidites above, and is locally marked by the *Glossifungites* Ichnofacies (Di Celma et al., 2010).

3.7. Bedset boundaries

A bedset is a meter-scale unit defined as “a relatively conformable succession of genetically related beds bounded by surfaces of erosion, non-deposition, or their correlative conformities” (Van Wagoner et al., 1990). Within shoreface to shelf cycles, bedsets define individual clinoforms that can be recognized along depositional dip if exposures are large enough (Hampson et al., 2008; Enge et al., 2010) (Fig. 23). Hampson et al. (2008) and Sømme



Figure 18. Example of downlap surface (arrows) separating prodelta sediments (below) from river-dominated delta front sands prograding to the left (above) in the Ferron Sandstone, Utah (from Catuneanu, 2006). Coal-bearing delta plain facies overlie the delta front, and are part of the topset of this highstand delta. The outcrop is about 30 m high.

et al. (2008) highlighted a relationship between bedsets and individual beach ridges, with bedset boundaries generated as a result of minor reorganization of the shoreline in response to variations in sediment supply, climate and autocyclic processes. Bedsets may be grouped to form packages characterized by distinctive stacking patterns, corresponding to beach ridge sets, which in turn may compose larger units (Hampson et al., 2008).

Bedset boundaries are represented by non-depositional or erosional discontinuities, which are most distinctive within lower shoreface to shelf deposits and usually become cryptic in both landward and seaward directions (Hampson, 2000; Sømme et al., 2008) (Figs. 6, 23 and 24). Non-depositional discontinuities are

contacts showing an abrupt decrease in thickness and amalgamation of storm-generated event beds, and an increase of bioturbation (Hampson, 2000) (Figs. 6 and 24). In contrast, erosional discontinuities may be marked by gutter casts and *Glossifungites* ichnofacies, and record an abrupt increase in bed amalgamation and grain size (Hampson, 2000) (Fig. 6). The formation of non-depositional discontinuities is inferred to be related to an abrupt decrease of sediment supply and/or wave energy, whereas the contrary is expected for erosional discontinuities (Hampson, 2000; Sømme et al., 2008). High-frequency, very low-amplitude relative sea-level changes were also considered in the generation of these surfaces (Hampson et al., 2008).

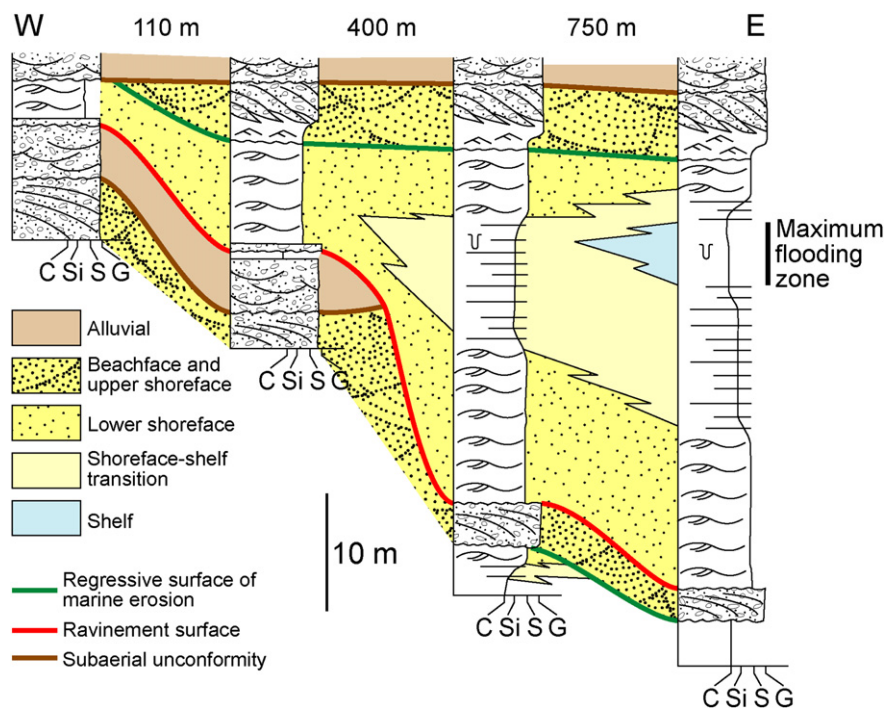


Figure 19. Dip section of an early Pleistocene shelf to continental succession in the Periadriatic Basin, central Italy (modified from Cantalamessa and Di Celma, 2004). The downlap surface is cryptic in this case, and is replaced by a deeper water interval characterized by finer grain size and higher bioturbation level, referred to as a 'maximum flooding zone'.

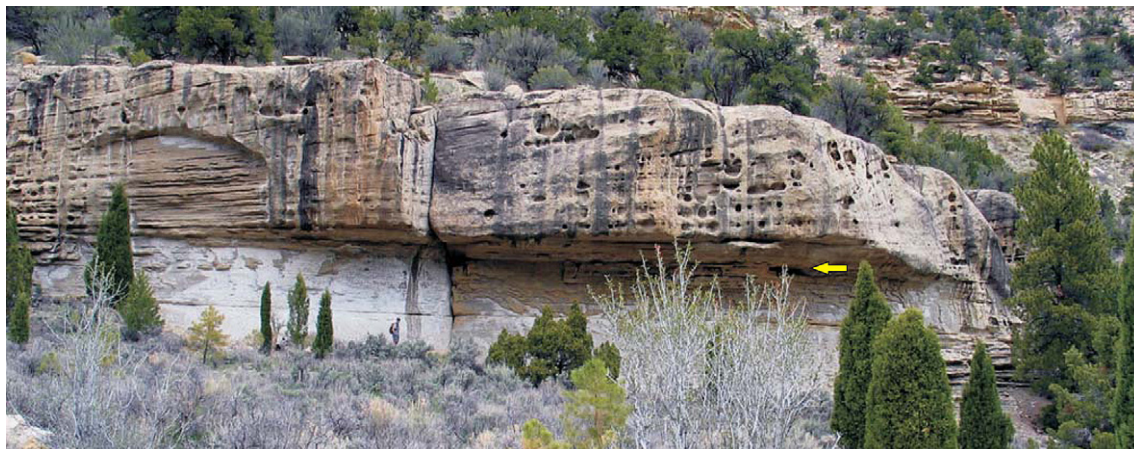


Figure 20. Within-trend forced regressive surface (arrow) at the contact between delta front (foreset) and prodelta (bottomset) facies in a forced regressive river-mouth setting (Panther Tongue, Utah; from Catuneanu, 2006).

The features of non-depositional and erosional discontinuities resemble those of FSs and RSMEs, respectively. However, bedset boundaries tend to have a more limited lateral extent, and their origin is not tied to shoreline shifts (Fig. 23). To avoid nomenclatural confusion between bedset boundaries and high-frequency FSs or RSMEs, it is suggested the use of the former if their origin is not linked to transgressions and regressions.

Therefore, the use of bedsets is recommended for small (typically meter-scale) subdivisions of the stratigraphic record that form independently of shoreline shifts, as a result of minor variations in sediment supply and/or wave height, and which are recognizable only for relatively short distances along depositional dip and strike.

4. Stratigraphic units

4.1. Systems tracts

Systems tracts are stratigraphic units bounded by sequence stratigraphic surfaces, forming the subdivisions of sequences (Brown and Fisher, 1977; Catuneanu et al., 2009) (Fig. 1). In shelf settings, systems tracts are directly associated with particular types of shoreline trajectory, including transgression, normal regression (lowstand or highstand) and forced regression (Catuneanu et al., 2009, 2011) (Fig. 25). The shoreline trajectory was defined as the 'cross-sectional shoreline migration path along depositional dip' (Helland-Hansen and Gjelberg, 1994), and is typically controlled by the interplay of relative sea-level change and sediment supply. Assuming 0° – seaward, 90° – upward, 180° – landward, and -90° – downward, transgressions are typified by trajectories between 90° and 180° , most commonly close to 180° ; normal regressions assume trajectories between 0° and 90° , most commonly close to 0° ; and forced regressions are normally characterized by shoreline trajectories between 0° and -30° (Helland-Hansen and Martinsen, 1996) (Figs. 23 and 25).

4.1.1. Transgressive systems tracts

Transgressive systems tracts (TST) are bounded at the base by the MRS or the RS and at the top by the MFS (Figs. 1 and 2). They are characterized by a retrogradational architecture resulting from rates of accommodation creation that outpace those of sediment supply at the shoreline, typically accompanied by a deepening-upward trend in shallow-marine settings (Posamentier and Allen, 1999; Catuneanu, 2002, 2006). The nomenclature of the TST is non-controversial, and common among all sequence stratigraphic

approaches. The revised Exxon depositional sequence model refers to the TST as a retrogradational succession set (Neal and Abreu, 2009; Abreu et al., 2010). Transgressive systems tracts may include various continental, back-barrier, shoreface/shelf, and deep-marine deposits (Posamentier and Allen, 1999; Catuneanu, 2006), as well as OSBs, BSBs or other condensed deposits (Figs. 1, 11 and 12). As the MFS typically lies within condensed sections (Figs. 11 and 12), such condensed deposits are commonly part transgressive and part highstand normal regressive (Fig. 1).

In shallow-water shelf settings, the relative thickness of transgressive deposits with respect to that of the entire sequence may vary considerably due to several factors, which include: accommodation to supply ratio, amplitude and shape of the relative sea-level curve, position in the shoreface–shelf system, local physiography, shoreline trajectory, climate, and ratio between siliciclastic input and carbonate production (Zecchin, 2007). Locally thicker transgressive deposits may be related to the migration of transgressive shelf ridges or shoals (Snedden and Dalrymple, 1999; Suter, 2006). A review of transgressive deposits and their classification was provided by Cattaneo and Steel (2003).

4.1.2. Normal regressive systems tracts: lowstand and highstand

Normal regressive systems tracts may be positioned between transgressive (below) and forced regressive (above) strata (i.e., the highstand systems tract: HST), or between forced regressive (below) and transgressive (above) strata (i.e., the lowstand systems tract: LST) (Fig. 1). In other cases, normal regressive deposits may alternate either with transgressive strata, in which case they are designated as HST, or with forced regressive strata, in which case they are designated as LST (Fig. 26). The nomenclature of the lowstand and highstand systems tracts was subject to debate among the various sequence-stratigraphic schools (see Catuneanu, 2006; Catuneanu et al., 2009, 2011; for a full discussion). The revised Exxon depositional sequence model refers to the LST as a progradational to aggradational succession set, and to the HST, as defined in this paper, as an aggradational to progradational succession set (Neal and Abreu, 2009; Abreu et al., 2010). Normal regressive systems tracts may be bounded by various sequence stratigraphic surfaces depending on their position relative to other systems tracts within a sequence. Lowstand systems tracts are bounded by the SU and its CC at the base, and by the MRS or the RS at the top (Figs. 1 and 2). Highstand systems tracts are bounded by the MFS at the base, and by the SU and the BSFR or the RSME at the top (Figs. 1 and 2).

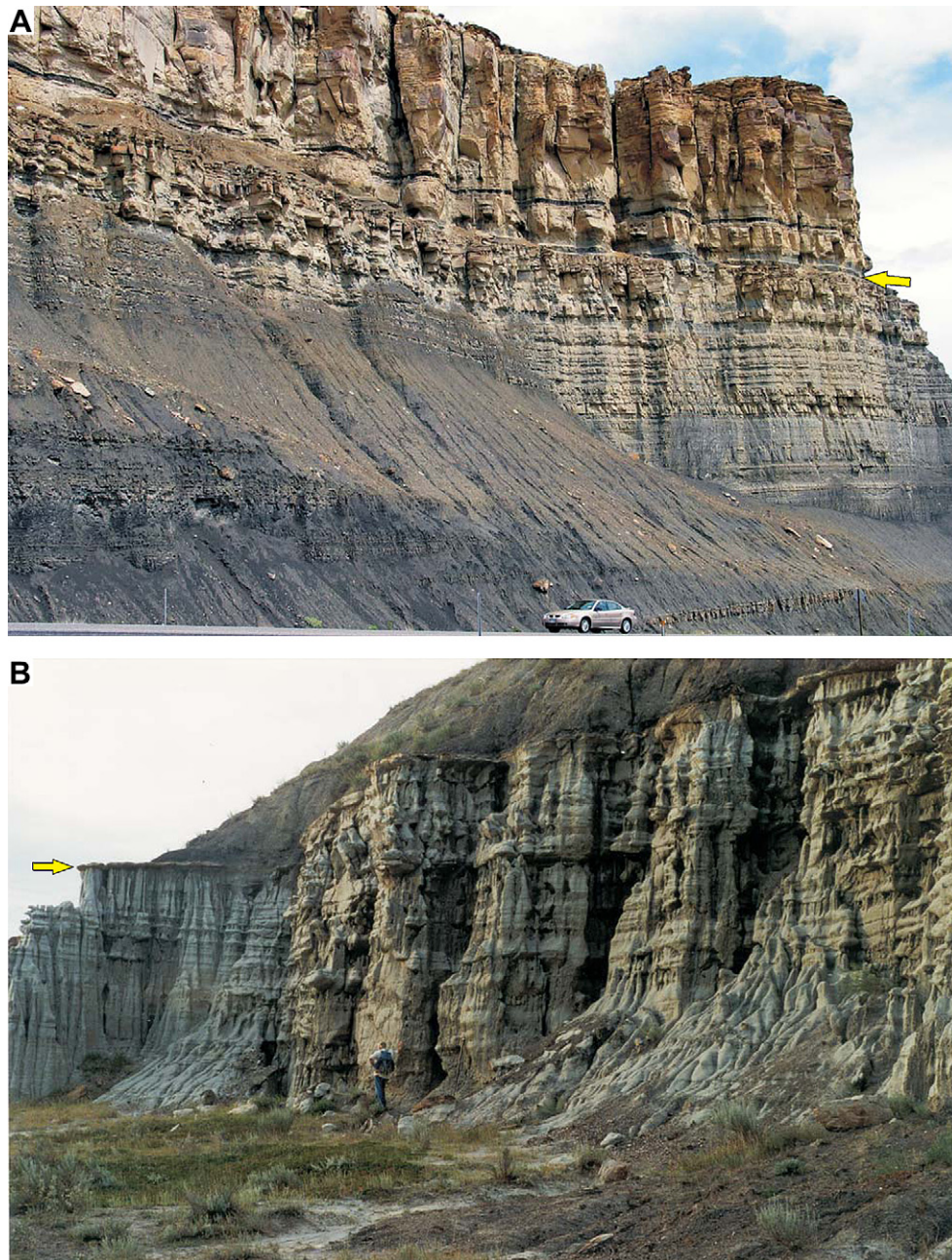


Figure 21. (A) Within-trend normal regressive surface (arrow) at the contact between delta front (foreset) and delta plain (topset) facies in a normal regressive river-mouth setting (Ferron Sandstone, Utah; from Catuneanu, 2006). (B) Within-trend normal regressive surface (arrow) at the contact between beach (foreset) and alluvial plain (topset) facies in a normal regressive open shoreline setting (Bearpaw to Horseshoe Canyon transition, Alberta; from Catuneanu, 2006).

Normal regressions are driven by sediment supply, where the rates of sediment influx outpace those of accommodation creation at the shoreline. In shallow-water areas adjacent to the shoreline, normal regressions are accompanied by shallowing-upward bathymetric trends; however, the relationship between normal regression and water shallowing may be offset in the deeper portions of the basin, where subsidence and sedimentation rates may differ significantly from those recorded in the shoreline area (Catuneanu, 2006). The stratal architecture of normal regressive deposits is typically characterized by both progradation and aggradation, allowing the accumulation of sedimentary bodies featured by clinoforms with aggrading topsets (Posamentier and Allen, 1999; Catuneanu, 2002, 2006) (Figs. 1 and 25). However, if normal regressive deposits include part of the condensed section

(Figs. 1 and 2), their architecture is not fully progradational, as condensed sections are not part of the shore-connected clastic wedge (Figs. 11 and 12). In the case of late highstand normal regressions, where the stacking pattern of shore-connected wedges is dominantly progradational with little or no aggradation, toplap shell beds may concentrate along the top of the HST, even though the mixing of shells with the highstand sediment may reduce the appearance of condensation (Kidwell, 1991; Kondo et al., 1998) (Fig. 10). The concentration of shells at the top and at the base of highstand normal regressive deposits (i.e., toplap and downlap shell beds, respectively; Fig. 10) is favored by environmental conditions related to the submergence of the shelf, a situation that usually does not characterize lowstand normal regressions.



Figure 22. Surf diastem (white line) separating lower shoreface from upper shoreface deposits in the middle Pleistocene Cutro terrace, southern Italy (modified from Zecchin et al., 2011b).

Normal regressive systems tracts commonly include continental, deltaic, shoreface/shelf, shelf margin, and deeper marine sediments (Posamentier and Allen, 1999; Catuneanu, 2006) (Fig. 1). In shoreface to shelf settings, progradation is marked by a transition from prevailing horizontal burrow traces of the *Cruziana* ichnofacies (e.g. *Cruziana*, *Thalassinoides*, *Chondrites* and *Planolites* ichnogenera), indicating relatively low energy levels, to mostly vertical traces of the *Skolithos* ichnofacies (e.g. *Skolithos*, *Ophiomorpha* and *Diplocraterion* ichnogenera) typifying higher energy, middle to upper shoreface deposits (Pemberton et al., 1992; MacEachern and Bann, 2008) (Fig. 6). As in the case of the TST, the relative thickness of normal regressive systems tracts with respect to that of the entire sequence is variable, depending on the interplay among the factors cited above (Zecchin, 2007).

4.1.3. Falling-stage systems tract

The falling-stage systems tract (FSST) consists of forced regressive deposits, and is bounded by the BSFR or the RSME at the base, and by the SU and its CC at the top (Figs. 1 and 2). The top of the FSST may also be truncated by younger RSs (Fig. 7). The FSST forms during relative sea-level fall when the shoreline is forced to regress irrespective of sediment supply (Catuneanu, 2002, 2006) (Fig. 25). With the exception of river-dominated deltas, forced regressive conditions typically result in the accumulation of sharp-based shorefaces on top of RSMEs (Fig. 16), and by an increase of sediment supply to the deep-marine settings (Plint,

1988; Hunt and Tucker, 1992; Helland-Hansen and Gjelberg, 1994; Plint and Nummedal, 2000). The shelf portion of the FSST commonly displays a foreshortening of the prograding clinoforms due to the progressive decrease in accommodation with time, resulting in thinner deposits in a seaward direction (Posamentier and Allen, 1999) (Fig. 7). Forced regressive deposits are characterized by offlap, without topset development, due to the prevailing conditions of negative accommodation (Hunt and Tucker, 1992; Helland-Hansen and Gjelberg, 1994) (Fig. 1). The development of condensed shell beds is not favored under conditions of high sediment supply that typically characterize forced regressions (Naish and Kamp, 1997). The FSST was subject to nomenclatural debate among the various sequence-stratigraphic schools (see Catuneanu, 2006; Catuneanu et al., 2009, 2011; for a full discussion). The revised Exxon depositional sequence model refers to the FSST as a degradational succession set (Neal and Abreu, 2009; Abreu et al., 2010).

4.1.4. The stacking pattern of systems tracts and exceptions to common assumptions

It is generally assumed that systems tracts are stacked in a predictable manner in response of cycles of relative sea-level change and sediment supply, that is a repetition of lowstand normal regressive, transgressive, highstand normal regressive and forced regressive deposits (Posamentier and Allen, 1999; Catuneanu, 2006; Catuneanu et al., 2009) (Fig. 1).

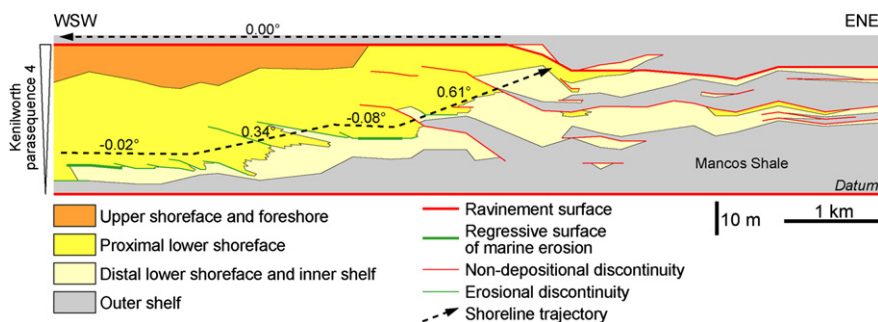


Figure 23. Main surfaces and minor discontinuities defining bedsets in the Kenilworth parasequence 4 of the Blackhawk Formation (USA), which is interpreted as a wave-dominated deltaic system (modified from Hampson, 2000; Helland-Hansen and Hampson, 2009). Note the changing direction between ascending and descending regressive shoreline trajectories within the prograding body.

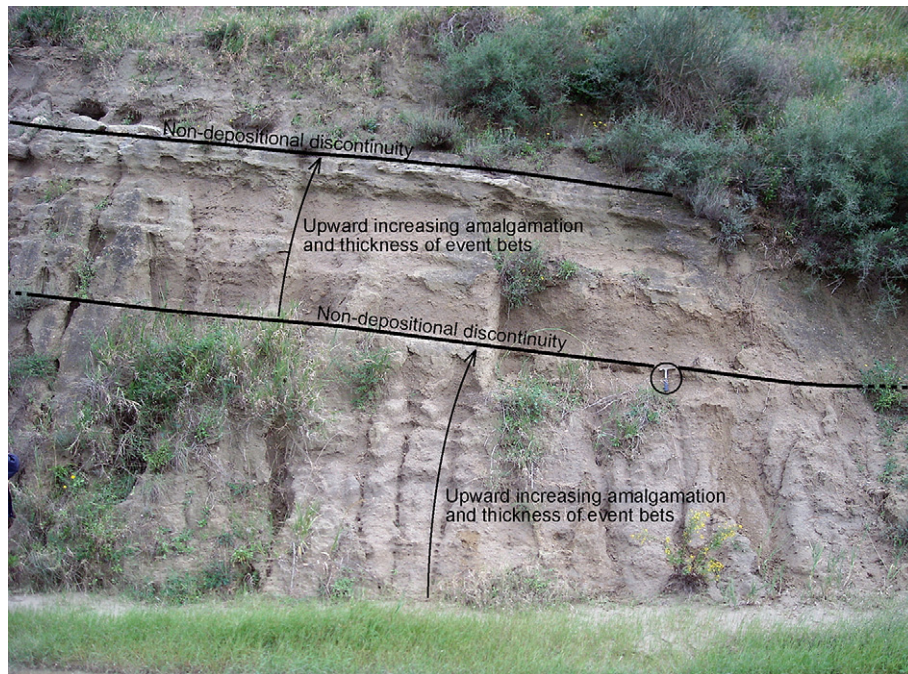


Figure 24. Two stacked bedsets showing a gradual upward thickening and increase in the degree of amalgamation of event beds, bounded by non-depositional discontinuities, in the shoreface–shelf transition deposits of the Gelasian Strongoli Sandstone (Crotone Basin, southern Italy). Hammer (circled) for scale.

The absence of a particular systems tract is commonly inferred to be the result of erosional processes during both transgressions and forced regressions, or of sediment starvation. However, relative sea-level changes may also be erratic and poorly predictable, and they do not form in all cases the expected complete succession of systems tracts (Helland-Hansen and Hampson, 2009; Catuneanu et al., 2011). This results in systems tracts that may stack in unpredictable ways, even though they may also form cycles. An example is the vertical repetition of normal regressive and transgressive deposits, reflecting long-term conditions of relative sea-level rise at variable rates or simply sediment supply variations (Helland-Hansen and Martinsen, 1996; Catuneanu, 2006) (Fig. 17).

In this case, cycles are defined by the recurrence of transgressive and highstand systems tracts. In other cases, cycles of relative sea-level change are reflected by an alternation of forced regressive and normal regressive deposits, as the rates of accommodation creation never outpace those of sediment supply during stages of relative sea-level rise, and, therefore, transgressions do not occur (Helland-Hansen and Martinsen, 1996; Catuneanu, 2006; Zecchin et al., 2010) (Fig. 26). In such case, cycles may be defined by the recurrence of falling-stage and lowstand systems tracts.

The variability in the stacking pattern of systems tracts, therefore, is a reality that needs to be accounted for in sequence stratigraphic analyses (Catuneanu et al., 2011).

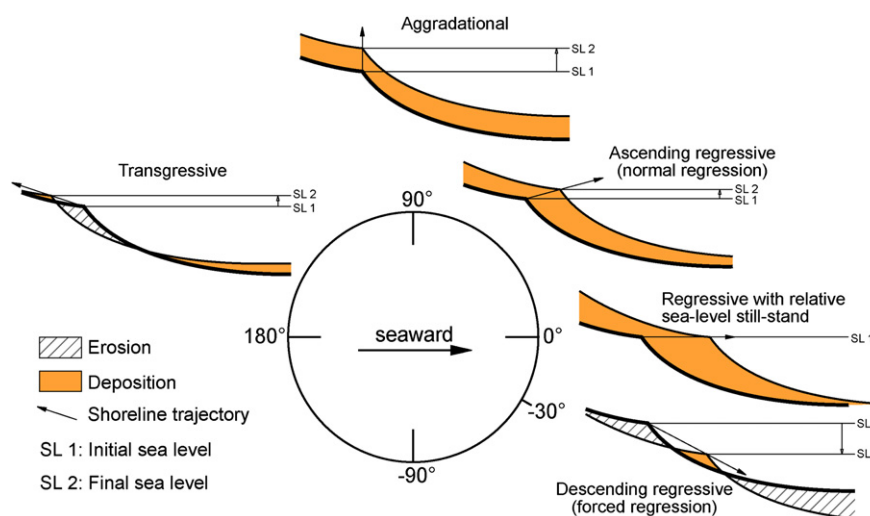


Figure 25. Main migratory classes of shoreline trajectory. Transgressive trajectories are directed between 90° and 180°, ascending regressive trajectories (normal regression) are between 0° and 90°, and descending regressive trajectories (forced regression) are mostly directed between 0° and –30°. Strictly aggradational trajectories correspond to an angle of 90°. Regressive trajectories related to relative sea-level stillstand are 0° directed.

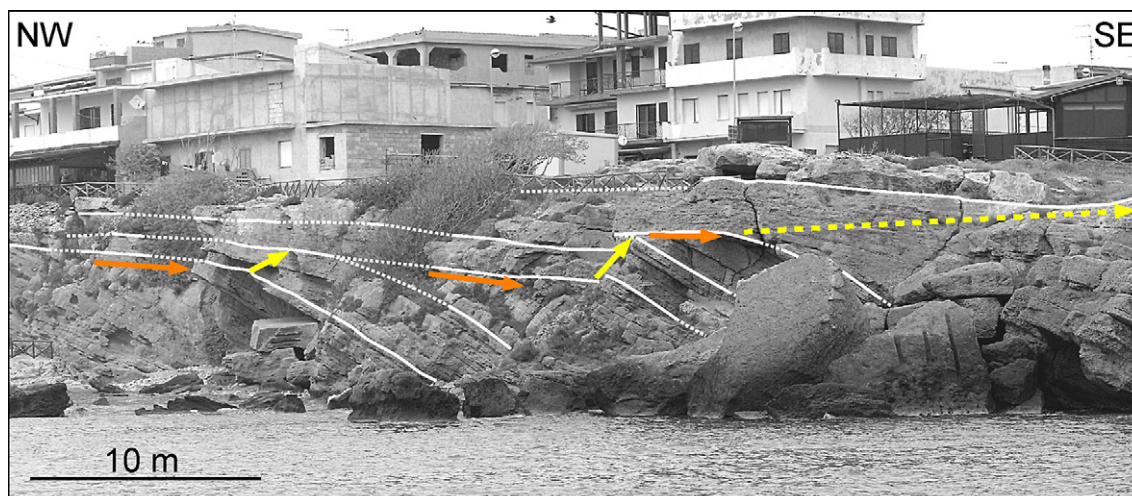


Figure 26. Alternation between prograding wedges with descending (orange arrows) and ascending (yellow arrows) shoreline trajectories in the late Pleistocene Le Castella shallow-marine succession, southern Italy (modified from Zecchin et al., 2010). Arrows indicate the trajectory of the rollover point, which reflects alternating forced and lowstand normal regressions.

4.2. Architectural units

Architectural units are sediment bodies bounded by the two nearest non-cryptic stratigraphic contacts in a sedimentary succession, whether sequence stratigraphic surfaces or facies contacts (Sections 2 and 3). Architectural units are typically smaller than systems tracts. They commonly form the depositional building blocks of systems tracts, although some may also cross systems tract boundaries. For example, a condensed section bounded at the base by the LFS and at the top by the DLS is an architectural unit which may form in part during shoreline transgression and in part during highstand normal regression (Figs. 1, 11A,B and 12). Most other architectural units, however, are part of, and form entirely during the deposition of a systems tract. For example, the shallow-water facies that prograde and aggrade during a highstand normal regression form an architectural unit that is bounded at the top by the SU and the BSFR or the RSME, and at the base by the DLS (Fig. 1).

The shoreline-detached architectural units (e.g., condensed sections) are typically independent of shoreline trajectories, and may include cryptic systems tract boundaries within (e.g., the MFS, Figs. 1, 11A,B and 12). Such architectural units are commonly bounded both at the top and at the base by facies contacts (e.g., the LFS and the DLS). The shoreline-attached architectural units are linked to shoreline trajectories, and therefore to specific systems tracts; they typically do not cross systems tracts boundaries, and may be bounded by a combination of sequence stratigraphic surfaces and facies contacts (Fig. 1). Architectural units are particularly useful in outcrop and core studies, and help define and refine the internal architecture of systems tracts. The identification of architectural units in the field relies on the integration of both facies analysis and sequence stratigraphic methodologies.

4.3. Trajectory analysis

Trajectory analysis represents an alternative way of studying the stratal architecture of sedimentary successions. Transgressive, normal regressive and forced regressive deposits correspond to migratory classes of transgressive, ascending regressive and descending regressive trajectories, respectively (Løseth and Helland-Hansen, 2001; Helland-Hansen and Hampson, 2009) (Fig. 25). Therefore, the identification of systems tracts can be made by means of both qualitative analysis of stratal stacking patterns

and quantitative trajectory analysis (e.g., Bullimore and Helland-Hansen, 2009; Hampson et al., 2009).

Trajectory analysis is effective in the recognition of both cyclical and non-cyclical styles of stacking of systems tracts, as it does not assume a predictable pattern in the occurrence of systems tracts but it rather considers trajectory classes that potentially may be stacked in any order (Bullimore and Helland-Hansen, 2009; Helland-Hansen and Hampson, 2009). The determination of the long-term shoreline trajectory is also useful to evaluate the degree of preservation of individual cycles, as well as their overall stacking pattern (Zecchin, 2007; Helland-Hansen and Hampson, 2009).

Another trajectory concept is the shelf-edge trajectory, defined as the 'pathway taken by the shelf edge during the development of a series of accreting clinoforms' (Johannessen and Steel, 2005). The shelf-edge trajectory is normally fixed or basinward directed (rarely landward directed), and is a long-term response to changes of relative sea level and sediment supply an order of magnitude larger than those controlling shoreline trajectories (Helland-Hansen and Hampson, 2009).

5. The classification of stratigraphic cycles

The description and classification of stratigraphic cyclicity at outcrop scale can be applied following various approaches, as summarized below (Fig. 27).

5.1. Allostratigraphic units and unconformity-bounded stratigraphic units

Allostratigraphic units are defined on the basis of their bounding discontinuity surfaces (North American Commission on Stratigraphic Nomenclature (NACSN), 1983, 2005), whereas the unconformity-bounded stratigraphic units (UBSU) are based on well recognizable and mappable unconformities (International Subcommission on Stratigraphic Classification (ISSC), 1987; Salvador, 1994) (Fig. 27). The definition of allostratigraphic units and UBUs does not consider the genetic relationships among strata nor the origin of bounding surfaces in response to relative sea-level changes. Despite this, allostratigraphy was successfully applied in various contexts (e.g., Bhattacharya and Walker, 1991; Martinsen et al., 1993; Varban and Plint, 2008), and its merit

Units	Bounding surfaces
Parasequences	FS
Depositional sequences	SU+CC; SU+CC*
Genetic sequences	MFS
T-R sequences	MRS
Stratigraphic sequences**	Any recurring sequence stratigraphic surface
Small-scale cycles***	RS, MRS, MRS+MFS
Allostratigraphic units and UBSUs	Any kind of lithologic discontinuity

*Equivalent to the BSFR of Hunt & Tucker (1992)
 **Following Catuneanu et al. (2009)
 ***Following Zecchin (2007)

Figure 27. Summary of stratigraphic units commonly used to describe successions in outcrop and core, and their bounding surfaces. Any type of sequence (i.e., depositional, genetic, T–R) qualifies as a generic ‘stratigraphic sequence’ defined by the recurrence of sequence stratigraphic surfaces through geologic time (Catuneanu et al., 2009, 2011). Abbreviations: BSFR – basal surface of forced regression; CC – correlative conformity; FS – flooding surface; MFS – maximum flooding surface; MRS – maximum regressive surface; RS – ravinement surface; SU – subaerial unconformity.

consists in the independence from models, resulting in long-lived allostratigraphic units. These characteristics allowed the inclusion of allostratigraphy within a formal scheme (NACSN, 1983, 2005), and the same consideration can be made for the UBSUs (ISSC, 1987).

Allostratigraphic units are hierarchically organized into alloformations, which may form allogroups and may consist of allomembers (Fig. 28). The choice of discontinuity surfaces as boundaries of allostratigraphic units may be in part interpretation-driven, as in the case of flooding surfaces bounding deltaic lobes designated as alloformations or allomembers (e.g. Bhattacharya, 1993) (Fig. 28). UBSUs have been termed “synthems” by the ISSC (the fundamental unit), which may be composed of subsynthems and may form super-synthems. However, this term has not gained popularity within the stratigraphic community. More informal designations such as “sequence” or “stratal unit” are widely used instead (Mitchum, 1977; Zecchin et al., 2004; Longhitano et al., 2010).

While allostratigraphic units and UBSUs remain practical tools for mapping and correlation, improving upon the lithostratigraphic

methodology, they are limited by the lack of process-based insight regarding the origin of the strata under analysis. As such, the concept of systems tract does not have an equivalent in allostratigraphy or the UBSU methodology, as the definition of systems tracts is unique to sequence stratigraphy and require a full genetic (i.e., sequence stratigraphic) interpretation.

5.2. Parasequences

A parasequence was defined as ‘a relatively conformable succession of genetically related beds or bedsets bounded by marine flooding surfaces and their correlative surfaces... Parasequences are progradational and therefore the beds within parasequences shoal upward’ (Van Wagoner et al., 1988, 1990) (Fig. 29). Parasequences may be stacked to form progradational, aggradational and retrogradational parasequence sets, which typify systems tracts composing a depositional sequence (Van Wagoner et al., 1990). Both autocyclic and allocyclic processes may be involved in the formation of parasequences (Catuneanu et al., 2009).

Although the parasequence concept has been widely used, some authors highlighted its significant limitations and the confusion generated by its use and abuse, suggesting its abandonment (Walker, 1992; Posamentier and Allen, 1999; Catuneanu, 2006; Zecchin, 2010). Limitations of the parasequence concept include the equivocal meaning of their bounding (“flooding”) surfaces (Section 3.1; Fig. 17); its architecture that considers only shallowing-upward trends without significant transgressive deposits (Fig. 29); its mappability only in coastal to shallow-water areas (in contrast with the concepts of sequence and systems tract); and its potential equivalence with high-frequency sequences of the same hierarchical rank (Arnott, 1995; Posamentier and Allen, 1999; Catuneanu, 2006; Zecchin, 2010) (Fig. 29). Further confusion was generated by the usage of the term parasequence only for cycles developed during relative sea-level rise, as well as for cycles that may be classified as small-scale or high-frequency sequences composed of systems tracts (Zecchin, 2010) (Fig. 29). Furthermore, even though the parasequence concept was introduced specifically for coastal to shallow-water settings, some authors expanded the usage of this term to alluvial and deep-water settings as well, to define any meter-scale cycles irrespective of origin (e.g., Spence and Tucker, 2007; Tucker and Garland, 2010). Following the original

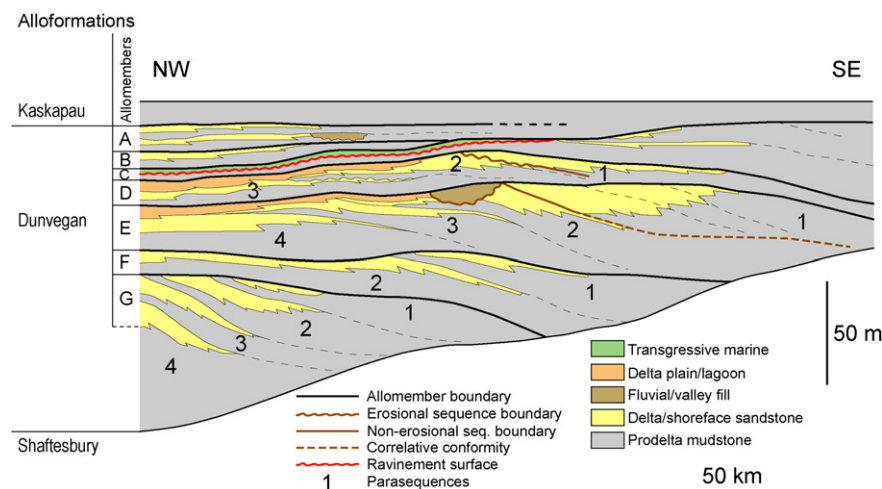


Figure 28. The allomembers and smaller scale deltaic units (parasequences) of the upper Cretaceous Dunvegan Alloformation (modified from Bhattacharya, 1993). Allomember boundaries consist of interpreted ‘major’ flooding surfaces, in contrast with the ‘minor’ flooding surfaces bounding parasequences. Other surfaces of sequence stratigraphic significance are indicated.

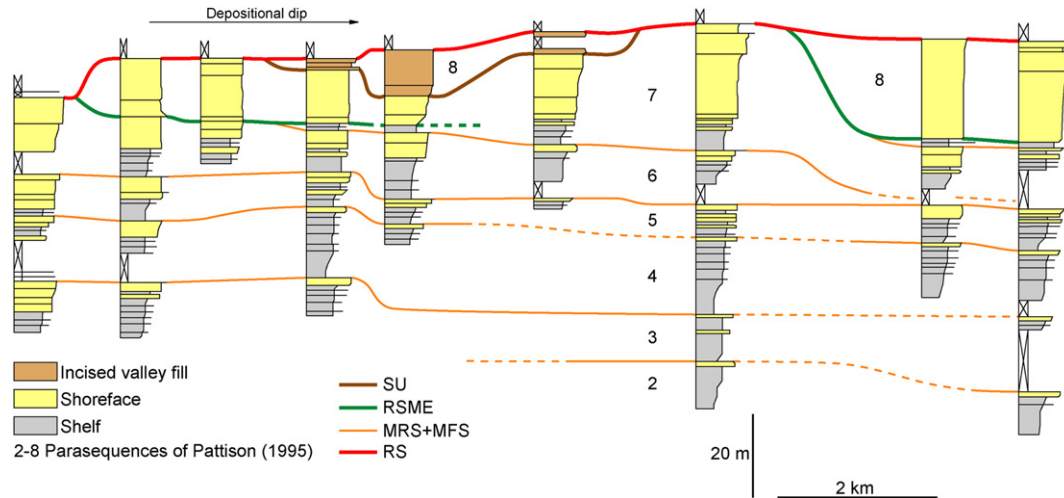


Figure 29. Cross-section showing meter-scale to decameter-scale units composing the Kenilworth Member of the Blackhawk Formation, USA (modified from Pattison, 1995). The succession was originally described in terms of parasequences bounded by flooding surfaces, here considered as MRSs merged with MFSs. Note that the uppermost two cycles contain RSMEs indicating forced regression, and therefore they should be classified as high-frequency sequences. Abbreviations: MFS – maximum flooding surface; MRS – maximum regressive surface; RS – ravinement surface; RSME – regressive surface of marine erosion; SU – subaerial unconformity.

definition of the parasequence concept, it has been recognized that the architecture of cycles that develop at parasequence scale is far more complex than originally envisaged, including any relative contributions from transgressive or regressive deposits, and involving a variety of types of stratigraphic contacts as bounding surfaces (e.g. Swift et al., 1991; Kidwell, 1997; Naish and Kamp, 1997; Saul et al., 1999; Di Celma et al., 2005; Zecchin, 2005, 2007; Di Celma and Cantalamessa, 2007) (Figs. 17 and 30).

Some authors, recognizing the problems inherent in the application of the parasequence concept, proposed its redefinition. For example, from the study of peritidal carbonate cycles, Spence and Tucker (2007) proposed to extend the term parasequence to all meter-scale cycles regardless if they are bounded or not by flooding surfaces and independent of their architecture. Apart from the ambiguity caused by the fact that some parasequences defined in this way match also the criteria for the definition of high-frequency sequences, a parasequence concept so different from the original meaning would rather justify a different terminology to avoid confusion. As concluded in the ISSC report on sequence stratigraphy (Catuneanu et al., 2011), “following the principle that a sequence stratigraphic unit is defined by specific bounding surfaces, most practitioners favor restricting the concept of parasequence to a unit bounded by marine flooding surfaces, in agreement with the original definition of Van Wagoner et al. (1988, 1990)” (Fig. 27).

Referring to the classic shallowing-upward trend of a parasequence, Hampson et al. (2008) proposed an additional geomorphic criterion, that is the recognition of a set of progradational clinoforms, to distinguish parasequences from minor and discontinuous stratigraphic subdivisions such as bedsets. Detailed information on the internal architecture of parasequences has been provided recently by Hampson (2000), Charvin et al. (2010), Enge et al. (2010) and Hampson et al. (2011), based on the study of Upper Cretaceous successions in central Utah.

5.3. Sequences

Sequence stratigraphic models have been summarized in a number of syntheses (e.g., Posamentier and Allen, 1999; Catuneanu, 2002, 2006; Catuneanu et al., 2009, 2011). Catuneanu (2006) stressed the importance of being flexible and adopting the approach that is most suitable to the data available. Depending on approach, different types of sequence have been defined, each bounded by different surfaces or combinations of surfaces (Catuneanu et al., 2011) (Fig. 27). The nomenclature of systems tracts may also vary with the model, although a standard terminology has now been adopted by the ISSC (Section 4.1).

The hierarchical classification of sequences based on the relative stratigraphic significance of their bounding surfaces, as opposed to a system that starts from parasequences as the basic building

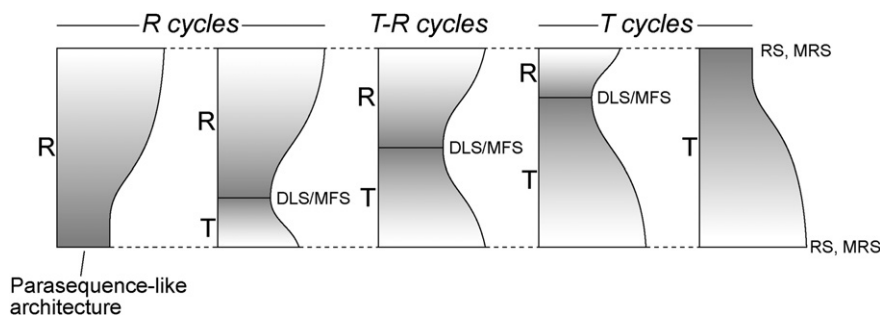


Figure 30. The variable symmetry found in transgressive–regressive cycles, following Zecchin (2007). *R* cycles and *T* cycles are dominated respectively by regressive and transgressive deposits, whereas *T–R* cycles show a symmetric architecture. Abbreviations: DLS – downlap surface; MFS – maximum flooding surface; MRS – maximum regressive surface; RS – ravinement surface; R – regressive; T – transgressive.

blocks of sequences, was preferred by some authors due to the reasons discussed by Catuneanu (2006) and Zecchin (2007, 2010). A similar approach was already adopted by Mutti et al. (1994), who recognized in the south-central Pyrenees a hierarchy consisting of elementary (meters to tens of meters) depositional sequences grouped into small-scale composite depositional sequences, which in turn compose large-scale composite depositional sequences. Another hierarchical approach was proposed by Neal and Abreu (2009) using the method of the 'accommodation succession', which was defined as 'a regional sedimentary package resulting from changes in rates of shelfal accommodation creation and depositional fill in response to changes in base level'. The basic motif of the accommodation succession consists of lowstand progradation to aggradation, transgressive retrogradation, and highstand aggradation to progradation, degradation and/or basinward shift, which define depositional sequences and larger scale sequence sets and composite sequences (Neal and Abreu, 2009).

The designation of depositional sequences assumes that the observed cyclicity is the product of changes in relative sea level, with stages of rise and fall. In contrast, the genetic stratigraphic sequences of Galloway (1989) and the transgressive–regressive sequences of Johnson and Murphy (1984) may correspond to cycles developed during continuous relative sea-level rise and driven by sediment supply variations or changes in the rate of accommodation creation (Catuneanu et al., 2009).

As noted above, the relationship between stratigraphic cyclicity and relative sea-level changes is not evident in all cases, since relative sea-level changes may be irregular, and sediment supply variations may also contribute to the formation of the observed cyclicity. This aspect was updated by Catuneanu et al. (2009, 2011) introducing the 'stratigraphic sequence' concept (Fig. 27), which unifies all types of sequences and considers sediment supply changes, together with accommodation, as possible driving mechanisms on sequence development. According to the revised definition, a sequence corresponds to 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. 27).

5.4. Generic units

Practitioners operating with sparse field or core data that may prevent or make difficult the recognition of controlling mechanisms, commonly refer to generic, descriptive cycle concepts, as suggested by Schlager (1991), Walker (1992) and Zecchin (2007, 2010). Such generic cycles are independent of temporal scales, genetic mechanisms (alloycyclic or autocyclic) and stratal stacking patterns; their definition and internal subdivision can be made by means of mapping surfaces with physical expression in outcrop or core. In shallow-marine shelf settings, all surfaces described in Sections 2 and 3 may be useful to define generic cycles and their internal components, although the mappability (and hence the usefulness) of each surface may vary with the case study.

Historically, the term 'cyclothem' was used to define generic cycles in the upper Paleozoic successions of North America (Weller, 1930; Wanless and Shepard, 1936); more recently, this term was also adopted to describe Plio-Pleistocene shelf cycles (Abbott and Carter, 1994). Zecchin (2005, 2007) proposed the concept of 'small-scale cycle' to describe cyclicity in shoreface to shelf successions at outcrop (meters to tens of meters) scale (Fig. 27). Small-scale cycles may be bounded by any recurring stratigraphic surface in a succession (usually RSs or MRSS, Fig. 27), and typically the most prominent surfaces are selected as cycle boundaries. The role of condensed shell beds is considered critical to recognize internal surfaces, according to the conceptual framework

developed for high-resolution stratigraphic analysis by Kidwell (1991), Abbott and Carter (1994), Naish and Kamp (1997), Carter et al. (1998) and Kondo et al. (1998). The small-scale cycle concept is more comprehensive than the concept of parasequence, as it is not limited to shallowing-upward trends and to the occurrence of flooding surfaces (Fig. 30).

Zecchin (2007) proposed a classification of small-scale cycles based on the relative development of retrograding and prograding units: *R* cycles (dominated by regressive deposits), *T* cycles (dominated by transgressive deposits) and *T–R* cycles (showing transgressive and regressive deposits of similar thickness) (Fig. 30). Following this descriptive classification, the parasequence architecture represents only one case among the possible architectures that can be found in the field (Fig. 30). The relative thickness of transgressive and regressive deposits within a regional context may provide very useful information on depositional conditions and forcing mechanisms (e.g., Catuneanu et al., 1997, 2000; Zecchin, 2007).

6. Discussion

6.1. High-frequency sequences

The different approaches to the classification of high-frequency cycles are to some extent the result of conceptual developments without formal guidance from the international stratigraphic commissions. The concepts of parasequence, small-scale cycle and high-frequency sequence may all be applied to similar scales of observation, often interchangeably. This generates methodological confusion, and adds redundancy to the nomenclature of cycles at sub-seismic scale. The need to employ parasequences and small-scale cycles in high-resolution studies may be replaced by the usage of high-frequency sequences. This aspect is discussed in more detail in Part II of this work (Catuneanu and Zecchin, 2012).

The concept of parasequence has divided the stratigraphic community, with arguments being made both to retain and to abandon this type of unit (Walker, 1992; Catuneanu, 2006; Spence and Tucker, 2007; Zecchin, 2010). The application of the sequence concept to the classification of high-frequency cycles related to transgressions and regressions in shallow-water settings makes the use of the parasequence concept unnecessary. Since flooding surfaces are always linked to episodes of transgression, every time a flooding surface occurs in the rock record, a maximum flooding surface can be defined as well at the same scale of observation (Fig. 17). The opposite is not true, as not every transgression leading to the formation of a maximum flooding surface is prone to generate an abrupt lithological contact that can define a flooding surface (Fig. 30). Therefore, maximum flooding surfaces (i.e., genetic stratigraphic sequence boundaries) are more reliable for correlation than flooding surfaces (i.e., parasequence boundaries). Beyond the issue of mappability in coastal to shallow-water settings, maximum flooding surfaces are much easier to extend into the coeval fluvial and deep-water settings (Posamentier and Allen, 1999; Catuneanu, 2006), making the high-frequency sequence a superior type of unit for regional correlation.

An example illustrating the practicality of using the stratigraphic sequence in field studies, rather than the parasequence, is the classification of glacio-eustatic cycles that form under Greenhouse and Icehouse climate regimes. Small-scale cycles developed during Greenhouse periods were commonly referred to as parasequences (e.g. Van Wagoner et al., 1990; Pattison, 1995) (Fig. 29), whereas those characterizing Icehouse periods were considered high-frequency depositional sequences (e.g. Kidwell, 1997; Naish and Kamp, 1997), despite the same driving mechanism being

inferred in both cases (i.e., orbital forcing). The use of different cycle concepts in these cases is not helpful, especially if the different styles of cyclicity are to be compared. The reason for this nomenclatural difference relates to contrasts in the physical appearance of cycles that form under the two climatic regimes, as the amplitude of sea-level changes is lower during Greenhouse periods, obscuring the recognition of forced regressions and related unconformities. The use of the stratigraphic sequence concept to describe the glacio-eustatic cyclicity, both in Greenhouse and Icehouse regimes, provides a solution to avoid nomenclatural ambiguities.

6.2. Choice of sequence boundary

The model-independent sequence stratigraphic methodology assumes the construction of a framework of systems tracts and bounding surfaces based on observations of stratal features and stacking patterns (Catuneanu et al., 2009, 2011). Beyond this, the placement of the sequence boundary can be made depending on the context and/or on the basis of personal preference. Surfaces that can be used as sequence boundaries in high-resolution studies are the same types of sequence stratigraphic surface that are employed as sequence boundaries at larger scales, but at a correspondingly lower hierarchical rank. These include the SU, CC, BSFR, RSME, MRS, RS and MFS (Figs. 1 and 2).

Where SUs are present in the succession, they are generally preferred to define the boundaries of sequences, as they commonly mark the most prominent breaks in the stratigraphic record (Fig. 4). The CC portion of the depositional sequence boundary has a more subtle expression in outcrop and core, particularly in the distal shelf settings. The placement of the marine portion of the sequence boundary at the BSFR (or the RSME, where the RSME reworks the BSFR; Posamentier and Allen, 1999) may be effective where forced regressive sharp-based shorefaces are part of the cycles (Plint, 1988) (Fig. 16).

In shoreface to shelf settings, the MRS (or the RS, where the RS reworks the MRS) may also have a good physical expression and represent a feasible choice to define the sequence boundary (e.g., Johnson and Murphy, 1984; Embry and Johannessen, 1992) (Figs. 8, 9 and 13). In continental settings, the MRS may be more difficult to recognize, although studies so far indicate that it can be taken at the contact between amalgamated fluvial channels and dominantly floodplain deposits (e.g., Amorosi and Colalongo, 2005) (Fig. 4).

The MFS is another candidate for a sequence boundary (e.g., Galloway, 1989), and it may have a good physical expression where the transgressive deposits are missing (Fig. 11E). In other cases, however, the MFS may lie within a condensed section with a cryptic expression in outcrop or core (e.g., Carter et al., 1998) (Figs. 11A,B and 14). At seismic scales, the MFS is often mapped as a downlap surface overlain by the HST clinoforms (e.g., Catuneanu, 2002). However, the high-detail observations afforded by outcrop and core data indicate that the cryptic horizon corresponding to the time of maximum transgression (i.e. the MFS) and the DLS may be two separate surfaces (e.g., Posamentier and Allen, 1999) (Figs. 11 and 12).

Carter et al. (1998) stated that the adoption of the DLS to separate transgressive and highstand deposits would represent a pragmatic choice for outcrop-based studies, as this facies contact physically marks the base of the shallowing-upward clastic wedge (Figs. 11 and 12). This choice was made by various authors working with field data (e.g. Kondo et al., 1998; Di Celma et al., 2005; Zecchin, 2007). However, the DLS is a diachronous surface that may be significantly younger than the MFS (Fig. 2). The DLS and the MFS may coincide only where the intervening condensed-section deposits are missing (Fig. 11C–E). An alternative solution was proposed by Abbott and Carter (1994), who considered the

condensed section as a distinct interval (their mid-cycle shell bed) that separates transgressive and highstand terrigenous deposits, avoiding the classification of the condensed section as fully transgressive. However, the DLS and the mid-cycle shell bed are more suitable for the detailed facies analysis of architectural units, as the true boundary between the transgressive and highstand systems tracts remains within the condensed section.

7. Conclusions

High-resolution sequence stratigraphy deals with the analysis of stratigraphic frameworks that develop at sub-seismic scales of observation, typically referred to as of 4th-order or lower rank. Outcrop and core data provide the best means of observing the physical attributes of various types of stratigraphic units and bounding surfaces that form at these scales. The high degree of detail afforded by outcrop and core data allows the identification of a wider array of stratigraphic surfaces as compared to those recognizable at the seismic scale. These surfaces can be classified as 'sequence stratigraphic', if they serve as systems tract boundaries, or as facies contacts, if they develop within systems tracts. While both types of stratigraphic contacts are important in high-resolution studies, the workflow of sequence stratigraphy highlights the importance of constructing a framework of sequence stratigraphic surfaces first, followed by the mapping of facies contacts within the context of this framework. This is because (1) sequence stratigraphic surfaces typically record a lesser degree of diachroneity as compared to facies contacts, and (2) sequence stratigraphic surfaces typically correlate over large distances, as their mappability is independent of lithological criteria.

Sequences are the fundamental units in sequence stratigraphy; their field expression is marked by the recurrence of the same types of sequence stratigraphic surface in the stratigraphic record, which defines 'cycles' of sedimentation. Sequences include component systems tracts which, particularly evident within the context of clastic shelves, correspond to specific types of shoreline trajectory: forced regression, normal regression and transgression. Furthermore, systems tracts may consist of architectural units bounded by the two nearest non-cryptic stratigraphic surfaces, whether sequence stratigraphic or facies contacts.

The use of high-frequency sequences in high-resolution studies eliminates the need to employ other concepts for the definition of cycles, such as the concepts of 'parasequence' or 'small-scale cycle'. The use of a consistent terminology eliminates the confusion created by the existence of alternative terms for the description of units that overlap conceptually and develop at similar scales of observation. This issue is discussed further in Part II of this work (Catuneanu and Zecchin, 2012). The sequence boundaries that may be employed in high-resolution sequence stratigraphy are represented by the same types of surfaces that are used traditionally in larger scale studies, but at a correspondingly lower hierarchical rank.

Acknowledgments

OC acknowledges support from the University of Alberta during the completion of this study. We thank Claudio Nicola Di Celma and Pat Eriksson for helpful and constructive comments during the review process.

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