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An Overview of the Fundamentals of Sequence stratigraphy

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Abstract: Sequence stratigraphy is a widely applied stratigraphic analysis practiced by both academicians and industry professionals alike. This new stratigraphic approach has great application in basin analysis and has shown to be highly successful exploratory technique for natural resource exploration. A sequence stratigraphic framework includes genetic units which are bounded by sequence stratigraphic surfaces, and systems tracts that link depositional systems. Each genetic unit depicts specific stratal stacking patterns in response to varying accommodation space creation and sediment supply through time. The methodology allows for the prediction of lithologies and recognition of facies, resulting in more realistic and meaningful paleogeographic interpretations. The purpose of this article is to simplify sequence stratigraphic fundamental ideas and terminologies so that earth science students, mentors, and amateur geoscientists in industry can understand them.

Keywords: Relative sea-level, accommodation, sequence stratigraphic surfaces, systems tracts,stratal stacking patterns.

Introduction

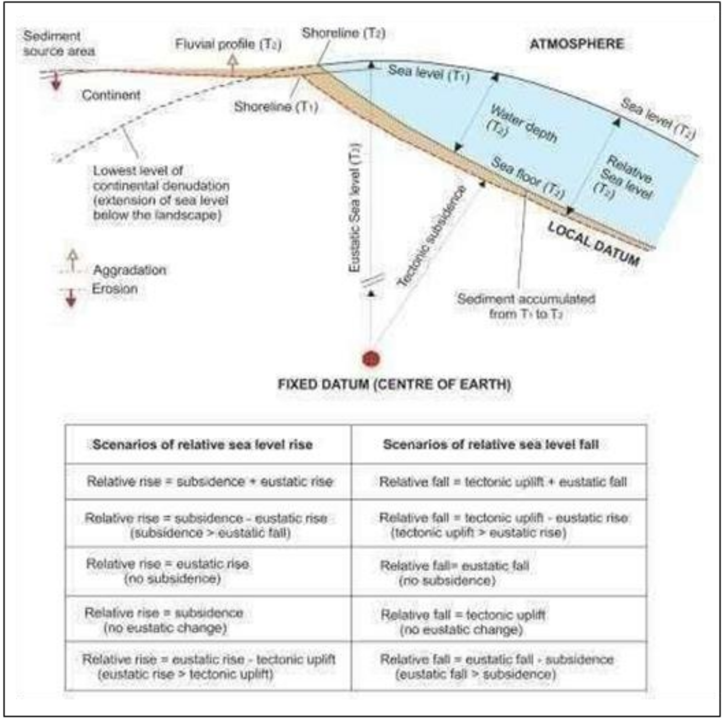
The introduction of sequence stratigraphy is the most recent and significant revolution in the field of sedimentology and stratigraphy. Since its inception, it has gradually evolved into process-based working methodology in interdisciplinary research fields of geoscience. Sequence stratigraphy deals with genetically related strata in space and time. It is essentially based on analysis of cyclicity in the sedimentation record controlled by some fundamental natural parameters; such as sediment supply, tectonic subsidence, sedimentary processes etc. (Posamentier and Allen, 1999). Sequence stratigraphy marks the breaks in the stratigraphic record through identification of stratigraphic units and their bounding surfaces, thereby providing a framework of stratal architecture. It helps in understanding the genesis of geomorphic elements within any particular depositional system through analysis of nature of sediments (autochthonous or allochthonous), facies relationships and their sequential organization in a three- dimensions. Sequence stratigraphy, in a sense, examines the depositional trend within a basin in response to changes in base level and sedimentation rate in chronologic terms (Catuneanu et al., 2009). Decoding the Earth's geological record in terms of genetic evolution of stratal package, changes in paleogeography (on a local, regional or global scale) and different sedimentary processes are all applications of sequence stratigraphy. This analytical technique has enormous potential in basin analysis, enhancing the predictive aspect of natural resource exploration. Hence, it has emerged as one of the most dynamic areas of research attracting both academic and industry interest.

Sloss et al. (1949) coined the term ‘sequence’ to describe a stratigraphic unit bounded by subaerial unconformities. However, sequence stratigraphy is generally thought to have originated with seismic stratigraphy in the 1970s (Vail et al., 1977). The introduction of ‘correlative conformity’ marked the beginning of modern seismic and sequence stratigraphy (Mitchum, 1977). Modern seismic and sequence stratigraphy began with the introduction of 'correlative conformity' (Mitchum, 1977). The incorporation of outcrop and well data (Posamentier et al., 1988; Posamentier and Vail, 1988; Van Wagoner et al., 1990) as well as a shift in emphasis from eustasy to relative sea-level (e.g., Hunt and Tucker, 1992; Posamentier and James, 1993; Posamentier and Allen, 1999; Catuneanu., 2006; Catuneanu et al., 2009) marked a major turnaround in sequence stratigraphy. Galloway (1989) presented a genetic stratigraphic approach that divided the stratigraphic succession at maximum flooding surfaces, including the unconformity surface within the sequence. The Exxon research group (led by seismic stratigraphers) used a sequence stratigraphic technique that preferred unconformities and their correlative conformities to define sequences. Embry (1993, 1995) proposed another type of stratigraphic unit, named as transgressive– regressive (T–R) sequence. In its present form and approach, sequence stratigraphy integrates all types of data (sedimentological, chronostratigraphic, paleontological, geomorphological, structural, geophysical and geochemical) available for a stratal package. It is currently widely acknowledged as the most effective analytical tool applied for basin analysis.

Basic Concepts

Base level and accommodation

The global reference surface to which continental denudation and marine aggradation tend to proceed is often known as the base level (of deposition or erosion) (Catuneanu et al., 2002). It is a dynamic surface to which sediment accumulation fills up or erodes down and is related to continental erosion. For simplicity, base level is equated with the sea-level (Schumm, 1993). In reality, base level is usually below sea-level due to the erosional action of waves and marine currents. The concept of ‘base-level change’ becomes equivalent to the concept of ‘relative sea-level change’ when base level is approximated as sea level (Posamentier et al., 1988; Catuneanu et al., 2009). Base level fluctuations are by a variety of exogenous (eustatic, tectonic, climatic), diagenetic (sediment compaction), and environmental (wave and current energy) controls. The term "accommodation" refers to the vertical distance between the sea surface and a reference plane, such as, a transgressive surface or an unconformity within already accumulated sediment pile or the basement (Jervey, 1988). This accommodation space can be created or destroyed by fluctuations in base level, and is gradually consumed by sedimentation (Catuneanu, 2006).



Scenarios of relative sea level rise	Scenarios of relative sea level fall
Relative rise = subsidence + eustatic rise	Relative fall = tectonic uplift + eustatic fall
Relative rise = subsidence - eustatic rise (subsidence > eustatic fall)	Relative fall = tectonic uplift - eustatic rise (tectonic uplift > eustatic rise)
Relative rise = eustatic rise (no subsidence)	Relative fall= eustatic fall (no subsidence)
Relative rise = subsidence (no eustatic change)	Relative fall = tectonic uplift (no eustatic change)
Relative rise = eustatic rise - tectonic uplift (eustatic rise > tectonic uplift)	Relative fall = eustatic fall - subsidence (eustatic fall > subsidence)

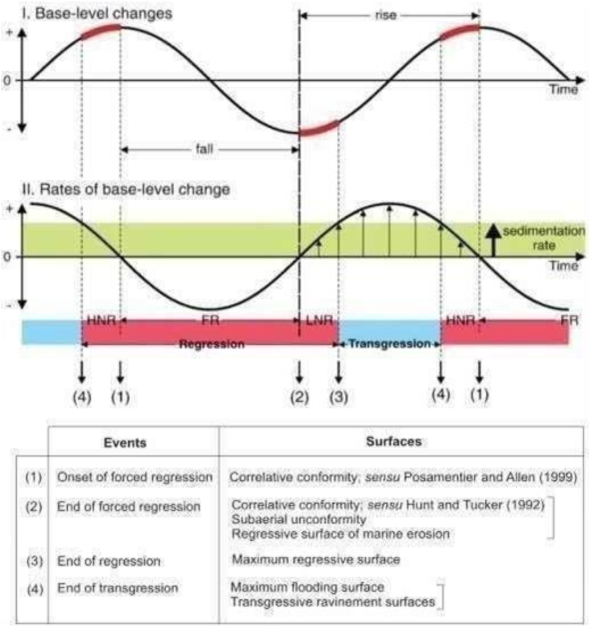
Fig. 1. Eustasy, relative sea-level, water depth and sedimentation as a function of sea-level, sea-floor and local datum surface (after Posamentier et al., 1988 and Catuneanu, 2006). Scenarios of relative sea- level rise and fall in relation to eustasy and tectonics have been summarized in table.

Eustasy vs. relative sea-level (RSL)

Eustasy is a global phenomenon involving changes in the volume of water in the world’s oceans. It is solely a function of sea-surface movement, as measured between the sea surface and a fixed point usually the centre of the earth (Fig. 1). Relative sea-level, on the other hand, is a function of both sea surface and sea-floor movement (Posamentier et al., 1988). The latter parameter may be controlled by tectonics, thermal cooling, sediment/water load, or compaction. Therefore, relative sea-level may vary from location to location corresponding to changes in accommodation space (Fig. 1).

Transgression and regression vs. relative sea-level rise and fall

A transgression occurs when the sea advances over land while a regression is a retreat of the sea from land. The direction of shoreline movement is a function of the balance between accommodation space and sediment supply. Transgression occurs when the rate of base level rise exceeds the rate of sedimentation at the shoreline (Fig. 2). Therefore, when relative sea-level rises, areas with low sediment influx may be characterized by transgressive shorelines (Posamentier and James, 1993). A normal regression, caused by the coastline moving seaward, occurs in the early and late stages of baselevel rise when the sedimentation rates exceed the available accommodation on the shelf, leading the shoreline to regress (Fig. 2). During normal regression, the coastal plain remains a depositional surface, alluvial accommodation increases, and fluvial aggradation occurs on the coastal plain as the shoreline regresses and the coastal plain expands (Catuneanu, 2002). A forced regression, on the other hand, occurs during stages of base level fall, when the shoreline is forced to regress regardless of the sediment supply (Fig. 2). During forced regression, the coastal plain is not a site of sedimentation but rather a zone of sedimentary bypass/erosion resulting in an unconformity (in both the nonmarine and shallow marine settings) and accompanied by fluvial incision landward of the shoreline (Posamentier et al., 1992).



	Events	Surfaces
(1)	Onset of forced regression	Correlative conformity; *sensu* Posamentier and Allen (1999)
(2)	End of forced regression	Correlative conformity; *sensu* Hunt and Tucker (1992) Subaerial unconformity Regressive surface of marine erosion
(3)	End of regression	Maximum regressive surface
(4)	End of transgression	Maximum flooding surface Transgressive ravinement surfaces

Fig. 2. Concepts of transgression, normal regression and forced regression, as interpreted by the interplay of base-level changes and sedimentation rate (adopted from Catuneanu, 2006). Abbreviations: FR= Forced regression; LNR= Lowstand normal regression; HNR= Highstand normal regression. The four events of the base-level cycle are (1): onset of forced regression; (2): end of forced regression; (3): end of regression; (4): end of transgression. These four events and their corresponding type of stratigraphic surfaces have been summarized in tabular form (after Catuneanu, 2002, 2006).

Retrogradation, aggradation and progradation

Retrogradation is the diagnostic depositional trend that is described as the backward (landward) movement or retreat of a shoreline by wave erosion; it results in a steepening of the beach profile at the breaker line (Bates and Jackson, 1987). It is characterized by relative sea-level rise and allows sediment flux (Fig. 3). Consequently, the increased accommodation is only partly filled and water depth rises, but not as much as the total relative sea-level rise and the magnitude of the rise vary by location. The sediments in all environments along the profile will simply build up without any variation in character if there is a balance between sediment influx and the rate of increase in accommodation, so that the position of the shoreline remains stable and the water depth at any given location remains constant. This phenomenon is known as aggradation (Fig. 3). The depositional trend that is forward or outward toward the sea of a shoreline by nearshore deposition of river-borne sediments or by continuous build-up of beach material thrown up by waves or transported by longshore drifting is known as Progradation. It occurs at shorelines when there is an oversupply of sediments in comparison to increasing accommodation; therefore, a regressive section develops with decreasing water depth (Fig. 3) (Bates and Jackson, 1987; Posamentier and Allen, 1999).

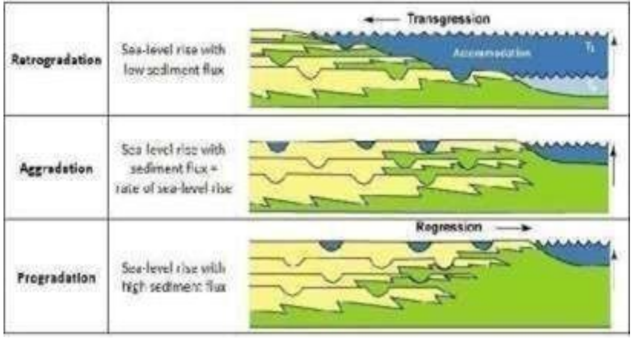


Fig. 3. Stratigraphic architecture of the succession during retrogradation, aggradation and progradation in accord to sea-level rise and sediment flux (after Posamentier and Allen, 1999).

Stratal terminations

Stratal terminations are the geometric relationships between strata and the stratigraphic surfaces against which they terminate, and may be observed on continuous surface or subsurface (two dimensional seismic transects and well-log cross-sections). Stratal terminations were first defined by Mitchum et al. (1977) when analyzing seismic profiles; however, they can also be observed in large scale outcrops above or below a stratigraphic surface. There are four stratal terminations can be used to identify sequence stratigraphic surfaces: two above the surface (onlap and downlap), and two below the surface (truncation and toplap). Offlap is a key stratal stacking pattern diagnostic for forced regressions and the delineation of sub-aerial unconformities and their correlative conformities. Stratal terminations are useful for interpreting depositional trends, and hence for the systems tracts because they provide critical information about the direction and type of syn-depositional shoreline shift. The understanding of stratal terminations in terms of shoreline shifts is evident in some cases. For example, coastal onlap and offlap denote transgression and forced regression, respectively. In some circumstances, stratal terminations may indicate alternative interpretations, such as downlap occurs in either normal or forced regressions. Additional criteria (as depositional trends; aggradational, erosional or progradational) have to be considered in such conditions (Catuneanu, 2006).

Type 1 vs. Type 2 unconformities

Vail and Todd (1981) proposed Type 1 vs. Type 2 unconformities in sequence stratigraphy, which was later improved by Posamentier and Vail (1988). Type 1 unconformity is formed by rapid fall in relative sea-level (forced regression) and followed by an abrupt basinward shift of coastal onlap, which is occasionally linked to fluvial incision. Type 2 unconformity, on the other hand, develops as a result of a decelerating, then accelerating, rise in relative sea-level (related to normal regression). This unconformity is characterized by an abrupt basinward shift of coastal onlap too, but without forced regression or significant fluvial incisions. In outcrop, Type 1 unconformities are easy to identify (Van Wagoner et al., 1990); however, Type 2 unconformities are difficult, if not impossible, to recognize. The concept of Type 2 unconformity is no longer recognized and has been abandoned. In sequence stratigraphy, the term unconformity refers just to those surfaces that are exposed by rapid fall in RSL i.e Type 1 unconformity.

Sequence Stratigraphic Surfaces

The identification of key stratigraphic surfaces that can be used to subdivide geological sections into sequences and their component sub-units is one of the most significant aspects of sequence stratigraphy. Sequence stratigraphic surfaces may correspond to conceptual horizons (i. e., without a lithologic contrast) or physical surfaces, depending on their outcrop manifestation (e. g., Carter et al., 1998) marking changes in stratal stacking pattern.

Subaerial unconformity (SU)

The subaerial unconformity (Sloss et al., 1949), also known as "lowstand unconformity" (Schlager, 1992) or regressive surface of fluvial erosion (Plint and Nummedal 2000) or fluvial entrenchment/incision surface (Galloway, 2004), develops under subaerial conditions during forced regression, transgression, during periods of negative fluvial accommodation or during relative sea- level fall as a result of fluvial erosion or bypass, pedogenesis, wind degradation, or dissolution and karstification (Posamentier et al., 1988; Leckie, 1994; Blum, 1994).

Correlative conformity (CC)

The unconformity that has developed on the coastal and alluvial plain after forced regression merges into a conformable surface, i.e., a correlative conformity, seaward of the shoreline. Because the coeval surface seaward of the coast lies below water, i.e., is overlain by shelf, some sediment accumulation occurs, and so no sedimentary hiatus or unconformity is recorded (Posamentier and Allen, 1999). However, in most outcrop sections, there are ongoing debates about its time and physical characteristics. The correlative conformity, according to Mitchum (1977), is a surface that is time equivalent to a sequence boundary indicating the start of a sea-level decrease. It was regarded as the paleo- seafloor at the start of forced regression by Posamentier et al. (1988), but it was seen as the paleo- seafloor at the end of forced regression by Hunt and Tucker (1992).

Maximum flooding surface (MFS)

It refers to the surface of deposition at the maximum landward position of the sea shore (i.e., the time of maximum transgression). In other words, it is the paleo-seafloor during the peak of transgression, as well as its non-marine corresponding surface. The Maximum flooding surface (MFS) represents the transition from transgression to highstand normal regression in stratal stacking patterns (Fig. 4). MFS can serve as a potential stratigraphic marker for regional correlation (Galloway, 1989).

Maximum regressive surface (MRS)

The maximum regressive surface (Helland-Hansen and Martinsen, 1996) is a stratigraphic surface that denotes a change from lowstand normal regression to transgression in stratal stacking patterns. It is the paleo-seafloor at the end of lowstand normal regression, as well as its non-marine correlative surface.

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Transgressive ravinement surface (TRS)

The transgressive ravinement surface (Nummedal and Swift, 1987) or transgressive surface of erosion (Posamentier and Vail, 1988) is diachronous erosional surfaces that emerge during transgression in coastal to shallow-water environments as a result of wave scouring or tidal scouring. Its basinward termination merges into the maximum regressive surface, whereas its landward end merges with the maximum flooding surface.

Sequence Stratigraphic Units

Sequence

Mitchum (1977) defined sequence as a relatively conformable succession of genetically related strata bounded by unconformities or their correlative conformities. Two types of sequences have been classified, viz. Type 1 and Type 2. Type 1 sequence is created when RSL falls significantly but Type 2 sequences generated when RSL falls insufficiently. Multiple similar episodes may make up a succession within a basin. A Mega sequence is a collection of numerous sequences bound by basin- wide unconformities.

Systems tract

Brown and Fisher (1977) defined a systems tract as “a linkage of contemporaneous depositional systems, forming the subdivision of a sequence” that represents ‘a specific sedimentary response to the interaction between sediment flux, physiography, environmental energy, and changes in accommodation’ (Posamentier and Allen, 1999). The definition of systems tract is independent of spatial and temporal scales. Systems tracts are interpreted on the basis of strata stacking patterns, position within the sequence, and types of bounding surface (Van Wagoner et al., 1987, 1988, 1990; Posamentier et al., 1988; Van Wagoner, 1995; Posamentier and Allen, 1999).

Falling-Stage Systems Tract (FSST)

The FSST is the result of a forced regression that includes all regressive deposits that accumulate after a relative sea-level fall but before the following relative sea-level rise (Fig. 4). At the end of forced regression, the erosion of the subaerially exposed sediment surface updip of the coastline as well as of a diachronous subaerial unconformity that caps the Highstand Systems Tract (HST), demonstrate the drop in sea level. The subaerial unconformity may be onlapped by fluvial deposits that belong to the lowstand or the transgressive systems tracts. A time-transgressive marine ravinement surface overlain by a sediment lag could likewise modify the subaerial unconformity (Catuneanu et al., 2011).

Lowstand Systems Tract (LST)

The LST contains deposits that accumulate on top of the FSST and the accompanying updip subaerial unconformity after the commencement of relative sea-level rise during normal regression. During forced regression, LST sediments frequently fill or partially fill incised valleys carved into the HST and other previous deposits (Fig. 4, 5). LST sediments often fill or partially infill incised valleys that were cut into the HST, and other earlier deposits (Fig.4, 5). The sheltered lowstand packages near a slope break that have escaped from erosion, are generally fan shaped and progradational. They are designated as lowstand wedge. During the next transgression, these wedges or fans (alluvial fan, fan delta, shelf fan, slope fan or deep submarine fan), resting on an unconformity surface are buried under deep water mud. Being enclosed by finer sediments, these fans often act as highly potential oil reservoirs or prospective placer deposits.

Transgressive Systems Tract (TST)

The TST comprises the deposits that accumulated from the start of transgression to the time of maximum transgression of the coast, right before the HST began to retreat again. The TST lies directly on the maximum regressive surface (MRS) formed at the end of regression and is overlain by the maximum flooding surface (MFS) formed when marine sediments reach their most landward position (Fig. 4). Sometimes, a zone of (commonly condensed) deep-water facies, rather than a unique surface in the rock succession, can signal the switch in depositional tendency from retrogradation (transgression) to progradation (regression) (Carter et al., 1998). It is denoted as the condensed zone characterized by fine sediments with high organic carbon content, pyrite, glauconite or phosphate enrichment, or volcanic ash fall deposits. This zone is anticipated to include a high concentration of generally intact fossils from a wide range of ages, due to extremely slow rate of sedimentation.

Highstand Systems Tract (HST)

During the late stages of relative sea-level rise, progradational deposits form when sediment accumulation rates exceed the rate of increase in accommodation. When marine sediments reached their greatest landward position, the HST lies directly on the MFS (Fig. 4). This systems tract is capped by the subaerial unconformity and its correlative conformity (Posamentier and Allen, 1999).

Parasequence

In its original definition (Van Wagoner et al., 1988, 1990), a parasequence, or basic building blocks of a succession, is an upward-shallowing succession of facies bounded by marine flooding surfaces might, be expanded to include all regional meter-scale cycles, regardless of whether they are bounded by flooding surfaces (Spence and Tucker, 2007; Tucker and Garland, 2010). Parasequence characterize individual prograding sedimentary bodies in siliciclastic environments (coastal to shallow-water). In case of carbonate setting, a parasequence corresponds to a lag deposit or thin deepening interval followed by a thicker shallowing-upward part (Catuneanu et al., 2011). All meter- scale shallowing upward strata packages may not be individually related to RSL but result of any internal mechanism of the depositional system (for ex. channel filling). Furthermore, intermediate scale strata packages may exist. These are designated parasequence sets.

Stacking Patterns

The basic constituents of any sequence stratigraphic unit (sequence, systems tract or parasequence) are deposits defined by specific stratal stacking patterns. Both shoreline-related and shoreline-independent deposits, as well as associated stacking patterns, may be found in these units. All stratal stacking patterns, on the other hand, reflect the interplay of the two fundamental variables: accommodation and sediment supply. Shoreline-related stacking patterns are defined by combinations of depositional trends: forced regression (forestepping and downstepping at the shoreline, interpreted as the result of negative accommodation); normal regression (forestepping and upstepping at the shoreline, interpreted as the result of positive and overfilled accommodation); and transgression (backstepping at the shoreline, interpreted as the result of positive and underfilled accommodation) (Catuneanu, 2006; Catuneanu et al., 2011 and references therein). Shoreline-independent stacking patterns, on the other hand, may form in areas far from contemporaneous shorelines, where sedimentation processes are unaffected by shoreline modifications.

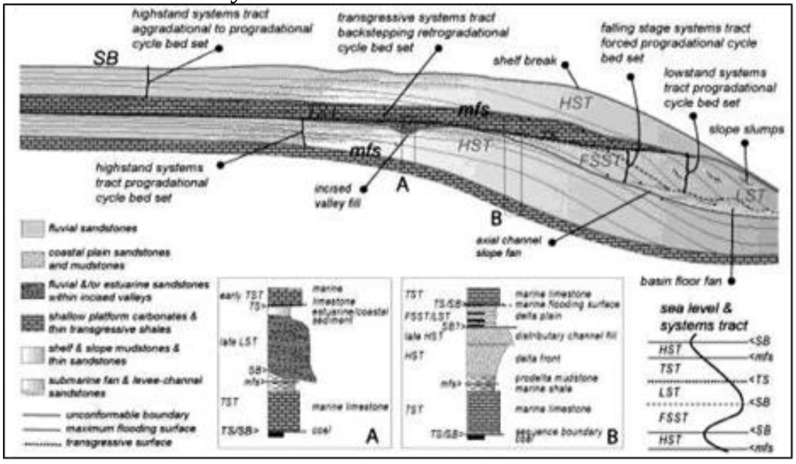

Fig. 4. Depositional sequences and systems tracts (after Kendall and Tucker, 2010). Abbreviations: HST = Highstand systems tract; TST = Transgressive systems tract; LST =Lowstand systems tract.

For example, the degree of amalgamation of channel deposits may reflect syn-depositional conditions of available fluvial accommodation, in upstream-controlled fluvial settings. I deep-water settings, the degree of channel confinement, which may reflect changes in accommodation on the shelf and/or variations in sediment supply in the staging area can characterize depositional patterns in deep - water situations (Catuneanu et al., 2011 and references therein). Sequence stratigraphy emphasizes changes in stratal stacking patterns involving geometries and facies relationships in response to relative sea -level rise or fall. A transgression is defined as the landward migration of the shoreline. This migration triggers a corresponding landward shift of facies, as well as a deepening of the marine water in the vicinity of the shoreline. Transgressions cause a fining-upward sequence and retrogradational (or backstepping) stacking patters, denoted as TST e.g., marine facies shifting towards and overlying non-marine facies (Fig. 5) (Catuneanu, 2002). Base of the TST would be sculpted by a basal, erosional unconformity (transgressive ravinement surface). A transgressive lag, which is often granular or pebbly in form, and gradually pinches out towards the basin interior, may demarcate this surface. The record of transgression may be locked up to the transgressive lag only if the erosion rate is high all the way through the transgressive phase, preventing the formation of TST.

The relative sea-level (RSL) varies over the time. Regression or seaward migration of the shoreline occurs invariably when RSL falls. This migration is accompanied by a shallowing of the marine water in the vicinity of the shoreline as well as seaward shift of facies, e.g., non-marine facies shifting towards and overlying marine facies. An overall coarsening-upward sequence, progradational stacking patterns developed over the TST, and an erosional unconformity at the top define a regressive facies pattern, is designated as Highstand System Tract (HST). Maximum Flooding Surface (MFS) occurs at the top of TST or at the bottom of HST (Fig. 4, 5). HST progradation may expose a vast area of depositional shelf or even slope as a result of rapid RSL fall. Under such circumstances, rivers will be rejuvenated, encroach onto the newly exposed marine depositional surface, incising deep channels containing extra-basinal conglomerates (Falling Stage systems Tract or FSST). The submarine sediment surface of previous regime would appear with emerging features. A subaerial unconformity would develop due to the forced regression topping the HST, which in turn may be onlapped by LST fluvial or by TST (Fig. 4). When a rise in RSL begins, the rate of rise is slow at first, but the rate of sedimentation eventually overtakes. As a result, next to prograding HST, another progradational succession (Lowstand System Tract or LST) will occur. Stacking patterns exhibit forestepping, aggrading clinoforms (in siliciclastic systems) that thicken downdip, and a topset of fluvial, coastal plain and/or delta plain deposits.

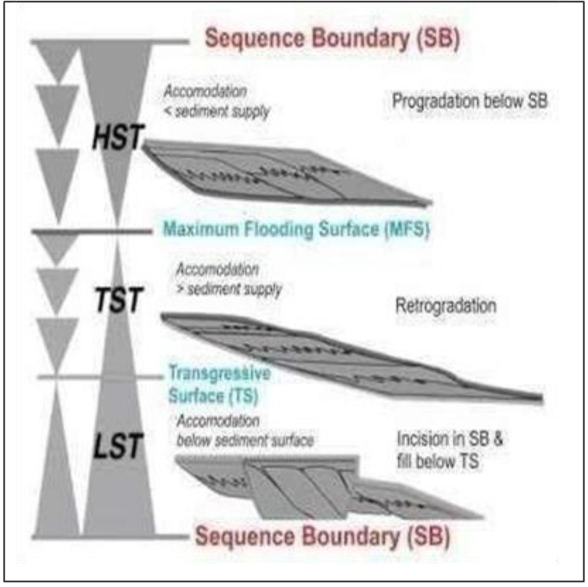

Fig. 5. Stratal stacking patterns showing its basic constituents (after Kendall, 2003). Abbreviations: HST = Highstand systems tract; TST = Transgressive systems tract; LST = Lowstand systems tract.

A LST top part is prone to aggradation as it tries to keep up with the gradually rising RSL (Catuneanu, 2006; Catuneanu et al., 2009, 2010 and references therein). Stratal stacking patterns describing normal regressions, transgressions or forced regressions can succeed each other in any order, as a function of syn- depositional conditions and/or post-depositional preservation (Catuneanu et al., 2011). Sequences may consist of any combination of these types of deposit, but not all of them must be included. Recurrence of TST and HST within a succession is characterized by cyclic variation in stacking patterns, which may be interrupted by unconformities at certain stratigraphic levels as a result of a sudden change in RSL. Hence, within an overall retrogradational (transgressive) or progradational (regressive) sequence both TST and HST may be internally characterised by shorter cycles (i.e. smaller packages known as parasequence) following smaller changes in

RSL From rock record it is evident that sequences may develop over a wide range of temporal and spatial scales, from a scale comparable to that of a parasequence or smaller (Krapez, 1996; Strasser et al., 1999).

Conclusions

Sequence stratigraphy is a modern approach for analyzing the sedimentary rock record within a time framework. Sequence stratigraphic methodology is a useful tool for understanding the major factors controlling sequential pattern (eustatic sea-level change, basin subsidence and sedimentation rate), enhance the power of lithology prediction, recognition of facies, paleogeographic interpretation and basin-wide correlation. In response to changes in the two major factors, accommodation and sediment supply, this analytical method stresses upon the identification of genetic types of deposits and sequence stratigraphic surfaces subdividing the stratigraphic section into component sequence and systems tracts. There are multiple combinations of component systems tracts that a sequence can preserve. However, no single template can provide a solution for every situation. Careful study and a full grasp of all sedimentation controlling parameters are essential, when making sequence stratigraphic interpretations.

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