CHAPTER ONE

Sequence Stratigraphy: Guidelines for a Standard Methodology

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Contents

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Abstract

The interplay of local and global controls on accommodation and sedimentation generates basin-specific sequence stratigraphic frameworks that record cyclicity at multiple scales. There are no temporal or physical standards for the scale of any type of sequence stratigraphic unit. Sequences, systems tracts, and depositional systems can be defined at different scales, depending on the scope of the study, the resolution of the data available, and the local conditions of accommodation and sedimentation. A scale-independent methodology and nomenclature is key to the standard application of sequence stratigraphy.

Stratal stacking patterns provide the basis for the definition of all units and surfaces of sequence stratigraphy. The same types of stacking patterns may be observed at different scales, in relation to stratigraphic cycles of different magnitudes. At any scale of observation (i.e., hierarchical rank), a specific type of stacking pattern defines a systems tract, and changes in stacking pattern mark the position of sequence stratigraphic surfaces. Beyond this model-independent framework, model-dependent choices with respect to the selection of the "sequence boundary" may be made as a function of the mappability of the different types of sequence stratigraphic surface that are present within the study area. The model-independent methodology, inherently simple and consistent, provides the flexible platform for a standard application of sequence stratigraphy across the entire range of geological settings, stratigraphic scales, and types of data available.

1. INTRODUCTION

Sequence stratigraphy is a type of stratigraphy that deals with the description, interpretation, classification, and nomenclature of sedimentary rocks based on their stratal stacking patterns and their stratigraphic relations. Sequence stratigraphy integrates all other types of stratigraphy and includes seismic stratigraphy (Fig. 1). The sequence stratigraphic methodology has gained considerable popularity among practitioners with interest in different aspects of the stratigraphic record, and its applications have been expanded to all depositional, tectonic, and climatic settings, from Precambrian to Phanerozoic successions (e.g., Csato et al., 2013, 2015; De Gasperi and Catuneanu, 2014; Eriksson et al., 2005, 2013; Zecchin et al., 2015). A standard workflow assumes a set of guidelines that afford a consistent application of the method across all spectrum of geological settings, stratigraphic scales, and types of data available.

Sequence stratigraphic units are bodies of sedimentary rocks that are defined and characterized on the basis of their stratal stacking patterns and their stratigraphic relations. The bounding surfaces of sequence stratigraphic units are sequence stratigraphic surfaces, which are stratigraphic contacts that

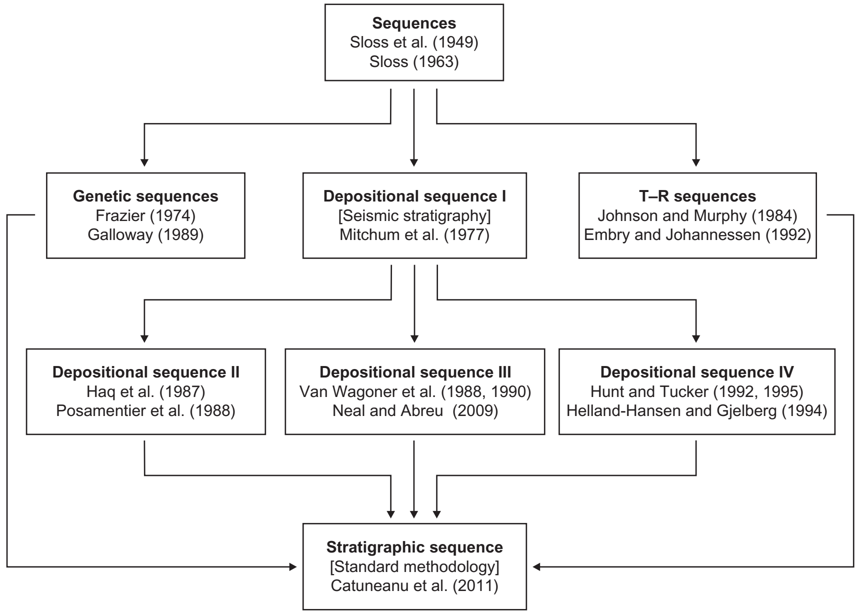

Fig. 1 Evolution of sequence stratigraphic approaches. *Modified from Catuneanu, O., Bhattacharya, J.P., Blum, M.D., Dalrymple, R.W., Eriksson, P.G., Fielding, C.R., Fisher, W.L., Galloway, W.E., Gianolla, P., Gibling, M.R., Giles, K.A., Holbrook, J.M., Jordan, R., Kendall, C.G.St.C., Macurda, B., Martinsen, O.J., Miall, A.D., Nummedal, D., Posamentier, H.W., Pratt, B.R., Shanley, K.W., Steel, R.J., Strasser, A., Tucker, M.E., 2010. Sequence stratigraphy: common ground after three decades of development. First Break 28, 21–34; Catuneanu, O., Galloway, W.E., Kendall, C.G.St.C., Miall, A.D., Posamentier, H.W., Strasser, A., Tucker, M.E., 2011. Sequence stratigraphy: methodology and nomenclature. Newsl. Stratigr. 44/3, 173–245.*

mark changes in stratal stacking pattern between the underlying and the overlying units. The sequence stratigraphic units and their bounding surfaces provide the basis for a genetic, process-based approach to stratigraphic mapping and correlation. This approach sets sequence stratigraphy apart from other correlation methods that rely on similarities of rock units in terms of lithology (i.e., lithostratigraphy), fossil assemblages (i.e., biostratigraphy), magnetic characteristics (i.e., magnetostratigraphy), geochemical signatures (i.e., chemostratigraphy), or age (chronostratigraphy).

Stratal stacking patterns provide the basis for the definition of all units and surfaces of sequence stratigraphy. At any scale of observation (i.e., hierarchical rank), a stratal stacking pattern defines a systems tract, and the surfaces that mark changes in stratal stacking pattern (i.e., systems tract boundaries) are sequence stratigraphic surfaces. A full stratigraphic cycle (i.e., which starts and ends with the same type of sequence stratigraphic surface) delineates a "sequence" (Catuneanu and Zecchin, 2013), which typically includes two or more systems tracts. This methodology transcends the difference between various approaches, as the selection of the sequence boundary takes a subordinate role in the workflow, being a function of mappability rather than an a priori model-dependent premise (Catuneanu et al., 2009, 2011). Advances in the development of the method reveal that the stratigraphic record is much more complex than theoretical models can predict; sequences may consist of variable combinations of systems tracts (e.g., Csato and Catuneanu, 2012; Zecchin and Catuneanu, 2013), which may or may not conform with the prediction of standard models; and consequently, stratigraphic frameworks may or may not include the entire spectrum of sequence stratigraphic surfaces. Additionally, the degree of mappability of each type of sequence stratigraphic surface depends on the types of data available for analysis (Catuneanu, 2006; Posamentier and Allen, 1999).

The existence of several competing approaches to the definition and classification of sequence stratigraphic units (Figs. 1 and 2) has generated considerable confusion among practitioners, with respect to the "best practice" in sequence stratigraphy. The various approaches differ in terms of (1) nomenclature of sequences, systems tracts, and sequence stratigraphic surfaces; (2) selection of surfaces which should be elevated to the rank of "sequence boundary"; (3) the approach taken to define a sequence hierarchy system; and (4) the assertions of the dominant controls on sequence development. Beyond these differences, there is a common ground of core principles that affords a unified application of sequence stratigraphy, irrespective of geological setting and types of data available. Formal recommendations on a model-independent methodology have been sanctioned by the International Subcommission on Stratigraphic Classification of the International Commission of Stratigraphy (Catuneanu et al., 2011). This work updates the core principles of sequence stratigraphy that afford a standard application of the method across the whole spectrum of geological settings, stratigraphic scales, and types of data available.

2. HISTORICAL DEVELOPMENT OF THE METHOD

Sequence stratigraphy started to emerge as a method of stratigraphic analysis ever since the recognition of unconformities in the rock record, which allowed the subdivision of the sedimentary succession into units separated by breaks in the depositional process. Following the initial definition

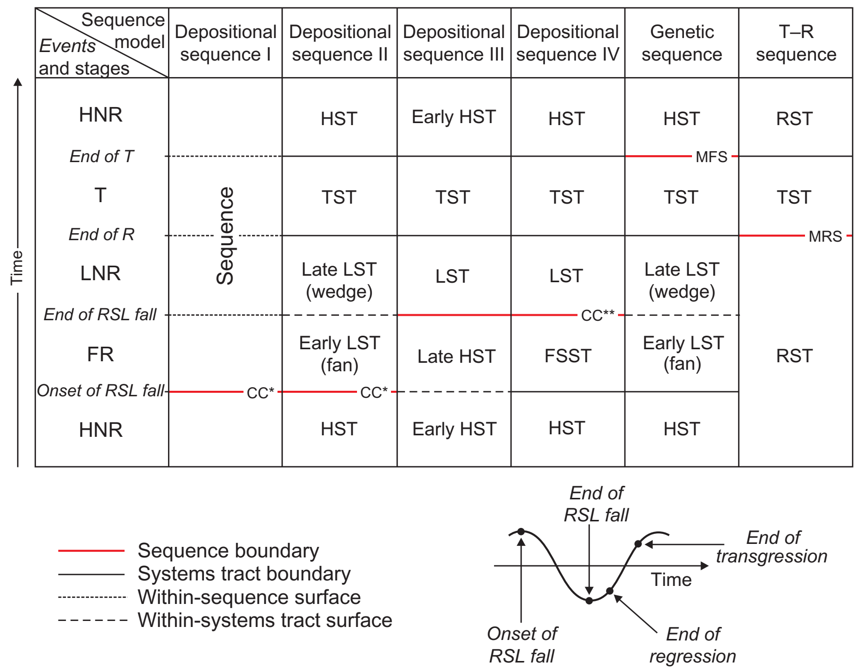

Fig. 2 Sequence stratigraphic approaches: nomenclature of systems tracts and timing of sequence boundaries. Abbreviations: *CC**, correlative conformity in the sense of Posamentier et al. (1988), referred to here as the "basal surface of forced regression"; *CC***, correlative conformity in the sense of Van Wagoner et al. (1988), referred to here as the "correlative conformity"; *FR*, forced regression; *FSST*, falling-stage systems tract; *HNR*, highstand normal regression; *HST*, highstand systems tract; *LNR*, lowstand normal regression; *LST*, lowstand systems tract; *MFS*, maximum flooding surface; *MRS*, maximum regressive surface; *R*, regression; *RSL*, relative sea level; *RST*, regressive systems tract; *T*, transgression; *T–R*, transgressive–regressive; *TST*, transgressive systems tract. References for the proponents of the various sequence stratigraphic approaches are provided in Fig. 1. *From Catuneanu, O., Galloway, W.E., Kendall, C.G.St.C., Miall, A.D., Posamentier, H.W., Strasser, A., Tucker, M.E., 2011. Sequence stratigraphy: methodology and nomenclature. Newsl. Stratigr. 44/3, 173–245.*

of a "sequence" as an unconformity-bounded unit (Longwell, 1949; Sloss et al., 1949), several sequence stratigraphic approaches have been proposed, which differ in terms of nomenclature of systems tracts and the selection of the "sequence boundary" (Fig. 2).

The concept of "sequence" evolved over time, in parallel to the trend of gradually increasing the resolution of stratigraphic analysis (Fig. 3). The development of the sequence concept started with unconformity-bounded units defined at a continental scale (Longwell, 1949; Sloss et al., 1949), by considering only interregional unconformities

Decade	Definition of "sequence"	Resolution
1940s	Rock-stratigraphic unit bounded by interregional unconformities (1)	10^2–10^3 m
1970s	A relatively conformable succession of genetically related strata bounded by unconformities or their correlative conformities (2)	10^1–10^2 m
2010s	A cycle of change in stratal stacking patterns defined by the recurrence of sequence stratigraphic surfaces in the rock record (3)	10^0–10^1 m

Fig. 3 Developments in the definition of a "sequence." Changes to the definition of a "sequence" reflect (1) the gradual increase in the resolution of stratigraphic studies and (2) the need for a more inclusive definition that accommodates all existing sequence stratigraphic approaches (Fig. 1). Following the refinements in definition and methodology, the applications of sequence stratigraphy have expanded from continental-scale correlations (1940s to 1960s) to 2D seismic-scale exploration (1970s) and subseismic-scale production development (2010s). References: (1) Longwell (1949), Sloss et al. (1949), Sloss (1963); (2) Mitchum (1977); (3) Catuneanu et al. (2011), Catuneanu and Zecchin (2013).

as sequence boundaries. As a result, the Phanerozoic sedimentary cover of North America was subdivided into only six sequences (Sloss, 1963). Subsequent work by Wheeler (1958, 1959, 1964) depicted stratigraphic cyclicity in a time domain (depth-to-time Wheeler transformation, or "Wheeler diagram" as it is known today; Qayyum et al., 2014, 2015) and recognized sequence-bounding unconformities of smaller magnitude and smaller areal extent than those considered by Sloss (1963). In doing so, Wheeler (1964) introduced the concept of "continuity surface" beyond the termination of an unconformity, which was later renamed as the "correlative conformity" in the 1970s. This was the first step toward increasing the resolution of stratigraphic studies, by decreasing the scale of a sequence. This trend continued in the 1970s, with the definition of sequences at scales compatible with the vertical seismic resolution (Mitchum et al., 1977). The trend continues today with the definition of sequences at subseismic scales (i.e., high-resolution sequence stratigraphy; Catuneanu and Zecchin, 2013; Catuneanu et al., 2011; Csato et al., 2014; Magalhaes et al., 2015; Zecchin and Catuneanu, 2013, 2015; Zecchin et al., 2015, 2017a,b).

The evolution of the concept of sequence is reflected in the revisions to the definition, which, as the scale of a "sequence" decreased through time, gradually changed the emphasis from the sequence-bounding unconformities to the stacking patterns that define the sequence itself (Fig. 3). Following this trend, the definition changed from "an unconformity-bounded unit" (1940s) to "a unit bounded by unconformities or their correlative conformities" (1970s), and eventually to "a unit bounded by any recurring surface of sequence stratigraphy" (2010s). This trend highlights the fact that as the scale of observation decreases, the magnitude and the areal extent of unconformities decrease as well, and conformable surfaces become increasingly important to delineate sequences. The result is that at high-resolution level, and also depending on the type of sequence stratigraphic surface selected as sequence boundary (Fig. 2), a sequence may no longer require unconformities at its boundaries. The latest definition of a sequence is independent of model, as it accommodates all sequence stratigraphic approaches.

3. CORE CONCEPTS

Multiple allogenic and autogenic processes interplay to generate the stratigraphic architecture of the rock record (Catuneanu and Zecchin, 2013; Muto and Steel, 1992, 1997, 2002). The nature, the intensity, and the relative importance of these controls may vary with stratigraphic age and tectonic setting, making it impossible to draw generalized conclusions with respect to the dominance of one control over others throughout geologic time and under all circumstances. However, the interplay of all controls on the architecture of the stratigraphic record always boils down to two fundamental variables, namely accommodation and sedimentation, which can be used to understand the formation of specific stratal stacking patterns that can be observed in the rock record irrespective of the dominant control(s) at *syn*-depositional time. This helps to focus the methodology on observational field criteria, irrespective of the interpreted origin of the units and bounding surfaces that are being mapped (Catuneanu and Zecchin, 2016).

3.1 Accommodation and Sedimentation

Accommodation is the space made available for sediments to fill (Jervey, 1988), primarily by basin-forming mechanisms (i.e., tectonism and sea/lake-level changes). Additional controls on accommodation include glacial isostasy, sediment loading, and compaction (Catuneanu, 2003, 2006; Miall, 2010; Posamentier and Allen, 1999). The reference horizon that marks the top of available accommodation within a sedimentary basin is represented by the eustatic sea level, in basins connected to the global ocean, and by the elevation of the outflow ridge in interior basins disconnected from the global ocean (Fig. 4). Relative to this reference horizon, accommodation

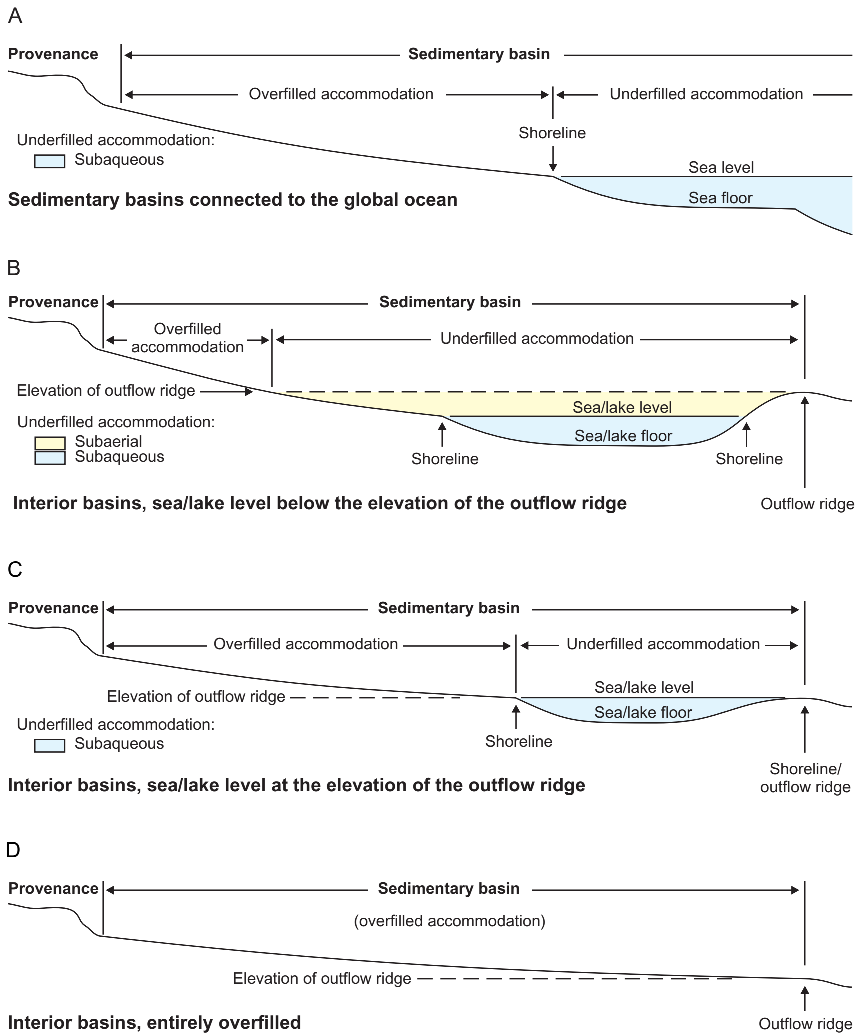

Fig. 4 Underfilled vs overfilled accommodation in sedimentary basins. Accommodation is measured up to the eustatic sea level, in basins connected to the global ocean, and up to the elevation of the outflow ridge in interior basins isolated from the global ocean. In the case of sedimentary basins connected to the global ocean (A), as well as interior basins where the sea/lake level is at the elevation of the outflow ridge (C), the shoreline marks the limit between underfilled and overfilled accommodation. In the case of interior basins where the sea/lake level is below the elevation of the outflow ridge (B), accommodation can also be underfilled in continental (e.g., fluvial, eolian) settings. Sedimentary basins become entirely overfilled where all accommodation is consumed by sedimentation (D). Note that sediment accumulation may continue in overfilled settings, driven by sediment supply that outpaces the energy of the sediment transport agents. In a long term, the sediment in excess of accommodation has a lower preservation potential where provenance areas are subject to denudation.

can be underfilled or overfilled (i.e., depositional surface below or above the reference horizon, respectively; Fig. 4). Sedimentary basins typically evolve from underfilled to overfilled stages, as accommodation is consumed by sedimentation.

Available accommodation in underfilled settings may be subaqueous (below the sea/lake level) or subaerial (in interior basins where the sea/lake level is below the elevation of the outflow ridge; Fig. 4). Subaqueous accommodation is relevant to "conventional" sequence stratigraphic frameworks, which form in relation to shoreline trajectories. Subaerial accommodation only becomes significant in interior basins devoid of subaqueous accommodation, where fluvial and/or eolian processes are isolated from any marine or lacustrine influence (e.g., the situation of a dry basin in Fig. 4B). Sequence stratigraphic frameworks may also form under overfilled accommodation conditions, as sedimentation is only in part dependent on accommodation.

Sedimentation is controlled by all processes that modify the balance between sediment supply and environmental energy, including accommodation, climate, source-area uplift, and autogenic shifts in the patterns of sediment distribution (Catuneanu, 2006). Note that sedimentation, rather than sediment supply, is the relevant variable which, along with accommodation, controls the development of stratal stacking patterns. The integration of sediment supply with the energy of sediment transport agents, as the driving force for deposition vs erosion (i.e., base-level changes), was first recognized by Barrell (1917). Base level is a surface of equilibrium between sedimentation and erosion, which can be observed at different scales in all depositional environments (Fig. 5). Changes in base level constantly shape the landscape and the seafloor profiles as the depositional surface strives to attain a state of equilibrium (Fig. 5).

The updip limit of the influence of changes in subaqueous accommodation on sedimentation provides the basis to subdivide a sedimentary basin into downstream- vs upstream-controlled settings (Fig. 5). In downstream-controlled areas, stratal stacking patterns relate to shoreline trajectories, and changes in subaqueous accommodation are described as "relative sea/lake-level changes" (Posamentier and Allen, 1999). The "conventional" systems tract nomenclature (i.e., lowstand, transgressive, highstand, falling-stage) applies specifically to downstream-controlled settings. In upstream-controlled areas, stratal stacking patterns form independently of shoreline trajectories and are described by an "unconventional" systems tract nomenclature that makes reference to the dominant depositional elements (e.g., high vs low degree of amalgamation of channels in fluvial systems).

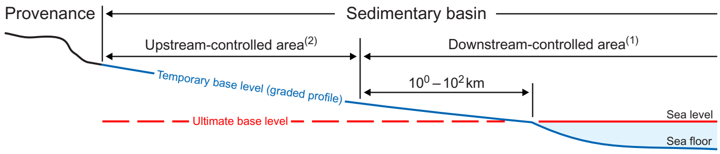

Fig. 5 Downstream-controlled vs upstream-controlled areas within a sedimentary basin. The downstream-controlled area includes continental, coastal, and marine/lacustrine systems which respond to changes in relative sea/lake level. Within a downstream-controlled area, stratal stacking patterns form in relation to shoreline trajectories. The upstream-controlled area includes continental systems beyond the influence of relative sea/lake-level changes, in which stratal stacking patterns form independently of shoreline trajectories. The same sequence stratigraphic methodology applies to both marine and lacustrine settings, whereby changes in subaqueous accommodation and shoreline trajectories control the formation and timing of "conventional" (i.e., downstream-controlled) systems tracts and bounding surfaces. Therefore, "sea level" also stands for "lake level" in terms of processes that are relevant to the construction of downstream-controlled sequence stratigraphic frameworks. The sea level is the *ultimate* base level for subaqueous deposition and continental erosion. *Temporary* base levels are also established in all depositional environments, as equilibrium profiles which the depositional surface strives to attain by means of sedimentation or erosion. The ultimate base level is linked to the concept of "accommodation," whereas the temporary base level (or "base level," as referred to in the text) is a descriptor of "sedimentation." Changes in the temporary base level lead to deposition (base-level rise) or erosion (base-level fall).

Updip from the shoreline, accommodation in continental settings (downstream- or upstream-controlled) may be either overfilled or underfilled, depending on the particular circumstances of each sedimentary basin (Fig. 4). However, the availability of subaerial accommodation takes a subordinate role in any sedimentary basin that includes subaqueous accommodation. Wherever present, the relative sea/lake level, due to its link to the shoreline, is the relevant variable that controls, along with sedimentation, the formation and timing of systems tracts and bounding surfaces in downstream-controlled settings. In such basins, subaerial accommodation also becomes irrelevant to the sedimentary processes in upstream-controlled areas. For this reason, *subaqueous* accommodation is typically inferred when reference is made to "accommodation," in any sedimentary basin that includes a marine or lacustrine depocenter, and hence, a shoreline.

The balance between the rates of sedimentation and accommodation at the shoreline is key to the formation of stratal stacking patterns that define "conventional" systems tracts in downstream-controlled settings. In underfilled basins, where accommodation is still available below the sea/lake level, the water depth represents the balance between concurrent creation of space (accommodation) and consumption of space (sedimentation). In upstream-controlled settings, whether overfilled or underfilled, stratal stacking patterns form in response to the interplay of accommodation, climate, source-area tectonism, and autogenic processes that modify the patterns of sediment distribution. Notably, accommodation is not the sole control on the formation of stratal stacking patterns, in both downstream- and upstream-controlled settings.

At any scale of observation, the balance between the rates of accommodation and sedimentation may change along a shoreline, resulting in the coeval deposition of different systems tracts along strike, and the formation of diachronous systems tract boundaries (e.g., Catuneanu, 2006; Catuneanu et al., 1998; Csato and Catuneanu, 2014; Posamentier and Allen, 1999).

3.2 Stratal Stacking Patterns

Stratal stacking patterns define the stratigraphic architecture of the sedimentary record within a sedimentary basin. Stratal stacking patterns are fundamental to the sequence stratigraphic methodology, as they provide the basis for the definition of all units and surfaces of sequence stratigraphy. Each type of stacking pattern defines a systems tract, and changes in stacking pattern (i.e., systems tract boundaries) define sequence stratigraphic surfaces. Furthermore, a full cycle of change in stratal stacking patterns, which begins and ends with the same type of sequence stratigraphic surface, defines a stratigraphic sequence (Fig. 3).

Stratal stacking patterns may be generated within the area of influence of relative sea/lake-level changes (i.e., "downstream-controlled" stacking patterns), or independently of changes in relative sea/lake level (i.e., "upstream-controlled" stacking patterns) (Fig. 5). The stacking patterns that develop in the downstream- and upstream-controlled settings are described below.

4. STRATAL STACKING PATTERNS IN DOWNSTREAM-CONTROLLED SETTINGS

Downstream-controlled settings include areas of underfilled accommodation in marine or lacustrine environments, as well as adjacent continental areas in which sedimentary processes respond to changes in the relative sea/lake level (Fig. 5). Stratal stacking patterns in downstream-controlled settings form in response to the interplay between accommodation and sedimentation *at the shoreline* (Catuneanu, 2002, 2006). The shoreline trajectory, as observed at different scales, is the key element

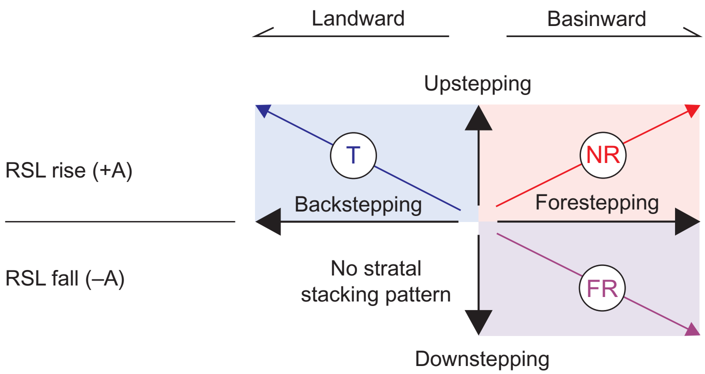

Fig. 6 Shoreline trajectories in downstream-controlled settings: normal regression (i.e., forestepping and upstepping), forced regression (i.e., forestepping and downstepping), and transgression (backstepping and upstepping). Abbreviations: *A*, accommodation; *FR*, forced regression; *NR*, normal regression; *RSL*, relative sea level; *T*, transgression.

in the definition of downstream-controlled stratal stacking patterns (Fig. 6; Catuneanu et al., 2009; Løseth and Helland-Hansen, 2001; Posamentier et al., 1992).

4.1 Normal Regression

Normal regression refers to a stratal stacking pattern defined by a combination of forestepping and upstepping of the shoreline (Figs. 7 and 8; Posamentier et al., 1992). Normal regressions occur when sediment supply outpaces the amount of accommodation generated by relative sea/lake-level rise at the shoreline. A normal regression corresponds to the "ascending regressive" shoreline trajectory of Helland-Hansen and Hampson (2009).

A normal regression that follows a forced regression of equal hierarchical rank is designated as a "lowstand" normal regression (Fig. 8). Lowstand normal regressive shorelines typically describe a concave-up trajectory, in response to the increase in the rates of creation of accommodation following the onset of relative sea/lake-level rise (Fig. 9).

A normal regression that follows a transgression of equal hierarchical rank is designated as a "highstand" normal regression (Fig. 8). Highstand normal regressive shorelines typically describe a convex-up trajectory, where the rates of creation of accommodation decrease following the maximum flooding at the end of transgression (Fig. 9).

Normal regressions are typically accompanied by the aggradation of continental topsets, with the rates of progradation being inversely proportional to the rates of topset aggradation. In turn, the rates of topset aggradation

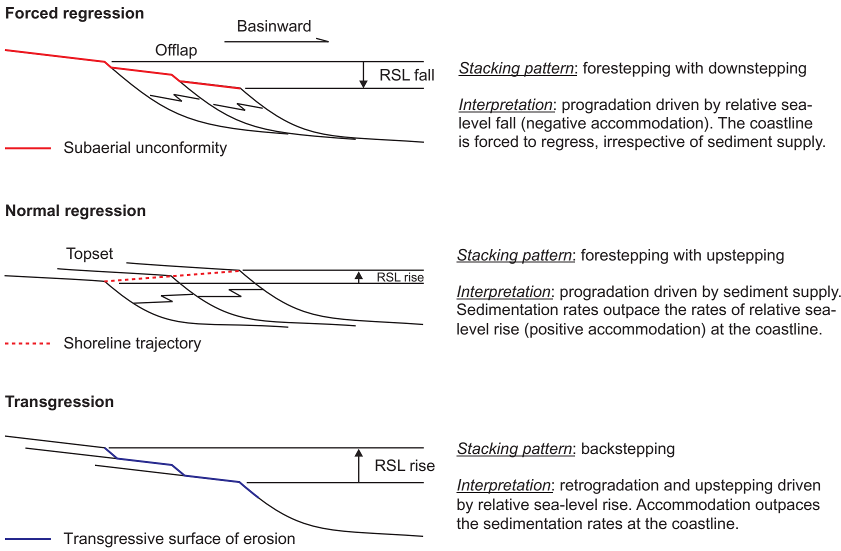

Fig. 7 Stratal stacking patterns in downstream-controlled settings: forced regression, normal regression, and transgression. The amount of upstepping of the coastline during normal regression or transgression, as well as the amount of downstepping of the coastline during forced regression, indicates the magnitude of relative sea/lake-level changes at *syn*-depositional time. This diagram illustrates common stratigraphic trends in the rock record (e.g., the development of offlap during forced regression, and the aggradation of coastal and fluvial systems during transgression). Deviations from these trends (e.g., fluvial and coastal aggradation during forced regression, and fluvial and coastal erosion during transgression) have been discussed by Catuneanu and Zecchin (2016). *From Catuneanu, O., Galloway, W.E., Kendall, C.G.St.C., Miall, A.D., Posamentier, H.W., Strasser, A., Tucker, M.E., 2011. Sequence stratigraphy: methodology and nomenclature. Newsl. Stratigr. 44/3, 173–245.*

reflect the rates of relative increase in coastal elevation (i.e., the rates of relative sea/lake-level rise). Therefore, the rates of progradation tend to decrease with time during lowstand normal regressions, and increase with time during highstand normal regressions (Fig. 8). These trends are reflected in the thickness of the beds that compose the topset units, and are particularly evident in carbonate systems where topsets include peritidal cycles (e.g., fig. 14 in Catuneanu et al., 2011).

Other contrasts between lowstand and highstand topsets are evident in fluvial systems, due to differences in gradients and energy levels between the lowstand and the highstand rivers. The patterns of change in fluvial energy within a sequence depend on the timing of the subaerial unconformity, which may form during forced regressions or transgressions (Figs. 10 and 11; see discussion in Catuneanu and Zecchin, 2016). In both cases, the gradients of the fluvial profile increase during the formation of the

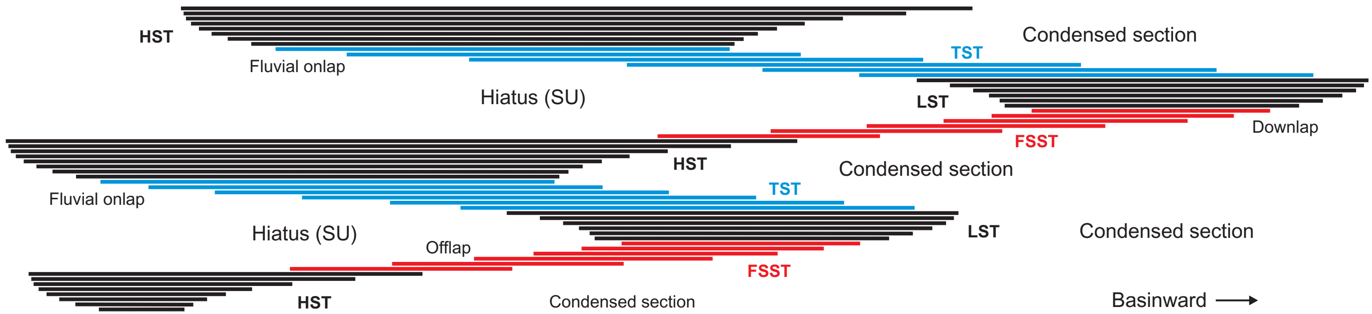

Fig. 8 Stratal stacking patterns in downstream-controlled settings, in a time domain (dip-oriented section, shelf setting). Each type of stratal stacking pattern defines a systems tract: FSST (forced regression), LST (lowstand normal regression), TST (transgression), and HST (highstand normal regression). The degree of preservation of the sedimentary record tends to increase in a downdip direction, from the continental to the marine portions of the basin. Abbreviations: *FSST*, falling-stage systems tract; *HST*, highstand systems tract; *LST*, lowstand systems tract; *SU*, subaerial unconformity; *TST*, transgressive systems tract.

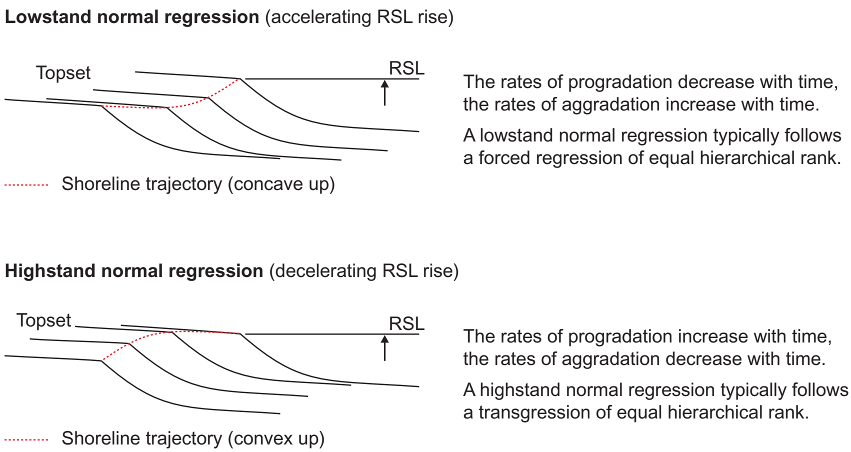

Fig. 9 Stratal stacking patterns of "lowstand" and "highstand" normal regressions. In both cases progradation is driven by sediment supply during a period of positive accommodation at the coastline (i.e., sedimentation outpaces accommodation at the coastline). A lowstand normal regression records a change in depositional trends from dominantly progradational to dominantly aggradational (concave-up shoreline trajectory). In contrast, a highstand normal regression records a change in depositional trend from dominantly aggradational to dominantly progradational (convex-up shoreline trajectory). Abbreviation: *RSL*, relative sea level. *Modified from Catuneanu, O., 2006. Principles of Sequence Stratigraphy. Elsevier, Amsterdam, 375 pp., fig. 7.20, p. 306.*

subaerial unconformity, and decrease during the rest of the stratigraphic cycle. Where the subaerial unconformity forms during forced regression (i.e., in settings where the gradient of the shoreline trajectory is steeper than the fluvial profile; Fig. 10), river systems aggrade during the deposition of the lowstand, transgressive, and highstand systems tracts (Fig. 11A). In this case, the lowstand topsets include the highest energy fluvial systems of the stratigraphic cycle. This scenario, which is most common in the stratigraphic record, is typically recorded where the provenance is far from the shoreline, allowing for the development of low-gradient fluvial profiles within the downstream-controlled settings. Where the subaerial unconformity forms during transgression (i.e., in settings where the fluvial profile is steeper than the gradient of the shoreline trajectory; Fig. 10), the aggradation of river systems occurs during the deposition of the highstand, falling-stage, and lowstand systems tracts (Fig. 11B). In this case, the highest energy fluvial systems are part of the highstand topsets. This scenario is likely where the provenance is proximal to the shoreline, leading to steep landscape gradients and the potential dominance of upstream controls all the way to the shoreline. In either case (fluvial incision during forced regression or transgression), the

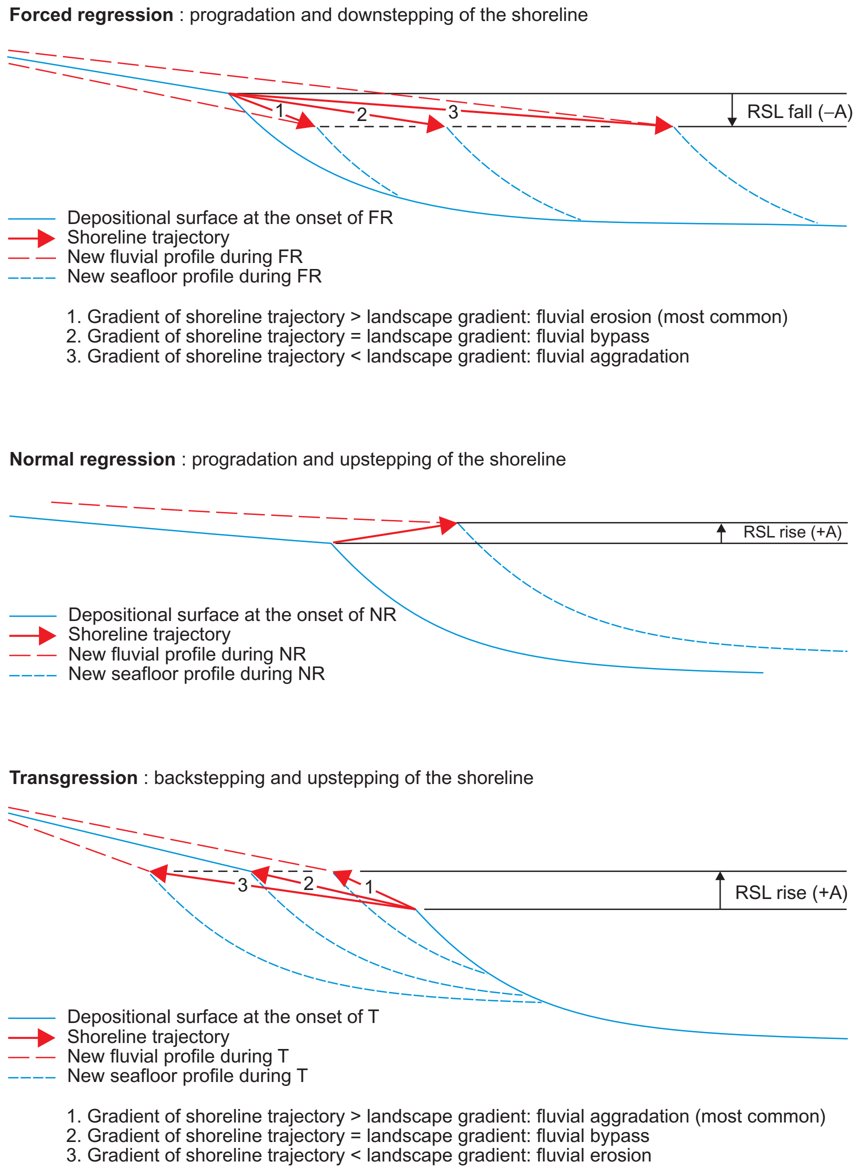

Fig. 10 Depositional trends during forced regression, normal regression, and transgression. Note that subaerial unconformities may form during either forced regression or transgression (see text for details). Abbreviations: – *A*, negative accommodation; +*A*, positive accommodation; *RSL*, relative sea level. *From Catuneanu, O., Zecchin, M., 2016. Unique vs. non-unique stratal geometries: relevance to sequence stratigraphy. Mar. Pet. Geol. 78, 184–195.*

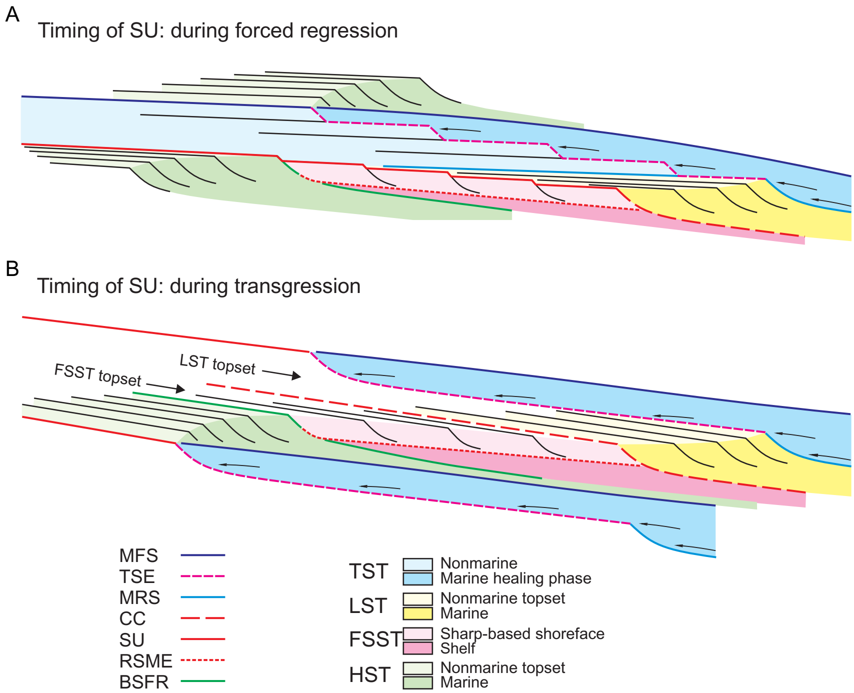

Fig. 11 Architecture of systems tracts and sequence stratigraphic surfaces in a shelf setting: (A) forced regressive and transgressive shoreline trajectories steeper than the landscape gradient, leading to the formation of the subaerial unconformity during forced regression; (B) landscape gradient steeper than the forced regressive and transgressive shoreline trajectories, leading to the formation of the subaerial unconformity during transgression. The strike variability in subsidence and sedimentation rates along the shoreline may result in the coeval development of different systems tracts between different areas of the same sedimentary basin (e.g., Catuneanu et al., 1998, 1999, 2002). Abbreviations: *BSFR*, basal surface of forced regression; *CC*, correlative conformity; *FSST*, falling-stage systems tract; *HST*, highstand systems tract; *LST*, lowstand systems tract; *MFS*, maximum flooding surface; *MRS*, maximum regressive surface; *RSME*, regressive surface of marine erosion; *SU*, subaerial unconformity; *TSE*, transgressive surface of erosion; *TST*, transgressive systems tract.

coarsest sediment is found above the subaerial unconformity, and the fluvial sequence displays a fining-upward profile that reflects the decrease in stream energy and competence with time. This trend also explains the increased likelihood of occurrence of channel amalgamation at the base of depositional sequences, in relation to the steeper gradients which promote higher energy and potentially unconfined river systems.

4.2 Forced Regression

Forced regression refers to a stratal stacking pattern defined by a combination of forestepping and downstepping of the shoreline (Figs. 7 and 8; Posamentier et al., 1992). Forced regressions are driven by relative sea/lake-level fall at the shoreline. The rates of forced regression are proportional to the rates of relative fall and sediment supply and inversely proportional to the seafloor gradients. Forced regression corresponds to the "descending regressive" shoreline trajectory of Helland-Hansen and Hampson (2009).

Forced regressions accompanied by the formation of the subaerial unconformity (Figs. 7, 8, and 11A) assume sediment accumulation primarily in the marine environment, as the downstream-controlled continental setting is subject to erosion or sediment bypass. Exceptions from this trend include processes of lateral accretion within fluvial systems, which may lead to the formation and even preservation of point bar deposits as part of a forced regressive unit. Notwithstanding this exception, a unit defined by an offlapping forced regressive stacking pattern (Figs. 7 and 8) is the only type of systems tract that consists exclusively of marine deposits. All other systems tracts in a downstream-controlled setting (i.e., defined by normal regressive or transgressive stacking patterns) typically include both continental and marine deposits. This is the case in settings where the provenance is located far from the shoreline, leading to the development of fluvial profiles with a gradient lower than the gradient of the shoreline trajectory.

Forced regressions may also be accompanied by fluvial aggradation, particularly in settings where the provenance is located close to the shoreline, leading to the development of landscape gradients steeper than the gradient of the shoreline trajectory (Catuneanu, 2006; Catuneanu and Zecchin, 2016; Posamentier and Allen, 1999; Figs. 10 and 11B). This scenario is less common in the stratigraphic record, but shows that processes of fluvial aggradation are not diagnostic of any particular systems tract. Criteria to differentiate normal regressions from atypical forced regressions with fluvial topsets have been outlined by Posamentier and Morris (2000) and discussed more recently by Catuneanu and Zecchin (2016).

4.3 Transgression

Transgression refers to a stratal stacking pattern defined by a combination of backstepping and upstepping of the shoreline (Figs. 7 and 8). Transgressions occur when sediment supply is insufficient to fill the amount of accommodation generated by relative sea/lake-level rise at the shoreline. The rates of transgression are proportional to the rates of relative rise and inversely proportional to sediment supply and the landscape gradients.

Most commonly, transgressions lead to the highest rates of fluvial aggradation, which reflect the high rates of increase in coastal elevation. Consequently, most sediment during transgression tends to be trapped within fluvial and backstepping coastal systems, leading to sediment starvation of the marine seafloors (Loutit et al., 1988). This is the case in settings where the provenance is located far from the shoreline, leading to the development of fluvial profiles with a gradient lower than the gradient of the shoreline trajectory (Fig. 11A).

Transgressions may also be accompanied by fluvial incision and the formation of subaerial unconformities, particularly in settings where the provenance is located close to the shoreline, leading to the development of landscape gradients steeper than the gradient of the shoreline trajectory (Catuneanu, 2006; Catuneanu and Zecchin, 2016; Leckie, 1994; Posamentier and Allen, 1999; Figs. 10 and 11B). This stratigraphic scenario also demonstrates that fluvial processes of aggradation or erosion are not diagnostic to the definition of systems tracts (see discussion in Catuneanu and Zecchin, 2016).

5. STRATAL STACKING PATTERNS IN UPSTREAM-CONTROLLED SETTINGS

Stratal stacking patterns in upstream-controlled settings develop beyond the influence of relative sea/lake-level changes (Fig. 5), in response to the interplay of all factors which modify the balance between sediment supply and energy flux (i.e., accommodation, climate, source-area tectonism, and autogenic controls on sediment dispersal patterns over various timescales). The degree of channel amalgamation is a key element in the definition of upstream-controlled stratal stacking patterns in fluvial systems (Fig. 12; Boyd et al., 2000; Shanley and McCabe, 1994). The ratio between channel and overbank depositional elements is the result of the interplay of three main processes in fluvial systems, namely, the rates of floodplain aggradation, the degree of channel confinement, and the frequency of avulsion (Fig. 13; Bristow and Best, 1993).

It is noteworthy that accommodation, while important, is not the sole control on the formation of upstream-controlled stratal stacking patterns

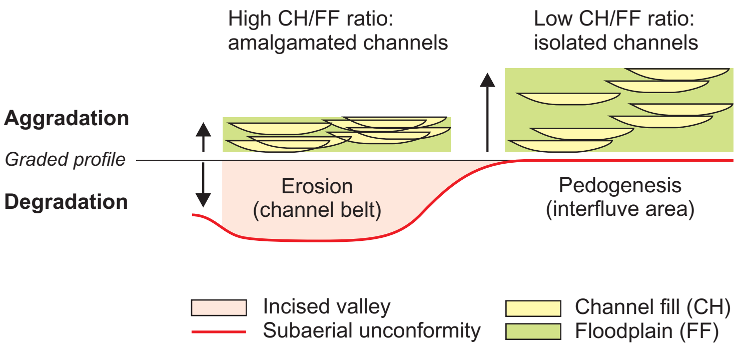

Fig. 12 Depositional trends in an upstream-controlled area. The development of "unconventional" stratal stacking patterns depends on (1) the rates of floodplain aggradation (proportional to the size of *arrows* in the diagram); (2) the ability of channels to shift laterally, which is a function of fluvial style; and (3) the frequency of avulsion. The processes and the rates of aggradation and degradation depend on all factors which control sedimentation (i.e., sediment supply vs energy flux), including accommodation, climate, source-area tectonism, and the autogenic controls on sediment dispersal patterns. The aggrading side of the diagram illustrates the seven-step evolution of a channel under identical conditions of avulsion and lateral shift. In this case, the contrast in stratigraphic architecture (i.e., amalgamated vs isolated channels) is the result of differences in the rates of floodplain aggradation.

(Bristow and Best, 1993; Miall, 2015). Early studies on the classification of stratal stacking patterns in fluvial systems have proposed a direct link between accommodation and the degree of channel amalgamation. As a result, the terminology of systems tracts made exclusive reference to accommodation conditions (i.e., low- vs high-accommodation systems tracts; e.g., Boyd et al., 2000; Leckie and Boyd, 2003). This approach is now considered as an oversimplification, as accommodation only plays a part in a much more complex interaction of controlling parameters (Miall, 2015). A more descriptive nomenclature, free of the interpretation of the underlying controls, is introduced below.

5.1 High-Amalgamation (Channel-Dominated) Stacking Pattern

The development of a high degree of channel amalgamation in fluvial systems (i.e., high channel-to-overbank ratio; Fig. 14A) is promoted by (1) low rates of floodplain aggradation; (2) unconfined channels; and (3) a high frequency of channel avulsion (Fig. 13; Bristow and Best, 1993). This fluvial architecture of amalgamated channels was previously referred to as a "low-accommodation" stacking pattern.

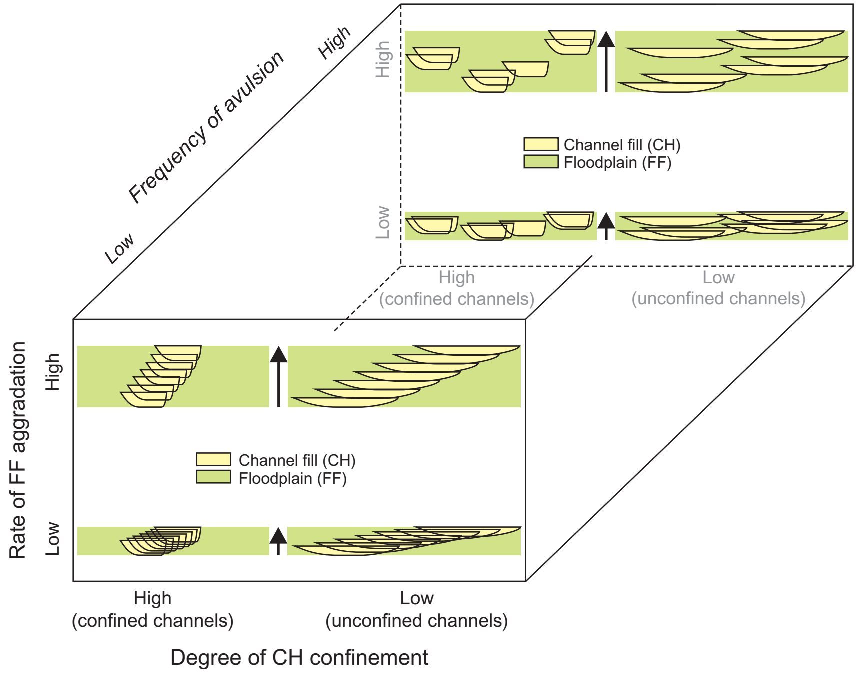

Fig. 13 Fluvial architecture under variable conditions of floodplain aggradation, channel confinement, and avulsion frequency, as illustrated by the seven-step evolution of a channel. The rates of fluvial aggradation depend on all factors which control sedimentation, including accommodation, climate, source-area tectonism, and autocyclic changes in sediment distribution. The degree of channel amalgamation is proportional to the rate of lateral channel migration (higher in unconfined rivers) and the frequency of avulsion, and inversely proportional to the rate of aggradation. *Modified from Bristow, C.S., Best, J.L., 1993. Braided rivers: perspectives and problems. In: Best, J.L., Bristow, C.S. (Eds.), Braided Rivers. Geological Society Special Publication No. 75, pp. 1–11.*

5.2 Low-Amalgamation (Floodplain-Dominated) Stacking Pattern

The development of a low degree of channel amalgamation in fluvial systems (i.e., low channel-to-overbank ratio; Fig. 14B) is promoted by (1) high rates of floodplain aggradation; (2) confined channels; and (3) a low frequency of channel avulsion (Fig. 13; Bristow and Best, 1993). This fluvial architecture, defined by isolated channels within floodplain deposits, was previously referred to as a "high-accommodation" stacking pattern.

Both types of upstream-controlled fluvial stacking patterns can be observed at different scales, in relation to stratigraphic cycles of different magnitudes (Fig. 15). The ratio between the high- and low-amalgamation

Fig. 14 Fluvial stacking patterns in an upstream-controlled setting (Triassic, Karoo Basin). (A) Channel-dominated succession: high-amalgamation stacking pattern (Molteno Formation: higher energy, coarser grained braided channels); (B) floodplain-dominated succession: low-amalgamation stacking pattern (Burgersdorp Formation: lower energy, finer grained meandering river system). The *arrows* mark the position of the subaerial unconformity that separates the two stacking patterns.

stacking patterns within lower rank sequences defines the type of higher rank (high- vs low-amalgamation) systems tract (e.g., a set of fourth-order sequences dominated by a high degree of channel amalgamation defines a third-order "high-amalgamation" systems tract; a set of fourth-order sequences dominated by floodplain deposits with isolated channels defines a third-order "low-amalgamation" systems tract; Fig. 15).

6. TYPES OF SEQUENCE STRATIGRAPHIC UNIT

Sequence stratigraphic units are defined by stratal stacking patterns and specific bounding surfaces, and not by their inferred origin, age, time span, or physical scales. The geographic extent of any type of sequence stratigraphic unit is highly variable, and determined by the development of its diagnostic stratal stacking patterns and bounding surfaces, which is a function of tectonic and depositional settings. All types of sequence stratigraphic unit consist of strata that are "genetically related"; i.e., strata that belong to the same cycle of accommodation or sediment supply (Catuneanu et al., 2009). Genetically related successions may be defined at different scales of observation (i.e., hierarchical ranks), in relation to stratigraphic cycles of different magnitudes. Therefore, there are no standards for the scale of any type of sequence stratigraphic unit.

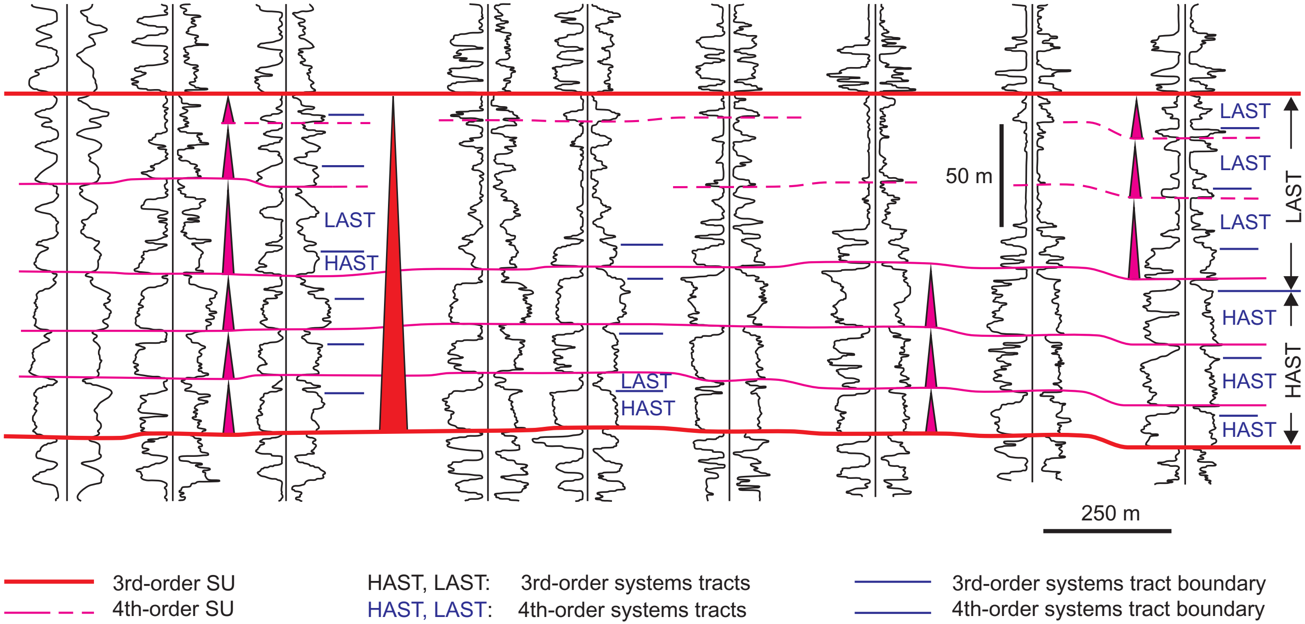

Fig. 15 Stratigraphic architecture of a fluvial succession in an upstream-controlled setting (Upper Cretaceous, Golfo San Jorge Basin). Well logs: spontaneous potential (*left*) and resistivity (*right*). The stratigraphic correlation is calibrated with production pressure data. The third-order sequence consists of nested fourth-order sequences. At each scale of observation (i.e., hierarchical level), depositional sequences display fining-upward trends (decline in fluvial energy with time) and can be subdivided into systems tracts based on the dominant fluvial stacking patterns (channel- vs floodplain-dominated successions). The ratio between the high- and low-amalgamation stacking patterns within the lower rank sequences defines the type of higher rank (high- vs low-amalgamation) systems tract. Abbreviations: *HAST*, high-amalgamation systems tract; *LAST*, low-amalgamation systems tract; *SU*, subaerial unconformity. *Data courtesy of YPF Argentina.*

The fundamental unit of sequence stratigraphy is the stratigraphic sequence. Sequences consist of component systems tracts, and systems tracts consist of depositional systems that accumulate during the development of particular stratal stacking patterns. This stratigraphic architecture can be observed at different scales, depending on the purpose of the study and the resolution of the data available. At the smallest stratigraphic scales, depositional systems consist of beds and bedsets (i.e., sedimentological cycles; Catuneanu and Zecchin, 2013). At any larger scales, systems tracts and depositional systems consist of higher frequency sequences (Figs. 15 and 16).

The scale-independent nature of sequences and systems tracts is consistent with the fact that depositional systems can also be observed at different scales (Fig. 16). The seismic stratigraphy of the 1970s imposed, by default, a minimum scale to the concepts of sequence, systems tract, and depositional system, which had to exceed the vertical seismic resolution. In reality, all these types of unit can also be defined and observed at subseismic scales

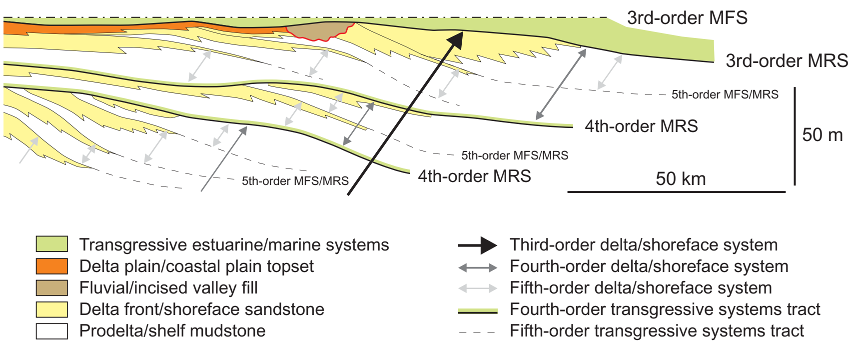

Fig. 16 Stratigraphic architecture of a prograding system in a downstream-controlled setting (Upper Cretaceous Dunvegan Formation, Western Canada Sedimentary Basin). Sequences, systems tracts, and depositional systems can be defined at different scales of observation (i.e., hierarchical levels). In this example, the third-order "delta" includes several different depositional systems that can be defined at the fourth- and fifth-order scales of observation. At all hierarchical levels, depositional systems have paleogeographic significance and correspond to specific environments of deposition. Abbreviations: *MFS*, maximum flooding surface; *MRS*, maximum regressive surface, potentially reworked in part by the transgressive surface of erosion. *Modified from Bhattacharya, J.P., 1993. The expression and interpretation of marine flooding surfaces and erosional surfaces in core; examples from the Upper Cretaceous Dunvegan Formation in the Alberta foreland basin. In: Summerhayes, C.P., Posamentier, H.W. (Eds.), Sequence Stratigraphy and Facies Associations. International Association of Sedimentologists Special Publication No. 18, pp. 125–160.*

in higher resolution studies (i.e., high-resolution sequence stratigraphy; e.g., Zecchin and Catuneanu, 2013).

Depositional systems form when the defining subenvironments and related geomorphic elements are established as dominant (but not necessarily exclusive) sediment fairways. For example, a "delta" observed at a seismic scale is defined by the dominant pattern of sediment progradation, even though, on shorter timescales, this dominant pattern is interrupted by stages of transgression (e.g., flooding of delta plain and the formation of estuaries) of lower hierarchical ranks (Fig. 16). Therefore, the dominance of a particular sediment dispersal pattern can be observed at different scales, depending on the resolution of the stratigraphic study (Fig. 16). Indeed, the definition of sequences, systems tracts, and depositional systems makes no reference to temporal or physical scales. All these types of unit are assumed to be "relatively conformable," but this conformable character is only relative to the resolution of the data available. In reality, unconformities exist at all scales, both below and above the resolution of the data available.

Despite the scale-independent and nested nature of sequence stratigraphic units, the stratigraphic architecture is not necessarily and truly "fractal," because sequences of different scales may have different controls and internal makeup (e.g., different combinations and/or relative development of component systems tracts).

6.1 Stratigraphic Sequence

A stratigraphic sequence corresponds to a cycle of change in stratal stacking patterns, defined by the recurrence of the same type of sequence stratigraphic surface in the rock record (Catuneanu and Zecchin, 2013; Catuneanu et al., 2011). A stratigraphic sequence is bounded at the base and at the top by the same type of sequence stratigraphic surface; e.g., from a maximum flooding surface to the next maximum flooding surface in the stratigraphic succession, on condition that the strata between the sequence boundaries belong to one cycle of change in accommodation or sediment supply at the selected scale of observation (Catuneanu et al., 2009).

Stratigraphic cycles may be symmetrical or asymmetrical, and the corresponding sequences may include a variable number of *distinct* systems tracts (i.e., a systems tract cannot be repeated within a sequence), up to four in the case of ideal "conventional" sequences that develop and preserve all systems tracts. Therefore, a sequence is not defined by its internal makeup, but by the recurrence of the sequence stratigraphic surface that marks its boundaries. Not all types of stratal stacking patterns (i.e., systems tracts) and bounding sequence stratigraphic surfaces may occur in the succession under analysis. For example, stratigraphic cyclicity may be defined by the repetition of transgressions and highstand normal regressions, without intervening stages of forced regression and lowstand normal regression; or, by the repetition of forced regressions and lowstand normal regressions, without intervening stages of transgression and highstand normal regression. Therefore, the types of recurring stacking patterns and bounding surfaces that define stratigraphic cyclicity may vary with the case study, which underlines the need for a model-independent approach to the sequence stratigraphic analysis.

The definition of a "sequence" was gradually revised from the 1940s to the present day, in response to the need for (1) an increase in the resolution of stratigraphic studies and (2) a more inclusive definition that accommodates all existing sequence stratigraphic approaches (Fig. 3). The current definition provides the flexibility to apply the sequence stratigraphic methodology in a manner that is independent of model, and at any scale afforded by the data available.

Different kinds of stratigraphic sequence may be defined as a function of the specific type of recurring sequence stratigraphic surface that is selected as the boundary of the cycle of change in stratal stacking pattern (Figs. 1 and 2).

6.1.1 Depositional Sequence

The depositional sequence is a stratigraphic sequence bounded by subaerial unconformities or their correlative conformities (Mitchum, 1977). Different types of "depositional sequence" have been defined (Fig. 1), which fall into two groups, as a function of the timing of the marine portion of the sequence boundary (i.e., the "correlative conformity"; Fig. 2): one group considers the correlative conformity as the paleo-seafloor at the onset of forced regression (i.e., the correlative conformity sensu Posamentier et al., 1988; herein referred to as the "basal surface of forced regression"); and another group considers the correlative conformity as the paleo-seafloor at the end of forced regression (i.e., the correlative conformity sensu Van Wagoner et al., 1988; herein referred to as the "correlative conformity").

All types of "depositional sequence," as originally defined, assume full cycles of change in accommodation and relate the sequence boundary to stages of negative accommodation. As a note of caution, however, subaerial unconformities may also form during stages of relative sea/lake-level rise and transgression (Fig. 10). Therefore, the interpretation of the underlying controls responsible for the formation of depositional sequences needs to be separated from the observation of stratal stacking patterns and be performed on a case-by-case basis (Catuneanu and Zecchin, 2016). The concept of depositional sequence applies to both downstream- and upstream-controlled settings, where subaerial unconformities may form.

6.1.2 Genetic Stratigraphic Sequence

The genetic stratigraphic sequence is a stratigraphic sequence bounded by maximum flooding surfaces (Galloway, 1989). As maximum flooding surfaces form during stages of positive accommodation, the formation of genetic stratigraphic sequences does not require stages of negative accommodation. At any scale of observation, a genetic stratigraphic sequence corresponds to a regressive–transgressive cycle, which may occur during a full cycle of change in accommodation or during a stage of positive accommodation. In the latter case, the genetic stratigraphic sequence does not include falling-stage and lowstand systems tracts, nor any sequence stratigraphic surfaces that are exclusively associated with forced regression (i.e., the basal surface of forced regression and the regressive surface of marine erosion).

The genetic stratigraphic sequence approach does not rely on the development and recognition of subaerial unconformities and correlative conformities. Instead, the physical record of transgression provides "readily recognized regionally correlative, easily and accurately datable, and robust sequence boundaries" (Galloway, 1989). The concept of genetic stratigraphic sequence applies to downstream-controlled settings, where maximum flooding surfaces may form.

6.1.3 Transgressive–Regressive Sequence

The transgressive–regressive (T–R) sequence is a stratigraphic sequence bounded by maximum regressive surfaces (Johnson and Murphy, 1984). In its original definition, the formation of T–R sequences does not require stages of negative accommodation. As maximum regressive surfaces of any hierarchical rank may form during stages of positive accommodation, the T–R sequences may be generated either during full cycles of positive–negative accommodation or during periods of positive accommodation.

A proposal to modify the definition of the T–R sequence was made to include the subaerial unconformity as the continental portion of the sequence boundary (Embry and Johannessen, 1992). However, as the maximum regressive surface is most commonly younger than the subaerial unconformity, the marine portion of the maximum regressive surface may not meet with the basinward termination of the subaerial unconformity (Embry and Johannessen, 1992). Therefore, the original definition of Johnson and Murphy (1984) is still recommended. The concept of T–R sequence applies to downstream-controlled settings, where maximum regressive surfaces may form.

6.2 Systems Tract

A systems tract is a linkage of contemporaneous depositional systems, forming the subdivision of a sequence (Brown and Fisher, 1977). Systems tracts are interpreted on the basis of stratal stacking patterns, stratigraphic relations, and types of bounding surfaces. The definition of a systems tract is independent of physical and temporal scales; systems tracts can be observed at different scales, depending on the resolution of the data available. The internal architecture of a systems tract may vary greatly from a succession of facies (beds and bedsets: sedimentological cycles within the lowest rank depositional systems) to a set of higher frequency sequences of lower hierarchical rank (Figs. 15 and 16). Systems tracts may be shoreline related, in downstream-controlled settings, or shoreline independent, in upstream-controlled settings (Fig. 5).

In downstream-controlled settings, systems tracts form in relation to specific types of shoreline trajectory (Fig. 6) and build a stratigraphic framework that may include the entire array of sequence stratigraphic surfaces and depositional systems (Fig. 11). At any scale of observation (i.e., hierarchical level), sequences may consist of different combinations of systems tracts, depending on the local conditions of accommodation and sedimentation at the time of deposition (Csato and Catuneanu, 2012). As such, systems tract successions are basin specific and may not conform with the predictions of idealized models. For this reason, the construction of the sequence stratigraphic framework needs to be performed on a case-by-case basis, with the emphasis on local data rather than model assumptions.

6.2.1 Falling-Stage Systems Tract

The falling-stage systems tract is defined by a forced regressive stratal stacking pattern (Figs. 6–8). Where the subaerial unconformity forms during forced regression, the falling-stage systems tract is bounded at the base by a marine basal surface of forced regression (i.e., the paleo-seafloor at the onset of forced regression), and at the top by the subaerial unconformity and the correlative conformity (Fig. 11A). In this case, with the exception of fluvial sediments that accumulate by processes of lateral accretion, the falling-stage systems tract consists solely of marine deposits.

Less commonly, forced regression may be accompanied by fluvial aggradation (Fig. 11B). In this case, the falling-stage systems tract is bounded at the base by a basal surface of forced regression with both continental and marine portions, and at the top by a conformity that marks the change in stacking pattern to the overlying lowstand systems tract (Fig. 11B; see Catuneanu and Zecchin, 2016 for a discussion of the field criteria that afford the distinction between a normal regression and an atypical forced regression with fluvial aggradation). The conformity at the top of the falling-stage systems tract may be reworked in part by erosional processes associated with subsequent transgression. In this case, the systems tract boundary becomes a composite surface whose precise nature at any location needs to be determined on a case-by-case basis. Where two or more sequence stratigraphic surfaces are superimposed, due to nondeposition or erosion, the name of the younger surface, which leaves the last imprint on the preserved contact, is typically used (Catuneanu, 2006).

6.2.2 Lowstand Systems Tract

The lowstand systems tract is defined by a normal regressive stacking pattern (Figs. 6–8) which follows a forced regression of the same hierarchical rank (Figs. 8 and 11). The lowstand systems tract is bounded at the base by the subaerial unconformity and/or the correlative conformity (Fig. 11). Where the lowstand systems tract is followed by transgression, the upper boundary is represented by the maximum regressive surface reworked in part by the transgressive surface of erosion (transgression accompanied by fluvial aggradation; Fig. 11A), or by a composite surface which includes the marine portion of the maximum regressive surface, the transgressive surface of erosion, and the subaerial unconformity (transgression accompanied by fluvial erosion; Fig. 11B). Where the lowstand systems tract is followed by forced regression, the upper boundary is represented by the subaerial unconformity and/or the basal surface of forced regression. Lowstand systems tracts typically include a continental topset and a marine foreset and bottomset, and tend to display a concave-up shoreline trajectory (Fig. 9).

6.2.3 Transgressive Systems Tract

The transgressive systems tract is defined by a retrogradational stratal stacking pattern (Figs. 6–8). The transgressive systems tract is bounded at the base by the maximum regressive surface reworked in part by the transgressive surface of erosion, and at the top by the maximum flooding surface (Fig. 11). Where transgression is accompanied by fluvial aggradation, the fluvial portion of the transgressive systems tract may also rest directly on top of the subaerial unconformity, beyond the updip termination of the lowstand topset (Fig. 11A). Most commonly, transgressive systems tracts record the highest rates of fluvial aggradation, as accommodation is generated rapidly during transgression, which leads to the lowest rates of siliciclastic sediment supply to the marine environment. This results in the sediment starvation of the seafloor and the formation of marine condensed sections (Loutit et al., 1988).

6.2.4 Highstand Systems Tract

The highstand systems tract is defined by a normal regressive stacking pattern (Figs. 6–8) which follows a transgression of the same hierarchical rank (Figs. 8 and 11). The highstand systems tract is bounded at the base by a maximum flooding surface with both continental and marine portions (transgression accompanied by fluvial aggradation; Fig. 11A), or by a marine maximum flooding surface and a subaerial unconformity (transgression accompanied by fluvial erosion; Fig. 11B). Where the highstand systems tract is followed by forced regression, the upper boundary is represented by the subaerial unconformity and/or the basal surface of forced regression (Fig. 11). Where the highstand systems tract is followed by transgression, the upper boundary is represented by the maximum regressive surface reworked in part by the transgressive surface of erosion (transgression accompanied by fluvial aggradation), or by a composite surface which includes the marine portion of the maximum regressive surface, the transgressive surface of erosion, and the subaerial unconformity (transgression accompanied by fluvial erosion). Highstand systems tracts typically include a continental topset and a marine foreset and bottomset, and tend to display a convex-up shoreline trajectory (Fig. 9).

In upstream-controlled settings, systems tracts form independently of relative sea/lake-level changes and shoreline shifts (Fig. 5), and reflect the combined influence of accommodation, climate, source-area uplift, and autocyclicity on depositional processes. Upstream-controlled systems tracts may also be observed at different scales (Fig. 15) and are interpreted on the basis of stratal stacking patterns defined by the dominant depositional elements. In fluvial settings, the upstream-controlled stacking patterns are defined by the high vs low channel-to-overbank ratio (Figs. 12–15).

6.2.5 High-Amalgamation Systems Tract

The high-amalgamation systems tract (formerly termed "low-accommodation" systems tract) is defined by a stacking pattern dominated by a high degree of channel amalgamation (i.e., high channel-to-overbank ratio; Figs. 14A and 15). The formation of high-amalgamation systems tracts is favored by (1) low rates of floodplain aggradation; (2) unconfined fluvial channels; and (3) a high frequency of channel avulsion (Fig. 13; Bristow and Best, 1993).

6.2.6 Low-Amalgamation Systems Tract

The low-amalgamation systems tract (formerly termed "high-accommodation" systems tract) is defined by a stacking pattern dominated by floodplain deposits, within which channels occur as isolated depositional elements (i.e., low channel-to-overbank ratio; Figs. 14B and 15). The formation of low-amalgamation systems tracts is favored by (1) high rates of floodplain aggradation; (2) confined fluvial channels; and (3) a low frequency of channel avulsion (Fig. 13; Bristow and Best, 1993).

Notably, accommodation generated by basin subsidence is, in many if not most cases, already overfilled during the development of upstream-controlled depositional sequences and component systems tracts. While accommodation (i.e., rates of subsidence) may still play an important role, fluvial processes, including the rates of floodplain aggradation, are also influenced by all other controls that modify the balance between sediment supply and energy flux at any location (i.e., climate, source-area uplift, and autocyclicity). In a long term, the rates of fluvial aggradation exceed the rates of subsidence, leading eventually to entirely overfilled basins (Fig. 4D).

The high- and low-amalgamation systems tracts were designated as "low-accommodation" and "high-accommodation" systems tracts, respectively, based on the assumption that accommodation is the main control on the degree of channel amalgamation (e.g., Boyd et al., 2000; Leckie and Boyd, 2003). However, it is becoming apparent that accommodation alone cannot always explain the development of fluvial stacking patterns, particularly where the rates of accumulation of depositional elements do not match the rates of creation of accommodation (Miall, 2015). Therefore, the revised systems tract terminology emphasizes the observation of stratal stacking patterns rather than the interpretation of the underlying controls.

6.3 Parasequence

The parasequence is a succession of genetically related beds or bedsets bounded by flooding surfaces (Van Wagoner et al., 1988, 1990). A flooding surface is a facies contact that marks an abrupt increase in water depth and, consequently, an abrupt shift to relatively more distal facies on top. The concept of parasequence applies to coastal and shallow-water settings, where flooding surfaces may form (Posamentier and Allen, 1999). Several issues with the parasequence concept led to the conclusion that other types of unit (i.e., bedsets in the case of sedimentological cycles, and high-frequency sequences in the case of stratigraphic cycles; discussion below) provide better alternatives to define sedimentary cyclicity at parasequence scales (Catuneanu, 2006; Posamentier and Allen, 1999; Zecchin and Catuneanu, 2013).

Historically, the parasequence was introduced as the building block of seismic-scale systems tracts in the low-resolution era of seismic stratigraphy. The concept of parasequence triggered confusion and controversy in sequence stratigraphy, due to its traits that are unlike the features of a sequence stratigraphic unit, including (1) restricted applicability to coastal and shallow-water settings, and (2) the allostratigraphic rather than sequence stratigraphic nature of its bounding surfaces. Another issue is the potential confusion of flooding surfaces with similar-looking facies contacts generated by processes unrelated to water-depth changes, such as the abandonment of deltaic lobes in the process of autocyclic delta-lobe switching.

Parasequence boundaries form during transgression, when "flooding" occurs. These abrupt water-deepening episodes are typically short-lived "events" that punctuate longer term trends of coastal progradation or retrogradation. The result is stepped progradation, marked by a set of forestepping parasequences (e.g., Amorosi et al., 2005, 2017), or stepped retrogradation, marked by a set of backstepping parasequences (e.g., Bruno et al., 2017).

In the case of stepped progradation, the regressive trend is interrupted by higher frequency transgressions that lead to short-term changes in coastal depositional environments during the formation of flooding surfaces (e.g., short-term estuaries that interrupt temporarily the longer term deltaic progradation; Fig. 16). The architecture of stepped progradation is commonly defined by asymmetrical forestepping parasequences, dominated by regressive deposits. Each high-frequency transgression *may* be accompanied by the formation of a flooding surface (if the diagnostic lithological discontinuity develops), but it always ends with a maximum flooding surface. For this reason, genetic stratigraphic sequences of the same hierarchical rank with parasequences provide a more reliable alternative for correlation, both within and beyond the confines of coastal and shallow-water systems (Catuneanu et al., 2009, 2011). The stepped progradation of the Po coastal plain during the Middle to Late Holocene (Amorosi et al., 2005, 2017) documents forestepping parasequences of 10^0 m and 1000 years scales, which indicate regressive–transgressive cycles, and therefore changes in coastal depositional systems, on millennial and submillennial (i.e., centennial or even smaller) timescales. In this case, sequences, systems tracts and depositional systems can also be defined at parasequence scale.

In the case of stepped retrogradation, the transgressive trend proceeds with variable rates, higher during the formation of flooding surfaces and lower during the intervening stages. The episodes of abrupt water deepening may result in the formation of several flooding surfaces during transgression, which can be used to subdivide the transgressive systems tract into parasequences (e.g., Bruno et al., 2017). In this case, there is no change in coastal depositional environments during transgression, but only episodic shifts of subenvironments in an updip direction (e.g., stepwise retreat of bayhead deltas within wave-dominated estuaries). The architecture of such stepped retrogradation is defined by backstepping parasequences dominated (or exclusively built) by transgressive deposits. The stepped retrogradation of the Po coastal plain during the Early Holocene (Bruno et al., 2017) provides an example of backstepping parasequences of 10^0 m and 1000 years scales within a millennial-scale transgressive systems tract. Without changes in coastal depositional environments during transgression, this systems tract cannot be subdivided into lower rank sequences. In this case, parasequences are bedsets within the lowest rank transgressive systems tract and component depositional systems.

The distinction between parasequences and sequences is not based on scale or internal architecture, but on the nature of their bounding surfaces. Both types of unit may include normal regressive, transgressive, and forced regressive deposits (Catuneanu et al., 2011). Furthermore, parasequences and sequences may form at overlapping scales (Catuneanu et al., 2011; Csato et al., 2014; Fielding et al., 2008; Strasser et al., 1999; Tucker et al., 2009), in which case they offer different alternatives for correlation and the definition of stratigraphic units. A stratigraphic framework of parasequences requires lithological discontinuities (i.e., flooding surfaces), whereas a stratigraphic framework of sequences relies on sequence stratigraphic surfaces which are independent of lithology (e.g., maximum flooding surfaces). Where stratigraphic cycles include both flooding surfaces and sequence stratigraphic surfaces of equal hierarchical rank (i.e., sequences developed at parasequence scales; the case of stepped progradation above), the use of high-frequency sequences is recommended (Zecchin and Catuneanu, 2013).

Flooding surfaces do not mark a change in stratal stacking pattern, unless they happen to coincide with a sequence stratigraphic surface (e.g., maximum regressive surface, transgressive surface of erosion, or maximum flooding surface). Where flooding surfaces are within-trend facies contacts (i.e., retrogradational stacking pattern below and above the contact), they do not carry the significance of a sequence stratigraphic surface. In such cases, parasequences and flooding surfaces are more appropriate for allostratigraphic rather than sequence stratigraphic studies, even though they may provide useful subdivisions for the lowest rank transgressive systems tracts that form during stepped retrogradation (e.g., Bruno et al., 2017). For all other types of conventional systems tracts, which involve shoreline regression, high-frequency genetic stratigraphic sequences that form at the scale of parasequences provide a better alternative for stratigraphic mapping and correlation. The fact that flooding surfaces do not require a change in stratal stacking pattern to form (i.e., they may or may not coincide with systems tract boundaries) is the reason why they are not included on the list of sequence stratigraphic surfaces.

7. SEQUENCE STRATIGRAPHIC SURFACES

A sequence stratigraphic surface is a type of stratigraphic contact that serves, at least in part, as a systems tract boundary (Catuneanu et al., 2011). As systems tract boundaries, sequence stratigraphic surfaces mark changes in stratal stacking pattern between the units below and above the contact (Fig. 11). This defining attribute separates a sequence stratigraphic surface from any other type of stratigraphic contact. Seven sequence stratigraphic surfaces have been defined.

7.1 Subaerial Unconformity

The subaerial unconformity (Sloss et al., 1949) is an unconformity that forms under subaerial conditions as a result of fluvial erosion or bypass, pedogenesis, wind degradation, or karstification. Subaerial unconformities may form in both downstream- and upstream-controlled settings, most commonly during periods of negative accommodation (Catuneanu et al., 2011; Fig. 11A).

Under particular circumstances (e.g., where the landscape gradient is steeper than the gradient of the shoreline trajectory), the subaerial unconformity may also form during periods of positive accommodation and transgression (Figs. 10 and 11B). Alternative terms include "lowstand unconformity" (Schlager, 1992) and "regressive surface of fluvial erosion" (Plint and Nummedal, 2000). However, the term "subaerial unconformity" is preferred because it does not link, nor restrict, the formation of this surface to stages of lowstand or regression.

The identification of a "subaerial unconformity" in the rock record requires the preservation of continental deposits (fluvial, eolian) on top. Notably, the facies preserved below a subaerial unconformity may range from continental to marine, and therefore, they are not diagnostic to the identification of this surface. Subaerial unconformities may be subsequently reworked and replaced by younger erosional surfaces, in which case the composite unconformity takes the name of the younger surface (e.g., a transgressive surface of erosion may replace an older subaerial unconformity).

7.2 Basal Surface of Forced Regression

The basal surface of forced regression (Hunt and Tucker, 1992) is a sequence stratigraphic surface that marks a change in stratal stacking pattern from normal regression (below) to forced regression (above). Most commonly, the underlying normal regression is highstand, in the case of sequences that include all systems tracts (Fig. 11), but it can also be lowstand in the case of incomplete sequences which only include falling-stage and lowstand systems tracts. In either case, the basal surface of forced regression marks the onset of forced regression.

Where the subaerial unconformity forms during forced regression (Fig. 11A), the basal surface of forced regression is a marine surface (i.e., the paleo-seafloor at the onset of forced regression) truncated at the top by the subaerial unconformity. Where the subaerial unconformity forms during transgression (Fig. 11B), the basal surface of forced regression includes both marine and continental portions. The basal surface of forced regression is also known as the "correlative conformity" in the sense of Posamentier et al. (1988).

7.3 Correlative Conformity

The correlative conformity (Hunt and Tucker, 1992; Van Wagoner et al., 1988) is a sequence stratigraphic surface that marks a change in stratal stacking pattern from forced regression (below) to lowstand normal regression (above) (Fig. 11). Where the subaerial unconformity forms during forced regression (Fig. 11A), the correlative conformity is a marine surface (i.e., the paleo-seafloor at the end of forced regression) which connects physically with the downdip termination of the subaerial unconformity at the location of the shoreline at the end of forced regression (hence, the name "correlative" conformity; Fig. 11A). This is the context in which the "correlative" conformity has been defined, and which is most common in the stratigraphic record. Where the subaerial unconformity forms during transgression (Fig. 11B), the "correlative conformity" becomes a conformable surface with both marine and continental portions, without a physical and temporal relationship with the subaerial unconformity. In either case, the correlative conformity marks the end of forced regression and the beginning of subsequent lowstand normal regression (Fig. 11); therefore, the criteria that afford the distinction between forced and normal regressive deposits (e.g., Catuneanu and Zecchin, 2016; Posamentier and Morris, 2000) are critical to the identification of this surface.

Both the basal surface of forced regression and the correlative conformity have physical expression that can be observed on various types of data, from seismic to core and outcrop. Field criteria that can be used to identify these surfaces in outcrop and subsurface have been discussed and exemplified in several publications, including Posamentier and Allen (1999), Catuneanu (2006), Catuneanu et al. (2011), and MacEachern et al. (2012).

7.4 Maximum Regressive Surface

The maximum regressive surface (Helland-Hansen and Martinsen, 1996) is a stratigraphic surface that marks the change from regression to subsequent transgression. Most commonly, this change is expressed as a shift in stratal stacking pattern from normal regression (below) to transgression (above) (Fig. 11). The underlying normal regression may be "lowstand," in the case of sequences that include stages of negative accommodation (Fig. 11), or "highstand," in the case of sequences that form during periods of positive accommodation. In the latter case, sequences consist only of transgressive and highstand systems tracts which repeat in the stratigraphic succession without intervening stages of negative accommodation (Csato and Catuneanu, 2012, 2014). Where sequences record both stages of positive and negative accommodation, but the lowstand normal regression is missing, the maximum regressive surface coincides with the correlative conformity at the end of forced regression (e.g., in extensional settings where accommodation is generated rapidly by the reactivation of faults; Martins-Neto and Catuneanu, 2010). Therefore, maximum regressive surfaces may top any type of regressive deposit (i.e., lowstand normal regressive, highstand normal regressive, or forced regressive), and the precise stratigraphic reality of each case study needs to be determined on a case-by-case basis. There are also sequences that may not include surfaces associated with transgression, at the scale of observation that matches the hierarchical rank of the sequence, where the stratigraphic cyclicity is defined by the repetition of falling-stage and lowstand systems tracts (i.e., transgressions suppressed by high sediment supply, at that particular scale of observation).

The maximum regressive surface is the paleo-seafloor at the end of regression, and its correlative surface within the nonmarine setting. At least part of the continental portion of the maximum regressive surface is reworked and replaced by the transgressive surface of erosion during subsequent transgression (Fig. 11). The marine portion of the maximum regressive surface has a better preservation potential, as it is typically onlapped by the transgressive marine "healing-phase" deposits (Posamentier and Allen, 1999).

An alternative term is "transgressive surface" (Posamentier and Vail, 1988). The term "maximum regressive surface" is recommended where emphasis is placed on the end of regression; the term "transgressive surface" is recommended where emphasis is placed on the onset of transgression.

7.5 Maximum Flooding Surface

The maximum flooding surface (Frazier, 1974; Galloway, 1989; Posamentier et al., 1988; Van Wagoner et al., 1988) is a stratigraphic surface that marks a change in stratal stacking pattern from transgression (below) to highstand normal regression (above) (Fig. 11). It is the paleo-seafloor at the end of transgression, and its correlative surface within the nonmarine setting where transgression is accompanied by fluvial aggradation (Fig. 11A). The continental portion of the maximum flooding surface is commonly associated with the highest water table relative to the topographic profile, and therefore, it may be marked by the development of regional coal seams (e.g., Bohacs and Suter, 1997; Fanti and Catuneanu, 2010; Gastaldo et al., 1993; Hamilton and Tadros, 1994; Holz et al., 2002; Shanley and McCabe, 1994; Wright and Marriott, 1993). Within marine sections, the maximum flooding surface is often "cryptic" from a lithological standpoint, at the heart of condensed sections (e.g., Carter et al., 1998; Catuneanu, 2006; Posamentier and

Allen, 1999). However, the identification of maximum flooding surfaces is still possible and aided by the integration of independent methods that may involve seismic data (e.g., observation of downlap reflection terminations on 2D seismic lines and/or paleogeographic reconstructions using 3D seismic horizon slices), well logs calibrated with lithologs (e.g., highest radioactivity in fine-grained sediments), and biostratigraphic data (e.g., highest abundance and diversity of microfossils).

Alternative terms include "final transgressive surface" (Nummedal et al., 1993), "surface of maximum transgression" (Helland-Hansen and Gjelberg, 1994), and "maximum transgressive surface" (Helland-Hansen and Martinsen, 1996). The term "maximum flooding surface" is strongly entrenched in the literature, and it is recommended for historical reasons. It is important to avoid confusion between maximum flooding surfaces and flooding surfaces. The distinction is not a matter of scale (e.g., major vs minor transgressions), but a matter of definition: a maximum flooding surface marks a change in stratal stacking pattern (i.e., it is a sequence stratigraphic surface), and it may or may not be associated with a lithological contrast; a flooding surface is a lithological discontinuity (i.e., an allostratigraphic surface), which may or may not mark a change in stratal stacking pattern. Maximum flooding surfaces and flooding surfaces may form at the same scale of observation, in relation to the same transgressions.

7.6 Transgressive Surface of Erosion

The transgressive surface of erosion (Posamentier and Vail, 1988) is an erosional surface that forms during transgression by means of wave scouring (i.e., "wave-ravinement surface"; Swift, 1975) or tidal scouring (i.e., "tidal-ravinement surface"; Allen and Posamentier, 1993) in coastal to shallow-water environments. Both types of transgressive ravinement surfaces young toward the basin margin (Nummedal and Swift, 1987) and invariably rework part of the maximum regressive surface, thus becoming systems tract boundaries (Catuneanu et al., 2011; Fig. 11). The amount of erosion associated with transgressive ravinement processes is proportional to the energy of waves and tides along the transgressive coastline (i.e., the depth of the wave base and the magnitude of the tidal range). In most cases, an average of 10–20 m of section is removed by ravinement processes during transgression (Abbott, 1998; Demarest and Kraft, 1987). This amount can increase significantly in areas of exceptionally high energy (e.g., 40 m along the Canterbury Plains shoreline in New Zealand; Leckie, 1994).

Diagnostic to the transgressive surface of erosion is the presence of backstepping estuary-mouth complex (in the case of tidal-ravinement surfaces) or shallow-water "healing-phase" (in the case of wave-ravinement surfaces) deposits on top (Catuneanu, 2006; Posamentier and Allen, 1999). The presence of a transgressive lag and/or a concentration of onlapping shell beds immediately above the contact are also common (Kidwell, 1991; Zecchin and Catuneanu, 2013). Notably, the facies preserved below a transgressive surface of erosion may range from continental to marine, and therefore are not diagnostic to the identification of this surface.

7.7 Regressive Surface of Marine Erosion

The regressive surface of marine erosion (Plint, 1988) is an erosional surface that forms during forced regression by means of wave scouring triggered by the lowering of the wave base in the process of relative sea/lake-level fall. The regressive surface of marine erosion youngs basinward and invariably reworks part of the basal surface of forced regression, thus becoming a systems tract boundary (Catuneanu, 2006; Fig. 11). The degree of preservation of the basal surface of forced regression on the shelf depends on the gradient of the forced regressive shoreline trajectory relative to the seafloor gradient. Where the shoreline trajectory is steeper than the seafloor gradient (unlike the situation depicted in Fig. 11), the basal surface of forced regression may be entirely reworked and replaced by the regressive surface of marine erosion within the shelf setting. The amount of scouring that accompanies the formation of the regressive surface of marine erosion is proportional to the magnitude of relative sea/lake-level fall. Alternative terms include "regressive ravinement surface" (Galloway, 2001) and "regressive wave ravinement" (Galloway, 2004).

Diagnostic to the regressive surface of marine erosion is the presence of "sharp-based" prograding shoreface deposits on top (Catuneanu, 2006; Plint, 1988). Below this surface, there is typically an abrupt shift to more distal and finer grained facies (Fig. 11).

8. SCALE IN SEQUENCE STRATIGRAPHY

The development of stratigraphic stacking patterns that define systems tracts in both downstream- and upstream-controlled settings requires, typically, timescales of minimum 10^2–10^3 years (e.g., Amorosi et al., 2005; Bridge and Leeder, 1979; Miall, 2015; Nanson et al., 2013; Nixon et al.,

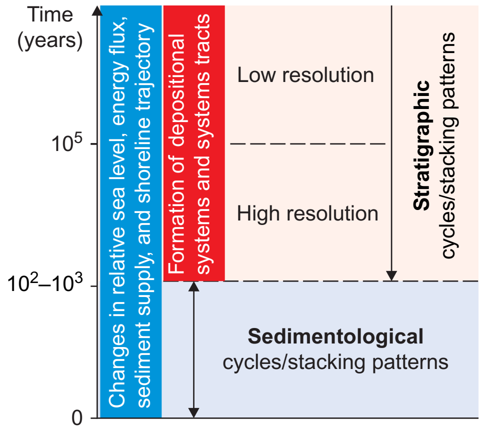

Fig. 17 Timescales of sedimentological vs stratigraphic cycles. Sedimentological cycles (i.e., beds and bedsets) are the building blocks of the lowest rank systems tracts and component depositional systems. In contrast, stratigraphic cycles (i.e., sequences) involve changes in systems tracts and component depositional systems. Both types of sedimentary cycle involve changes in stratal stacking pattern. Sedimentological stacking patterns refer to a stratal architecture that describes the internal organization of a depositional system, without changes in systems tract (e.g., cycles of change in the degree of amalgamation of storm beds; Zecchin et al., 2017b). Stratigraphic stacking patterns refer to a stratal architecture that involves changes in systems tracts and component depositional systems. The minimum timescales required to form a depositional system are commonly within a range of 10^2–10^3 years, as indicated by simulation models and high-resolution studies (e.g., Amorosi et al., 2005; Bridge and Leeder, 1979; Miall, 2015; Nanson et al., 2013; Nixon et al., 2014). Changes in relative sea level, energy flux, sediment supply, and shoreline trajectory occur at all scales, starting with the scale of tidal and fairweather-storm cycles, and may accompany the formation of both sedimentological and stratigraphic cycles. Criteria to discriminate between sedimentological and stratigraphic units and bounding surfaces have been summarized by Zecchin et al. (2017a,b).

2014; Fig. 17). These timescales afford the formation of depositional systems, whereby the defining subenvironments and related geomorphic elements are established as dominant sediment fairways in a paleogeographic context. The minimum scale of depositional systems defines the scale of the lowest rank systems tracts and stratigraphic sequences. Depositional systems can be observed at different scales, depending on the purpose of the study and the resolution of the data available (Fig. 16). Therefore, systems tracts and sequences can also be observed at different scales.

High-frequency sequences (and component systems tracts and depositional systems) are commonly observed at scales of 10^0–10^1 m and 10^2–10^5 years (e.g., Ainsworth et al., 2017; Amorosi et al., 2005; Lobo et al., 2004; Magalhaes et al., 2015; Miall, 2015; Nanson et al., 2013; Nixon et al., 2014; Tesson et al., 1990, 2000; Zecchin et al., 2017a,b), which defines the scope of high-resolution sequence stratigraphy (Fig. 17). The stacking pattern of high-frequency sequences defines systems tracts, and component depositional systems, of higher hierarchical ranks in lower resolution studies (Figs. 15 and 16).

The sequence stratigraphic framework is scale invariant in the sense that the same stratal stacking patterns can be observed at different scales (Schlager, 2004, 2010). However, the stratigraphic architecture is not truly fractal, because sequences of different scales may have different controls and internal makeup in terms of component systems tracts. The internal architecture of sequence stratigraphic units becomes increasingly complex with the increase in the scale of observation. For example, the internal makeup of a systems tract may vary widely from a succession of beds and bedsets (i.e., sedimentological cycles) to a set of higher frequency (lower rank) sequences (i.e., stratigraphic cycles).

The scale of sequence stratigraphic units is highly variable in terms of duration, thickness, and geographic extent. There are no standards for the scale of any type of unit that contributes to the sequence stratigraphic framework, from depositional systems to systems tracts and sequences. In the context of seismic stratigraphy, the "genetically linked" processes that operate within the confines of seismic-scale depositional systems and systems tracts are interrupted by changes in depositional environment and sediment dispersal patterns that occur at smaller scales, some of which may fall below the seismic resolution (Fig. 16). Therefore, with the exception of the smallest stratigraphic scales, whereby depositional systems consist only of sedimentological cycles (e.g., 5th-order scale in Fig. 16), the stacking patterns that define systems tracts reflect *dominant trends* rather than an uninterrupted manifestation of genetically linked processes within stable environments (e.g., 4th- and 3rd-order scales in Fig. 16). Changes in paleogeography and depositional environments are recorded at different scales, with magnitudes that are proportional to their hierarchical rank (Fig. 16). The scale at which changes in the stratigraphic staking pattern can be demonstrated is a function of data resolution, which defines the stratigraphic resolution that can be achieved in any particular case study.

The notion that a sequence is a "relatively conformable" succession (i.e., with negligible internal unconformities; Mitchum, 1977; Fig. 3) cannot be used as a standard for the scale of a sequence, because the "relatively conformable" character itself is *relative* to the scale of observation and/or the resolution of the data available. In seismic stratigraphy, the scale of a sequence exceeds, by default, the vertical seismic resolution, which in turn varies with the seismic data set. Outcrop, core, and well-log data provide better resolution, and afford the recognition of sequences and unconformities at smaller scales. Any change in the type and/or the resolution of the data available results in changes to the scale of what can be perceived as a "relatively conformable" succession, and hence in inconsistencies with respect to the scale of a sequence. For this reason, the definition of a sequence must remain independent of scale and variables that change with the case study (e.g., types and resolution of data available). Sequences may be defined at different scales; at any particular scale (hierarchical rank), sequences may include internal unconformities of equal and/or lower hierarchical ranks. Moreover, depending on the selection of the sequence boundary (Fig. 2), sequences may or may not be "relatively conformable." However, sequences of any hierarchical rank consist of "genetically related" strata in the sense that they belong to the same cycle of accommodation and/or sediment supply (Catuneanu et al., 2009, 2011).

The trend in the development of sequence stratigraphy was to gradually improve the resolution of stratigraphic studies, by applying the method to increasingly smaller scales of observation. This implies refinements to the definition of a sequence and the recognition of sequences at smaller scales. Following this trend, the resolution of sequence stratigraphy improved from 10^2–10^3 m in the 1940s–1960s (i.e., scales relevant to continent-wide correlations; Sloss, 1963; Sloss et al., 1949), to 10^1–10^2 m in the 1970s (i.e., scales relevant to petroleum exploration in seismic stratigraphy; Payton, 1977), and eventually to 10^0–10^1 m with the advent of high-resolution sequence stratigraphy (i.e., scales relevant to reservoir compartmentalization and petroleum production development; e.g., Magalhaes et al., 2015; Zecchin and Catuneanu, 2015; Fig. 3). A resolution below 10^0 m is also possible, especially in carbonate systems which are more sensitive to small changes in environmental conditions (e.g., Mawson and Tucker, 2009).

With the increase in stratigraphic resolution, which is now approaching the scale of sedimentology, it becomes important to define criteria to separate between sedimentological and stratigraphic units which may form at similar scales (e.g., Zecchin et al., 2017a,b). The development of both types of unit may involve an interplay of allogenic and autogenic controls, and may be accompanied by changes in accommodation, energy flux, sediment supply, and shoreline trajectory (Fig. 17). The difference between the two types of sedimentary cycle is that the depositional environment does not change during the formation of sedimentological units (i.e., beds and bedsets within the lowest rank depositional systems), whereas stratigraphic sequences involve changes in depositional systems and systems tracts, which can be observed at different scales (Figs. 16 and 17). At any scale of observation, sequences can be subdivided into systems tracts and component depositional systems which describe the dominant architectural and depositional trends at that particular hierarchical level.

9. SEQUENCE STRATIGRAPHIC HIERARCHY

Stratigraphic cyclicity within a sedimentary succession can be observed at different scales. The classification of sequence stratigraphic units and bounding surfaces based on their relative scale and stratigraphic significance defines the concept of sequence stratigraphic hierarchy. Several sequence stratigraphic hierarchy systems have been proposed since the 1970s, based on criteria that highlight different attributes of sequences, including their temporal scales, their physical scales, or their "relatively conformable" nature. None of these hierarchy systems has received universal acceptance or validation by data in all depositional or tectonic settings.

One group of models asserts that hierarchical orders provide an adequate solution to the classification of sequences of different scales (i.e., sequences of first-order, second-order, third-order, fourth-order, etc.; Embry, 1995; Posamentier and Allen, 1999; Vail et al., 1977, 1991), although the criteria for the definition of different orders of cyclicity are subject to debate (e.g., temporal vs physical criteria). An alternative approach is to use a different nomenclature for units that develop at different scales, starting with the "relatively conformable" sequence as a reference for the hierarchy system (e.g., sequences, sequence sets, composite sequence sets; Mitchum and Van Wagoner, 1991; Sprague et al., 2003; Van Wagoner et al., 1990).

Statistical surveys show that sequences which can be observed in sedimentary basins worldwide are not organized into discrete classes of temporal or physical scales, but are rather part of a stratigraphic continuum (Carter et al., 1991; Drummond and Wilkinson, 1996). This variability of stratigraphic sequences in terms of time spans and physical dimensions is the result of the complex interplay of multiple local and global controls on accommodation and sedimentation. Indeed, the interplay of various processes within a sedimentary basin can alter or override the orderly patterns that may be expected from the natural periodicities of any specific controls on accommodation or sedimentation. Therefore, the classification of stratigraphic sequences based on their temporal or physical scales becomes arbitrary and difficult to generalize for all depositional and tectonic settings.

Attempts to define hierarchical ranks on the basis of the internal characteristics of stratigraphic cycles have also met with shortcomings and criticism. The notion that a sequence is a "relatively conformable" unit (Mitchum, 1977) fails to provide an objective standard for the scale of a sequence, as "relatively conformable" successions can be observed at different scales, depending on the resolution of the data available. Therefore, a "relatively conformable" sequence does not provide an objective reference for the construction of a hierarchy system that promotes a scale-dependent nomenclature. The definition of hierarchical ranks based on the systems tract composition of stratigraphic cycles (e.g., including or excluding lowstand systems tracts; Duval et al., 1998) is also unrealistic, because the systems tract architecture of sequences is independent of scale. For example, sequences of different scales may consist of the same combinations of systems tracts, and sequences of similar scales may consist of different combinations of systems tracts, depending on the *syn*-depositional conditions of accommodation and sedimentation (Catuneanu et al., 2011; Csato and Catuneanu, 2012, 2014).

The hierarchy systems which predict orderly patterns in the stratigraphic record are underlain by the assumption that "sequences" (i.e., the classic third-order cycles of seismic stratigraphy, which include lowstand systems tracts) are defined by full cycles of accommodation, whereas any lower rank cycles form during periods of positive accommodation, therefore missing the lowstand systems tracts (Duval et al., 1998). In reality, accommodation cycles are recorded at all scales, starting from the scale of tidal cycles, and exposure surfaces are as common as flooding surfaces in the rock record (Schlager, 2010; Vail et al., 1991). The scale of the smallest accommodation cycles that can be recognized in a particular case study remains a matter of resolution of the data available. Therefore, the classification of stratigraphic cycles based on their internal makeup is also artificial and cannot be generalized as a reproducible hierarchy system.

Stratigraphic cyclicity is basin specific, reflecting the importance of local controls on accommodation and sedimentation. The stratigraphic frameworks of individual basins reflect the unique evolution of those basins, and may differ from the stratigraphic frameworks of other sedimentary basins in terms of timing and duration of cycles, as well as the geometry of sequences and their controlling mechanisms. Moreover, stratigraphic frameworks may also differ between subbasins of the same sedimentary basin, as a result of changing accommodation and sedimentation conditions across sub-basin boundaries (e.g., Catuneanu et al., 1999, 2002; Miall et al., 2008).

The natural variability of the stratigraphic record indicates that the classification of sequences and bounding surfaces (i.e., the definition of a hierarchy system) is best approached on a basin-specific basis, rather than using any global standards or reference cycle charts. The stratigraphic reality of each sedimentary basin needs to be described on the basis of local data rather than information extrapolated from other basins. Within the context of each sedimentary basin, the relative stratigraphic significance of sequences and bounding surfaces may be measured by the degree of facies shifts associated with their formation, irrespective of the interpreted origin of their controlling mechanisms. In downstream-controlled settings, facies shifts reflect the magnitude of the associated shoreline shifts. In upstream-controlled settings, the magnitude of facies shifts is measured by the degree of change in depositional system (e.g., changes in fluvial style) or dominant depositional elements.

Hierarchical orders may be assigned within the context of each sedimentary basin, starting with the basin fill as a reference. A first-order sequence is defined as the entire sedimentary basin fill that accumulated within a specific tectonic setting (i.e., with accommodation controlled by a related set of subsidence mechanisms). In the case of "polyphase" basins, first-order sequence boundaries mark changes in the tectonic setting, which are the most significant changes that can be observed within a sedimentary succession. First-order sequences can be subdivided into lower rank sequences whose hierarchical orders are defined by the relative magnitude of facies shifts that are associated with their formation. In this approach, sequences of different hierarchical orders have no time or thickness connotations, but only a relative stratigraphic significance in relation to each other.

The possibility that stratigraphic frameworks may correlate from one basin to another in response to global controls on accommodation may not excluded, particularly in the case of tectonically "passive" settings and/or icehouse periods, but also, it cannot be generalized. The importance of local controls on accommodation, particularly in the case of tectonically active basins, cannot be underestimated and should be considered as a safe norm. For this reason, hierarchical orders are only meaningful within the context of the sedimentary basin in which they are defined, and their meaning may change from one basin to another. For example, "third-order" sequences may occur in any sedimentary basin, but they will differ from one basin to another in terms of duration, thickness, geographic extent, and controlling mechanisms. The "third-order" connotation is only meaningful with the context of the sedimentary basin in which it was defined, *relative* to the lower and higher rank cycles that occur within the same basin.

10. DISCUSSION AND CONCLUSIONS: METHODOLOGY AND NOMENCLATURE

The sequence stratigraphic framework consists of sequences and component systems tracts, which may be observed at different scales. Systems tracts may be further subdivided into sequence stratigraphic cycles (higher frequency sequences), allostratigraphic cycles (parasequences), or sedimentological cycles (beds and bedsets). The scope of the sequence stratigraphic methodology is to identify the different types of sequence stratigraphic units and bounding surfaces that develop at different scales, based on the observation of stratal stacking patterns. The existence of several competing approaches (Figs. 1 and 2) hindered, for decades, the definition of a standard methodology and the inclusion of sequence stratigraphy in international stratigraphic codes. These competing approaches differ in terms of nomenclature of sequence stratigraphic units and bounding surfaces (Figs. 1 and 2), the selection of the sequence boundary (Fig. 2), the criteria used to define a hierarchy system (e.g., temporal vs physical scales), and the assertions of the dominant controls on sequence development (e.g., global eustasy: Haq et al., 1987; Vail et al., 1977, 1991; tectonism: Embry, 1995; accommodation: Neal and Abreu, 2009; interplay of accommodation and sediment supply: Catuneanu, 2006; Catuneanu et al., 2009; Schlager, 1993; interplay of allogenic and autogenic controls: Catuneanu and Zecchin, 2013).

The standard methodology transcends the differences between the various schools, and relies on the common ground (i.e., set of core principles) that underlies all competing approaches. The model-independent guidelines are simpler than the workflow of any particular model, thus promoting greater flexibility in the application of the method. Significant progress has been made in outlining the common ground in sequence stratigraphy (Catuneanu et al., 2009, 2010, 2011), which led to the publication of formal recommendations by the International Subcommission on Stratigraphic Classification of the International Commission of Stratigraphy (Catuneanu et al., 2011): "The definition of the common ground in sequence stratigraphy should promote flexibility with respect to the choice of approach that is best suited to a specific set of conditions as defined by tectonic setting, depositional setting, data available, and scale of observation" (Catuneanu et al., 2011, p. 176); "A standard methodology can be defined based on the common ground between the different approaches, with emphasis on the observation of stratal stacking patterns in the rock record" (Catuneanu et al., 2011, p. 233). It has become clear that none of the models in Fig. 2 provides the "best practice" under all circumstances, as defined by different geological settings and types of data available.

The fundamental common ground protocol is the acquisition of local data (i.e., derived from the basin under analysis), followed by the observation of all features that help indentify stratal stacking patterns at scales selected by the practitioner or afforded by the resolution of the data available (Fig. 18). The same types of stratal stacking patterns may form at different scales, in relation to stratigraphic cycles of different magnitudes. At each scale of observation, stratigraphic cycles (i.e., sequences) may include internal unconformities of equal and/or lower hierarchical ranks. Therefore, "relatively conformable" successions, whether sequences or systems tracts, can be observed at different scales, depending on the scope of the study and the resolution of the data available (e.g., seismic-scale systems tracts typically include outcrop-scale sequences). Sequence stratigraphic frameworks are basin specific in terms of the temporal and physical scales of their units and bounding surfaces, reflecting the interplay of local and global controls on accommodation and sedimentation. Therefore, the methodology and

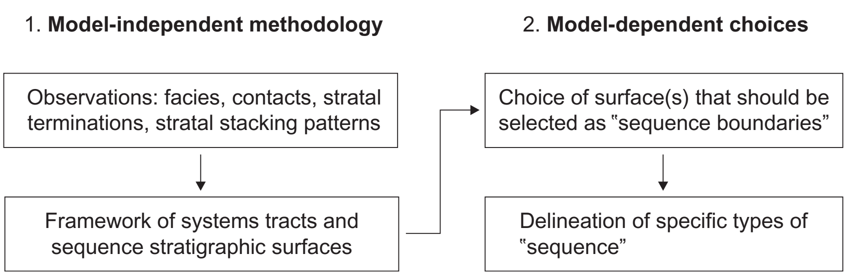

Fig. 18 Model-independent methodology vs model-dependent choices in sequence stratigraphy. The model-independent methodology is based on the observation of data and results in the construction of a stratigraphic framework of systems tracts and bounding surfaces at scales selected by the practitioner and/or afforded by the data available. Further model-dependent choices may be made with respect to the selection of surfaces that should be elevated to the status of "sequence boundary." This selection is often guided by the mappability of the different types of surface with the data available. *Modified from Catuneanu, O., Galloway, W.E., Kendall, C.G.St.C., Miall, A.D., Posamentier, H.W., Strasser, A., Tucker, M.E., 2011. Sequence stratigraphy: methodology and nomenclature. Newsl. Stratigr. 44/3, 173–245.*

nomenclature must remain independent of scale, and of the resolution of the data available, for a consistent and objective application of sequence stratigraphy.

The definition of all types of sequence stratigraphic units and bounding surfaces is independent of temporal and physical scales, and of the mechanism(s) of formation (Catuneanu et al., 2011, p. 175). The definition of a "sequence" has been revised and refined over time, to reflect conceptual developments and improvements in stratigraphic resolution (Fig. 3). With the decrease in the scale of observation (i.e., increase in stratigraphic resolution), as well as with the definition of different types of "sequence" (Fig. 1), the role of conformable surfaces as part or whole of the "sequence boundary" has become increasingly important. Within a common ground approach, a stratigraphic sequence is a cycle of change in stratal stacking patterns, defined by the recurrence of the same type of sequence stratigraphic surface (i.e., the "sequence boundary") in the rock record (Fig. 3). This definition is independent of scale, and independent of model (i.e., it accommodates all types of "sequence"). Sequences may form at different scales, and their relative stratigraphic significance is indicated by hierarchical orders. Sequences may or may not be "relatively conformable," depending in part on the selection of the sequence boundary, but always include sediments that are genetically related (i.e., which belong to the same cycle of accommodation or sedimentation; Catuneanu et al., 2009, 2011).

Stratal stacking patterns provide the basis for the definition of all units and surfaces of sequence stratigraphy. Sequences, systems tracts, and depositional systems can be observed at different scales, depending on the purpose of the study and the resolution of the data available (Fig. 16). Coastal depositional systems play a key role in defining the scales of systems tracts in downstream-controlled settings. The three-dimensional assemblages of lithofacies that are genetically linked by sedimentary processes and environments (i.e., depositional systems; Fisher and McGowen, 1967) can be observed from $<10^3$ to $>10^6$ years, depending on the resolution of the stratigraphic study (Fig. 16). The highest frequency changes in coastal environments (e.g., deltas vs estuaries in river-mouth settings, or prograding strandplains vs backstepping lagoon—barrier island systems in open coastline settings) define the lowest rank depositional systems, which consist truly and solely of genetically linked lithofacies accumulated in specific environments. These lowest rank depositional systems may form at scales of $\leq 10^0$ m and $\leq 10^3$ years, with an internal architecture defined by sedimentological cycles (beds or bedsets). At any larger scales (higher hierarchical ranks, including seismic exploration scales), depositional systems reflect dominant depositional trends rather than uninterrupted sedimentary processes in stable depositional environments, and may be subdivided into lower rank stratigraphic cycles (Figs. 16 and 17). Similarly, depositional systems in upstream-controlled settings may also undergo cyclic changes in fluvial styles and dominant depositional elements, at different scales (Fig. 15).

The observation of depositional systems at different scales affords the definition of systems tracts at different hierarchical levels. At each scale of observation (i.e., hierarchical level), systems tracts are defined by specific stacking patterns, and changes in the stacking pattern mark the position of sequence stratigraphic surfaces (e.g., a transgressive systems tract is defined by a retrogradational stacking pattern associated with shoreline transgression, and a maximum flooding surface is defined by a change from transgression to highstand normal regression; both transgressions and maximum flooding surfaces can be observed at different scales). The construction of a framework of systems tracts and bounding surfaces, at scales selected by the practitioner or afforded by the resolution of the data available, fulfills the practical purpose of sequence stratigraphy (Fig. 18). Within this framework, the practitioner can explain and predict the patterns of sediment distribution between the different depositional environments within a sedimentary basin.

Beyond the construction of a model-independent framework of systems tracts and bounding surfaces, the practitioner can make model-dependent choices with respect to the selection of the "sequence boundary" (Fig. 18). Such choices are often guided by the mappability of the different types of surface that are present within the studied section, which depends on the data available (e.g., well logs vs seismic lines). The flexibility of this model-independent workflow frees the practitioner from the rigid guidelines of any specific approach (e.g., the need to find a particular type of surface as "sequence boundary"), and from the expectations to fulfill the predictions of any particular model (e.g., the need to find orderly patterns in the stratigraphic record, or ideal successions of systems tracts). This promotes an objective construction of sequence stratigraphic frameworks, which may consist of variable successions and combinations of systems tracts (e.g., Csato and Catuneanu, 2012), at scales controlled by the geological setting (i.e., local conditions of accommodation and sedimentation), the resolution of the data available (e.g., seismic vs well-log data), and/or the scope of the study (e.g., petroleum exploration vs production development). Furthermore, the observation of stratal stacking patterns (i.e., methodology) needs to be separated from the subsequent interpretation of underlying controls (i.e., modeling) (Catuneanu and Zecchin, 2016).

Despite the scale invariance of stratal stacking patterns (i.e., same types observed at different scales), the stratigraphic architecture is not truly fractal, as sequences of different hierarchical ranks may have different controls and internal makeup in terms of component systems tracts. The internal makeup of systems tracts also becomes increasingly complex with the increase in the scale of observation, from a succession of beds and bedsets (i.e., sedimentological cycles) to a set of higher frequency sequences (i.e., stratigraphic cycles) of lower hierarchical rank. Within a framework of nested stratigraphic cycles, "relatively conformable" successions can be defined at different scales, depending on the resolution of the data available and/or the scope of the study, and therefore, they do not provide an objective reference for scale. The classification of nested sequences is basin specific, starting with the basin fill as a reference, with scales controlled by local conditions of accommodation and sedimentation.

It can be concluded that a scale-independent methodology is key to the standard application of sequence stratigraphy. The definition of sequence stratigraphic units and bounding surfaces must be independent of any variables that change with the case study (e.g., depositional and tectonic settings, and the types and resolution of the data available), in order to remain objective and consistent. The observation of stratal stacking patterns, at scales selected by the practitioner or imposed by the resolution of the data available, takes precedence over any model assumptions in terms of constructing a sequence stratigraphic framework. The model-independent methodology, inherently simple and consistent, provides the flexible platform for a standard application of sequence stratigraphy across the full spectrum of geological settings, stratigraphic scales, and types of data available.

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