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Stratal Stacking Patterns in Underfilled Basins

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Summary

Stratal stacking patterns provide the basis for the definition of all units and surfaces of sequence stratigraphy. In underfilled sedimentary basins, stacking patterns are related to shoreline trajectories, including normal regression, forced regression and transgression. The same types of stratal stacking patterns may be observed at different scales, and their relative stratigraphic significance is indicated by hierarchical orders. As hierarchy systems are basin-specific, reflecting the interplay of global and local controls on accommodation and sediment supply, the nomenclature of stratal units and bounding surfaces must remain independent of scale, and the same set of terms should be used for all hierarchical levels.

Systems tracts are defined by specific stratal stacking patterns, and changes in stacking pattern mark the position of sequence stratigraphic surfaces (i.e., systems tract boundaries), at any hierarchical level. The construction of a framework of systems tracts and bounding surfaces on the basis of observed stratal stacking patterns defines the model-independent sequence stratigraphic methodology. Beyond this model-independent framework, model-dependent choices with respect to the selection of sequence boundaries may be made as a function of the mappability of the various sequence stratigraphic surfaces within the studied section. In a generic sense, a sequence corresponds to a cycle of change in stratal stacking patterns defined by the recurrence of the same types of sequence stratigraphic surface in the rock record. As both allogenic and autogenic processes may contribute to the formation of sequence stratigraphic surfaces, the definition of sequences and systems tracts is based on the observation of stacking patterns and not on the interpreted origin of cycles.

Introduction

The sequence stratigraphic method provides the means of correlation on the basis of stratal stacking patterns that can be recognized across variable (but generally large) scales, in contrast with other correlation methods that rely traditionally on similarities of rock units in terms of lithology (i.e., lithostratigraphy), fossil assemblages (i.e., biostratigraphy), magnetic characteristics (i.e., magnetostratigraphy) or geochemical signatures (i.e., chemostratigraphy).

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 order), 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. 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 the sequence stratigraphic surfaces which are part of a stratigraphic framework may vary with the type(s) of data available and the field expression of these surfaces. Formal recommendations on a model-independent methodology have been sanctioned by the International Subcommission on Stratigraphic Classification (Catuneanu et al., 2011).

Stratal stacking patterns

Stratal stacking patterns refer to the architecture of the sedimentary rock record, and are key to the model-independent sequence stratigraphic methodology. Stratal stacking patterns define systems tracts, and changes in stratal stacking pattern define sequence stratigraphic surfaces. This simple and yet fundamental principle provides the basis for a unified methodology (Catuneanu et al., 2009, 2010, 2011), and promotes an objective approach based on the observation of data independently of any model-driven assumptions (e.g., with respect to the dominant control on sequence development). Stratal stacking patterns are defined by the interplay of accommodation and sedimentation, and have different expressions in the downstream-controlled (i.e., accommodation modified by changes in relative sea level) vs. upstream-controlled (i.e., accommodation modified by climate and/or source area tectonism, independently of relative sea-level changes) settings (Fig. 1).

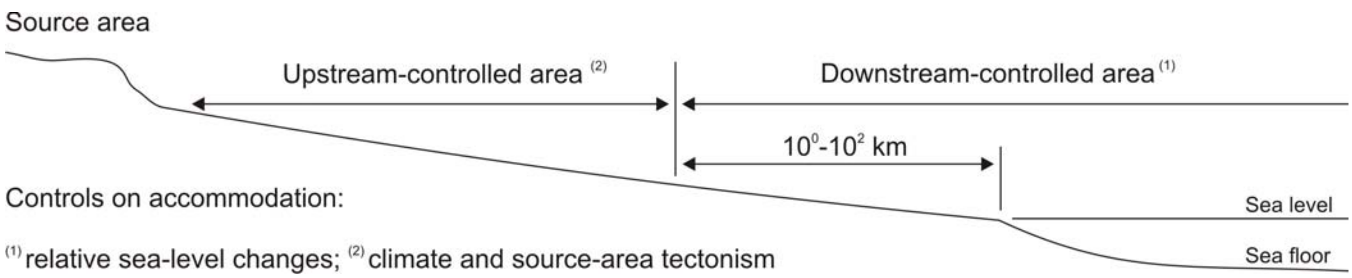

Figure 1. Accommodation in downstream- vs. upstream-controlled areas. The downstream-controlled area includes marine, coastal, and continental systems which respond to changes in relative sea level. The upstream-controlled area includes continental systems remote from the influence of relative sea-level changes, which respond to climate and source-area tectonism.

Stratal stacking patterns in downstream-controlled settings form in response to the interplay between relative sea-level changes and sediment supply *at the coastline*. A relative sea-level rise may lead to either progradation (i.e., 'normal' regression: sedimentation > accommodation at the coastline) or retrogradation (i.e., transgression: accommodation > sedimentation at the coastline), whereas a relative sea-level fall leads to 'forced' regression (negative accommodation at the coastline) (Fig. 2). Changes in relative sea level and, implicitly, in accommodation conditions, can be reconstructed by observing the evolution of the coastline. A relative rise in sea level implies a relative increase in coastal elevation, which translates into creation of space for sediment to accumulate (i.e., positive accommodation). Consequently, the magnitude of relative sea-level rise is quantified by the amount of coastal upstepping during transgression or normal regression. Conversely, a relative fall in sea level implies a relative decrease in coastal elevation, which translates into a loss of (i.e., negative) accommodation. Therefore, the magnitude of relative sea-level fall can be measured as the amount of coastal downstepping during forced regression (Fig. 3).

The depositional trends recorded in downstream-controlled settings include upstepping (aggradation), downstepping (subaerial exposure of former seafloor), forestepping (progradation), and backstepping (retrogradation) (Fig. 2). The combinations of depositional trends define stratal stacking patterns: normal regressive (i.e., forestepping and upstepping), forced regressive (i.e., forestepping and downstepping), and transgressive (backstepping and upstepping) (Figs. 2, 3; Posamentier et al., 1992; Posamentier and Morris, 2000; Catuneanu et al., 2011). These stacking patterns correspond to the ascending regressive, descending regressive, and transgressive shoreline trajectories of Loseth and Helland-Hansen (2001) and Helland-Hansen and Hampson (2009). Theoretical situations of pure aggradation (stable shoreline; i.e., neither forestepping nor backstepping during aggradation) or pure forestepping (regression during relative sea-level stillstand) have also been postulated (Loseth and Helland-Hansen, 2001; Helland-Hansen and Hampson, 2009), but are rare in nature as the positions of the shoreline and of the relative sea level depend on the interplay of multiple independent variables, and hence are unlikely to be stable over geological time scales.

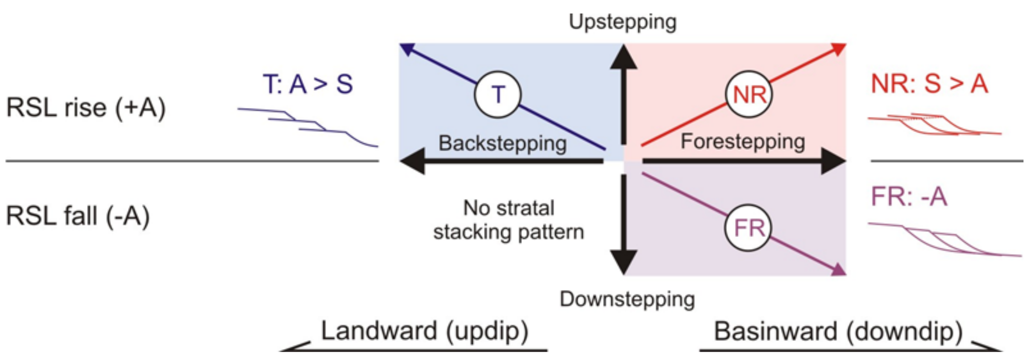

Figure 2. Depositional trends in a downstream-controlled area: upstepping, downstepping, forestepping, and backstepping. The combinations of depositional trends define stratal stacking patterns: normal regressive (progradation and aggradation), forced regressive (progradation and downstepping), and transgressive (retrogradation and aggradation). Abbreviations: NR - normal regression; FR - forced regression; T - transgression; A - accommodation rate; S - sedimentation rate; RSL - relative sea level; +A - positive accommodation; -A - negative accommodation.

The two types of regression are fundamentally different, with the 'normal' regression being relatively slow and driven by sediment supply, and the 'forced' regression being typically fast and driven by a fall in relative sea level. Normal regressions are further classified into 'lowstand', if the normal regression follows a forced regression, and 'highstand', if the normal regression follows a transgression (e.g., Csato and Catuneanu, in press; Fig. 4). A lowstand normal regression is typically characterized by a concave-up shoreline trajectory, which reflects a shift from a dominantly progradational to a dominantly aggradational trend (i.e., a consequence of accelerating relative sea-level rise). In contrast, a highstand normal regression displays a convex-up shoreline trajectory, which is the result of decelerating relative sea-level rise and a consequent shift from a dominantly aggradational to a dominantly progradational trend (Fig. 4; see fig. 19 in Catuneanu et al., 2009, for a seismic example).

Forced regressions assume sediment accumulation primarily in the marine environment, as the downstream-controlled continental setting is subject to erosion or sediment bypass during relative sea-level fall (i.e., negative accommodation, accompanied by the formation of subaerial unconformities). Exceptions from this general 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 systems tract defined by a forced regressive stacking pattern is the only type of sequence stratigraphic unit 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.

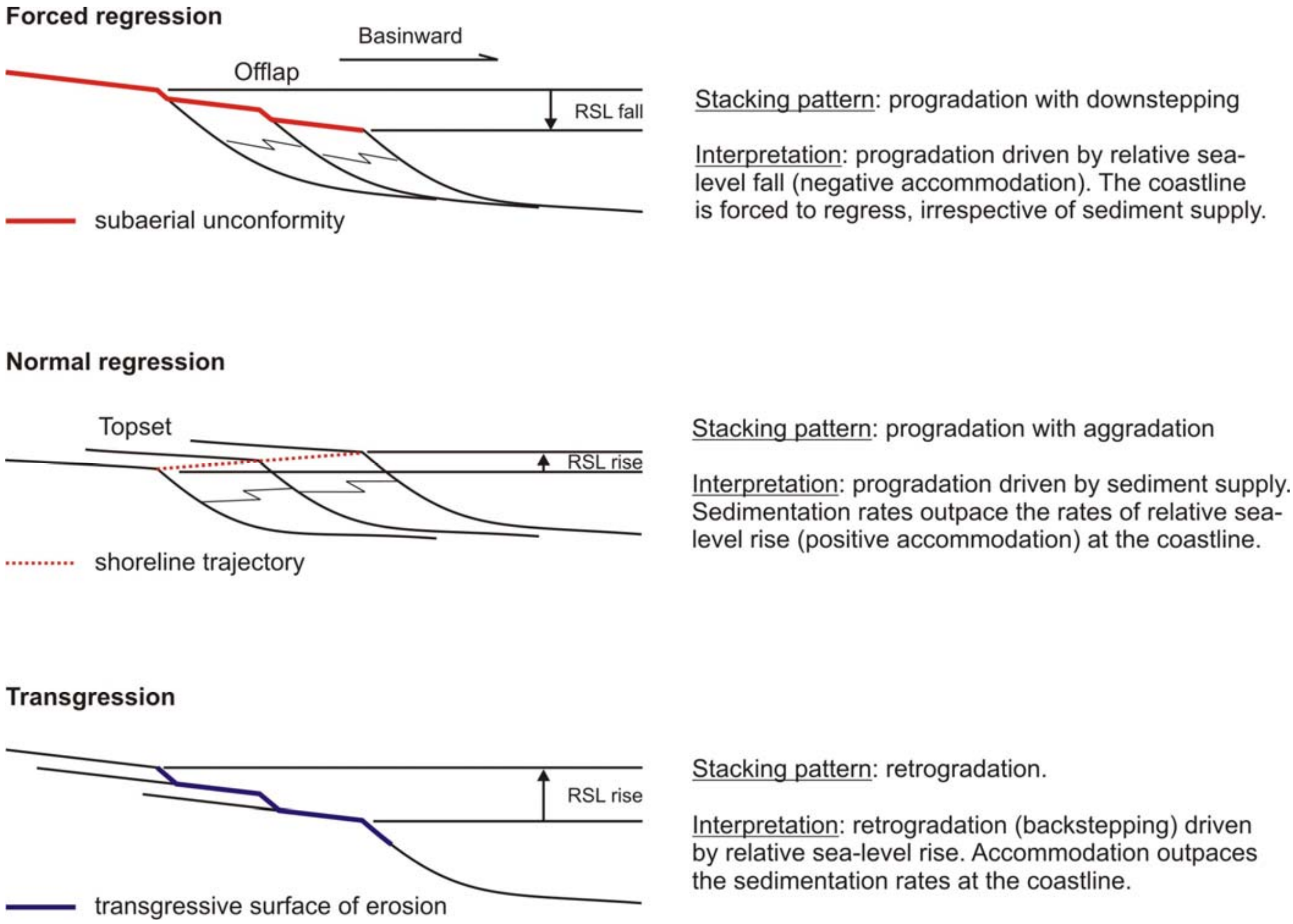

Figure 3. Stratal stacking patterns in a downstream-controlled area: forced regression, normal regression, and transgression (from Catuneanu et al., 2009, 2011). The amount of upstepping of the coastline during normal regression or transgression, and the amount of downstepping of the coastline during forced regression, can be used to quantify the magnitude of relative sea-level changes at syn-depositional time.

Normal regressions assume the aggradation of continental topsets during progradation, with the rates of topset aggradation being inversely proportional to the rates of progradation. Therefore, the rates of topset aggradation typically increase with time during lowstand normal regressions, and decrease with time during highstand normal regressions. 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 highstand rivers. Owing to the decrease in coastal elevation during forced regression, lowstand fluvial systems tend to include the highest energy rivers of the entire accommodation cycle, with the highest probability of developing unconfined channels (e.g., braided style). At the opposite end of the spectrum, and owing to the increase in coastal elevation during relative sea-level rise, highstand fluvial systems tend to include the lowest energy rivers of an entire sequence, with the highest probability of developing confined channels (e.g., meandering style). For this reason, and due to differences in the ability of channels to shift laterally (i.e., low for confined channels and high for unconfined channels) lowstand topsets typically display a higher degree of channel amalgamation relative to the highstand topsets, even though accommodation conditions may be similar (i.e., low). Moreover, the difference in energy levels and fluvial styles between the lowstand and the highstand rivers also explains the decrease in competence and grain size within the fluvial portion of a depositional sequence, from base to top.

Discussion and conclusions

Sequence stratigraphy is still a developing methodology, as more knowledge, disciplines, and supporting data are integrated to constrain its conceptual framework. At the same time, its applications have gradually expanded to unravel the higher resolution details of the stratigraphic record (Csato et al., in press), and significant progress has been made to shift the emphasis from models to data. In this light, the definition of a sequence has also evolved as *a stratigraphic cycle of change in stratal stacking patterns defined by the recurrence of the same types of sequence stratigraphic surface in the rock record* (Catuneanu and Zecchin, 2013).

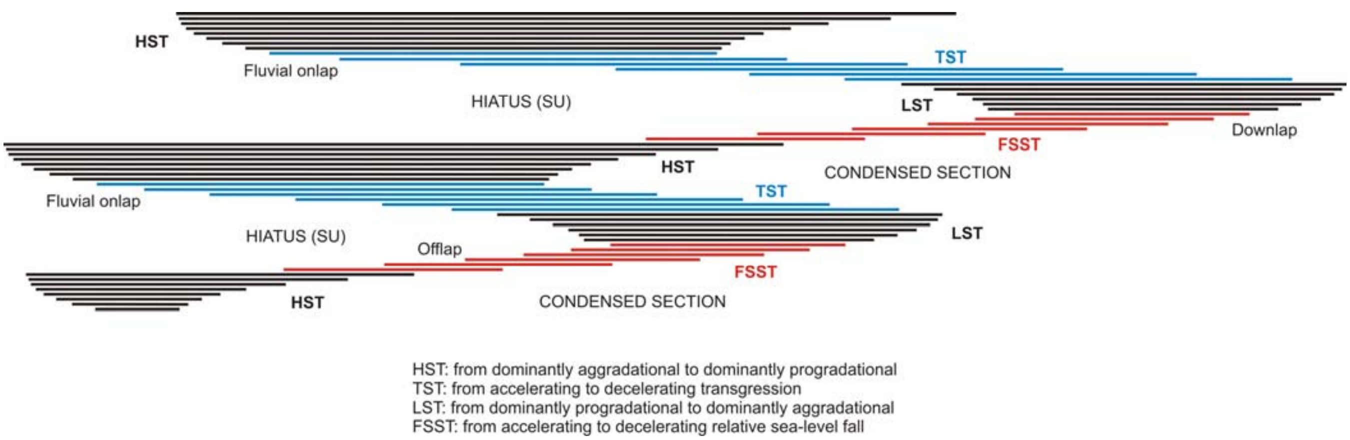

Figure 4. Stratal stacking patterns in a time domain. Each type of stratal stacking pattern defines a systems tract: FSST (forced regression), LST (lowstand normal regression), TST (transgression), and HST (highstand normal regression). The degree of preservation of the sedimentary record increases from the continental to the marine portions of the basin. The preserved stratal units reflect the patterns of change in accommodation, which enables the application of sequence stratigraphy despite the sparse preservation of the sedimentary record. Abbreviations: FSST - falling-stage systems tract; LST - lowstand systems tract; TST - transgressive systems tract; HST - highstand systems tract; SU - subaerial unconformity.

The most significant adjustment to the sequence stratigraphic methodology is the change from a model-driven to a data-driven workflow. The early assumptions on the dominance of the eustatic control on sequence development led to the construction of a global cycle chart that was used as a reference for the construction of sequence stratigraphic frameworks worldwide (Vail et al., 1977; Haq et al., 1987). In this approach, the global cycle chart, rather than the local data, took precedence in the interpretation of sequence stratigraphic surfaces in any particular sedimentary basin. However, many of such interpreted surfaces would have no relevance to the basin under analysis, where sedimentary processes are controlled at least in part by local tectonics and sediment supply. The understanding of the importance of local controls on accommodation and sediment supply triggered a fundamental change in the methodological approach, with the local data representing the starting point for the construction of local sequence stratigraphic frameworks.

The data-driven workflow emphasizes stratal stacking patterns as the basis for the definition of all units and surfaces of sequence stratigraphy. At any scale of observation (i.e., hierarchical order), stratal stacking patterns define systems tracts, and the surfaces that mark changes in stratal stacking pattern (i.e., systems tract boundaries) are sequence stratigraphic surfaces. Therefore, the data-driven, model-independent methodology is scale invariant. In this approach, the local data, rather than any *a priori* model assumptions, reveal the sequence stratigraphic framework that characterizes any particular sedimentary basin or sub-basin. Within this framework, a stratigraphic unit (e.g., sequence, systems tract, parasequence) is defined by its specific bounding surfaces, and not by scale or inferred controlling mechanisms (Catuneanu and Zecchin, 2013).

The stacking patterns illustrated in Figures 3 and 4 describe the stratal architecture of continental to shallow-water systems in the vicinity of the coastline. Farther downdip, sedimentary processes in the deep-water environment are also linked to changes in accommodation and sediment supply on the shelf, which affords the application of the sequence stratigraphic methodology beyond the shelf edge. The delineation of systems tracts in the deep-water system is based on the predictable change in the type of gravity flows and/or the caliber of the sediment delivered from the shelf during an accommodation cycle (Catuneanu et al., 2011; De Gasperi and Catuneanu, 2014).

The nomenclature of sequence stratigraphic units and bounding surfaces needs to be consistent, irrespective of the scale of the observed stratigraphic cycle. For example, every cycle of change in accommodation or sediment supply may have its own 'maximum flooding surface', irrespective of the hierarchical level of that sequence. The nomenclature applied to the sequence stratigraphic surface does not change with the scale of observation, but only the modifier that indicates the hierarchical order (e.g., fourth-order vs. third-order 'maximum flooding surface', etc.). The same principle applies to the nomenclature of sequences and systems tracts (e.g., fourth-order vs. third-order 'sequence'; fourth-order vs. third-order 'transgressive systems tract'; etc.). The application of a scale-dependent nomenclature would result in confusion and subjectivity with respect to the terminology that should be applied at various scales of observation, as well as in the proliferation of an unnecessarily complex terminology.

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