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Methods of Sequence Stratigraphic Analysis

1-Sedimentological data

Facies analysis (outcrops and core).

2- Well logs

Vertical stacking patterns; grading trends; depositional systems; depositional elements; inferred lateral facies trends; calibration of seismic data

3- Seismic data

Continuous subsurface imaging; tectonic setting; structural styles; regional stratigraphic architecture; imaging of depositional elements; Geomorphology.

4- Geochemical data

Depositional environment; depositional processes; diagenesis; absolute ages; paleoclimate

5- Paleontological data

Depositional environment; depositional processes; ecology; relative ages.

1 : Facies analysis: outcrops and core.

Facies analysis is a fundamental sedimentological method of characterizing bodies of rocks with unique lithological, physical, and biological attributes relative to all adjacent deposits.

1-2: Principles of flow and sediment motion

All natural systems tend toward a state of equilibrium that reflects an optimum use of energy. This state of equilibrium is expressed as a graded profile in fluvial systems, or as a base level in coastal to marine systems. Along such profiles, there is a perfect balance between sediment removal and accumulation.

Fluid and sediment gravity flows tend to move from high to low elevations, following pathways that require the least amount of energy for fluid and sediment motion.

Flow velocity is directly proportional to slope magnitude.

Flow discharge (subaerial or subaqueous) is equal to flow velocity times cross-sectional area.
Sediment load (volume) is directly proportional to the transport capacity of the flow, which reflects the combination of flow discharge and velocity.
The mode of sediment transport (bedload, saltation, suspension) reflects the balance between grain size/weight and flow competence.

1-3: Principles of sedimentation

Walther's Law: within a relatively conformable succession of genetically related strata, vertical shifts of facies reflect corresponding lateral shifts of facies.
The direction of lateral facies shifts (progradation, retrogradation) reflects the balance between sedimentation rates and the rates of change in the space available for sediment to accumulate.
Processes of aggradation or erosion are linked to the shifting balance between energy flux and sediment supply: excess energy flux leads to erosion, excess sediment load triggers aggradation.
The bulk of clastic sediments is derived from elevated source areas and is delivered to sedimentary basins by river systems.
As environmental energy decreases, coarser-grained sediments are deposited first.
Facies (Walker, 1992): a particular combination of lithology, structural and textural attributes that defines features different from other rock bodies.
Facies are controlled by sedimentary processes that operate in particular areas of the depositional environments. Hence, the observation of facies helps with the interpretatiosn of syn-depositional processe.

Facies Association (Collinson, 1969): groups of facies genetically related to one another and which have some environmental significance.
The understanding of facies associations is a critical element for the reconstruction of paleo-depositional environments. In turn, such reconstructions are one of the keys for the interpretation of sequence stratigraphic surfaces.
Facies model (Walker, 1992): a general summary of a particular depositional system, involving many individual examples from recent sediments and ancient rocks.

Depositional systems: (Fisher and McGowan, 1967, in Van Wagoner, 1995): three-dimensional assemblages of lithofacies, genetically linked by active (modern) processes or inferred (ancient) processes and environments.

Sequence: (Mitchum, 1977): a relatively conformable succession of genetically related strata bounded by unconformities or their correlative conformities.

Depositional systems represent the sedimentary product of associated depositional environments. They grade laterally into coeval systems, forming logical associations (Fig. 1).

Systems tract: (Brown and Fisher, 1977): a linkage of contemporaneous depositional systems, forming the subdivision of a sequence.
A systems tract includes all strata accumulated across the basin during a particular stage of shoreline shifts.

Systems tracts are interpreted based on stratal stacking patterns, position within the sequence, and types of bounding surfaces. The timing of systems tracts is inferred relative to a curve that describes the base-level fluctuations at the shoreline.

Sequences correspond to full stratigraphic cycles of changing depositional trends. The conformable or unconformable character of the bounding surfaces is not an issue in the process of sequence delineation, nor the degree of preservation of the sequence.

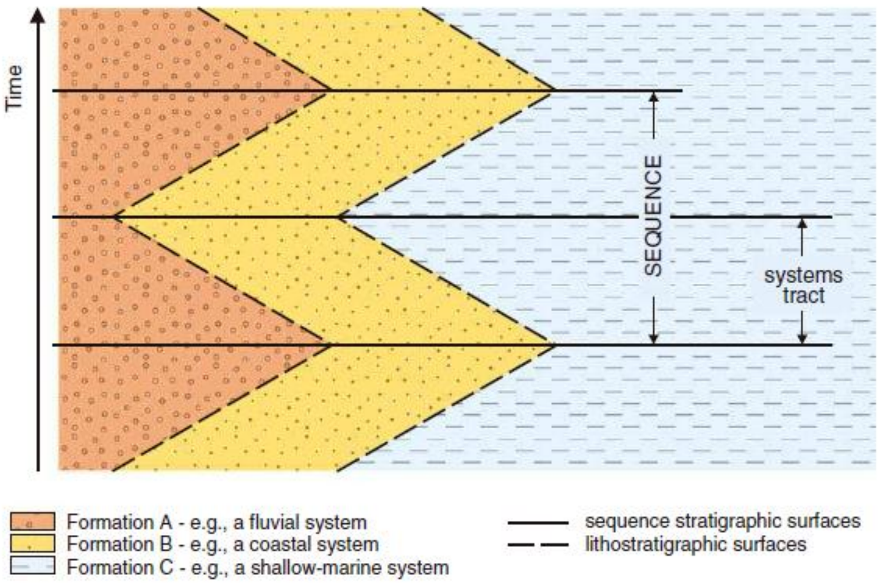

Fig. 1 Conceptual contrast between lithostratigraphy and sequence stratigraphy. Sequence stratigraphic surfaces are event-significant, and mark changes in depositional trends. In this case, their timing is controlled by the turnaround points between transgressions and regressions. Lithostratigraphic surfaces are highly diachronous facies contacts. Note that the system tract and sequence boundaries cross the formation boundaries. Each systems tract is composed of three depositional systems in this example, and is defined by a particular depositional trend, i.e., progradational or retrogradational. Asequence corresponds to a full cycle of changes in depositional trends. This example implies continuous aggradation, hence no breaks in the rock record, with the cyclicity controlled by a shifting balance between the rates of base-level rise and the sedimentation rates.

2-Sequence boundary

During sea-level fall erosion of the shelf occurs as rivers erode into the sediment deposited during the previous cycle: where erosion is localised the rivers cut incised valleys. This erosion creates an unconformity, which in this context is also called a sequence boundary (SB) Fig. 2and 3. It marks the end of the previous depositional sequence and the start of a new one: depositional sequences are defined as the packages of beds that lie between successive sequence boundaries. If the sea level falls to the level of the shelf edge then both the detritus from the hinterland being carried by the rivers and the material eroded from the shelf are carried beyond the edge of the shelf.

This sediment forms a succession of turbidites on the basin floor that are deposited during the period of falling sea level, forming a basin floor submarine fan. There is no unconformity within the basin floor succession to mark the sequence boundary, so the start of the next sequence is marked by a correlative conformity, a surface that is laterally equivalent to the unconformity that forms the sequence boundary on the shelf..

Sequence boundaries are generated by a relative fall in sea level. as this is a relative fall in sea level, it may be produced by changes in the rate of tectonic subsidence or by changes in the rate of eustatic rise, as long as those changes result in a net loss of accommodation space. Early models of sequence boundary formation argued that the sequence boundary formed at the time of maximum rate of fall, but subsequent models suggest that the age of the sequence boundary can range in age from the time of maximum rate of fall to the time of eustatic lowstand.

Early seismic studies recognized two types of sequences reflecting the case of sea-level fall below the shelf-slope break (type 1) Fig. 2 and the case where sea level does not fall below this break (type 2) Fig. 3.

According to Van Wagoner *et al.* (1988), a type 1 sequence boundary is characterized by subaerial exposure and concurrent subaerial erosion associated with stream rejuvenation, a basinward shift in facies, As a result of the basinward shift in facies, non-marine or marginal marine rocks, such as braided-stream or estuarine sandstones, may directly overlie shallow-marine rocks, such as lower shoreface sandstones or shelf mudstones, across a sequence boundary with no intervening rocks deposited in intermediate depositional environments Fig. 2 .

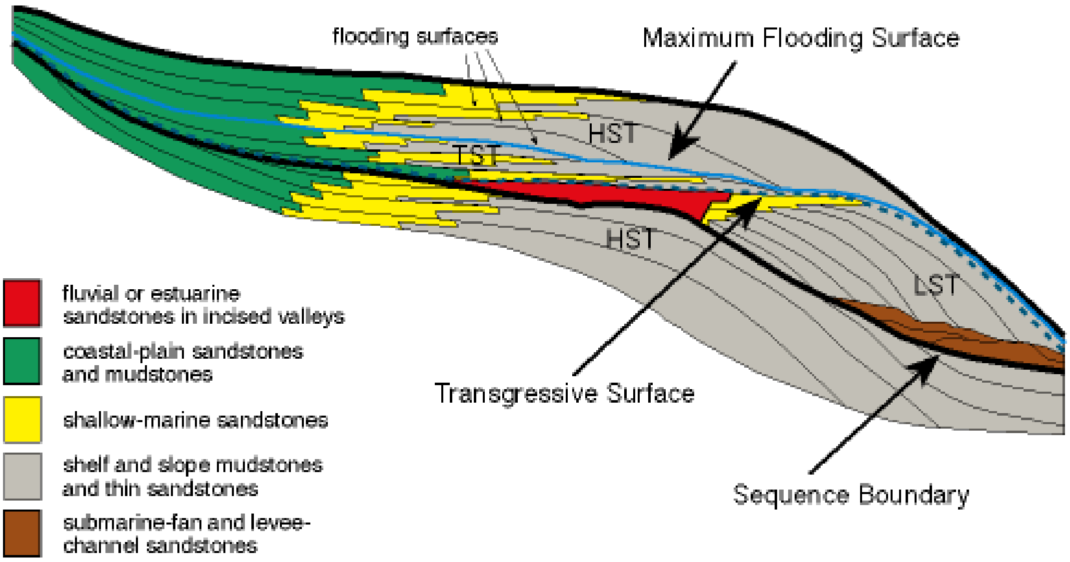

Fig. 2 Type 1 sequence boundary

Type 2 sequences (shown below) are similar to type 1 sequences (shown above) in nearly all regards except for the extent of the sequence-bounding unconformity and its expression in the marine realm. In addition, the two sequences differ in the name of the systems tract lying above the sequence boundary but below the transgressive surface.

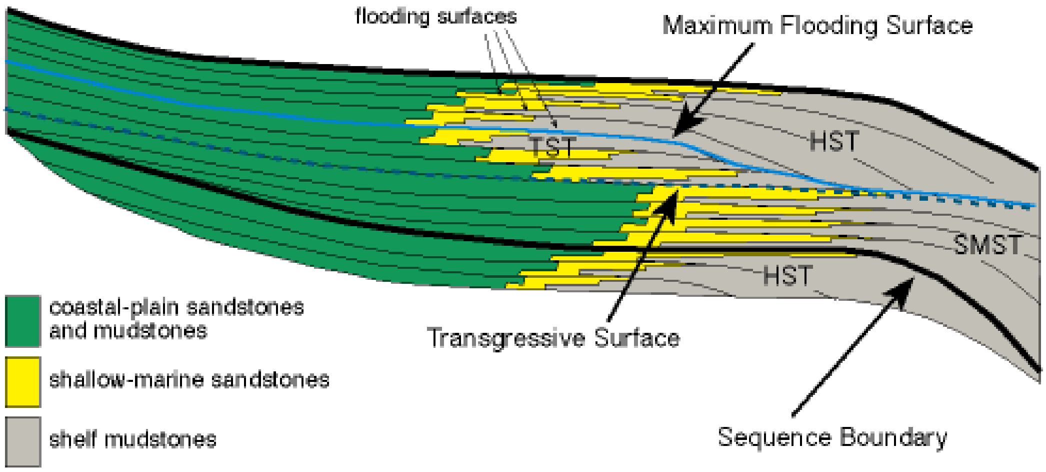

Fig. 3 Type 2 sequence boundary

In a type 2 sequence, the extent of the sequence-bounding unconformity can reach seaward only to the position of the previous shoreline, but no further. the sequence bounding unconformity is expressed as for a type 1 sequence, but no incised valley forms as sea level does not fall far enough for incision. In the marine realm, no basinward shift of facies occurs as in a type 1 sequence, and the type 2 sequence boundary is characterized only by a slight change in stacking patterns .

The **shelf margin systems tract** in a type 2 sequence is equivalent in stratigraphic position to the lowstand systems tract of a type 1 sequence. As stated above, the shelf margin systems tract is characterized by aggradational stacking. Like the lowstand systems tract, the shelf margin systems tract is capped by the transgressive surface.

In general, far more type 1 sequences have been reported than type 2 sequences.

3- Systems Tracts

The term was first used by Brown and Fisher(1977) to represent contemporaneous depositional systems. a system tract is therefore a three dimensional unit of deposition, and the boundaries of a system tract are depositional boundaries.

Within one relative sea-level cycle, four main systems tracts are frequently developed fig 4.

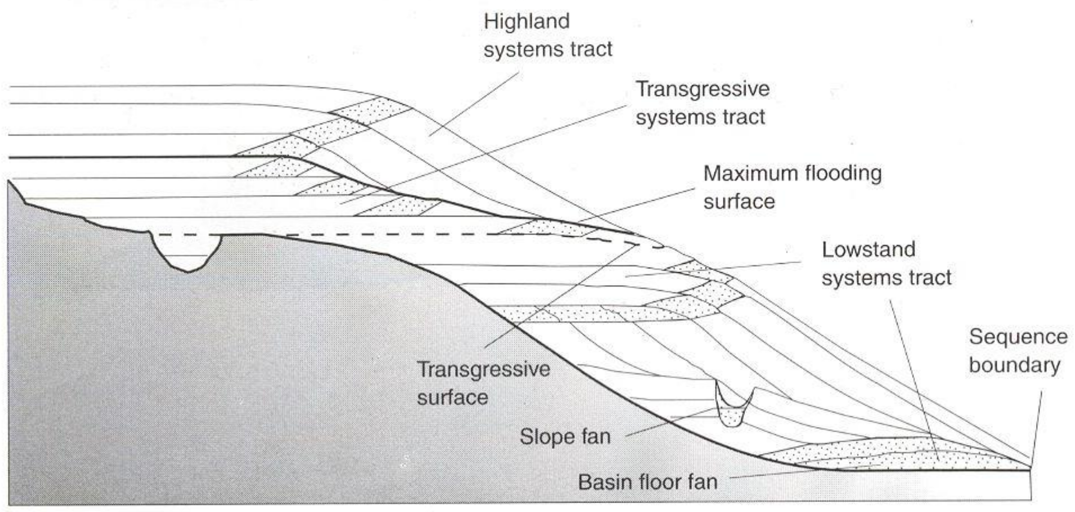

Fig. 4 Systems tract- idealized type-1 sequence shown is representative of a shelf-break margin. Deposition in a basin is not uniform and continuous but occurred in a series of discrete packets bounded by seismic reflection terminations.

The system tract represents the fundamental mapping unit that contains depositional systems for which a paleogeographic map can be drawn.

3-1 Falling- stage system tract (FSST)

The FSST consists of a set of basinward-stepping and downward-stepping high-frequency sequences, each bounded below by a surface of forced regression. This is the only systems tract to have this unusual architecture. The base of the FSST is placed at the basal surface of forced regression (bsfr) and the top lies at the sequence boundary (sb). The FSST is the only systems tract to form during a relative fall in sea level, and as a result, it is typically thin. In many cases, it is eroded away entirely during subsequent subaerial exposure and formation of a sequence boundary. Because of its thinness and relative rarity, the FSST was originally not regarded as a distinct systems tract and was included as part of the late highstand systems tract Fig. 5.

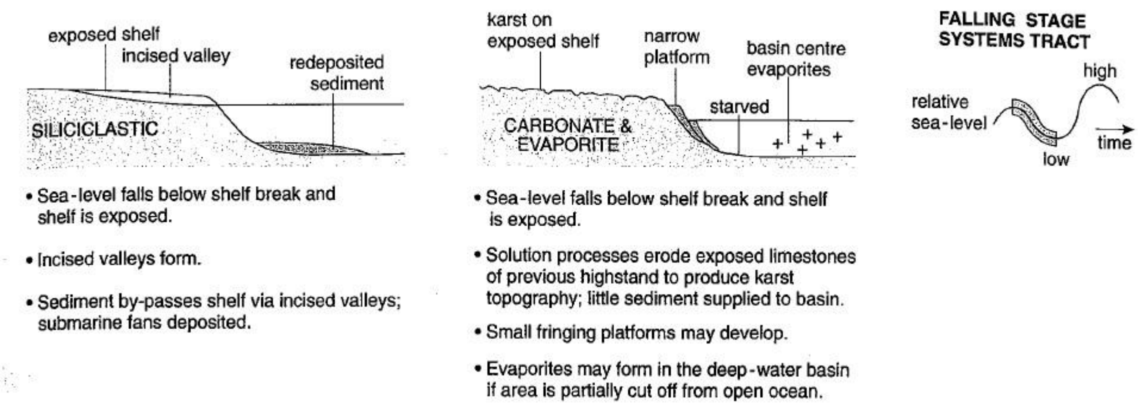

Fig. 5 Falling stage systems tract.

3-2 Lowstand System Tract (LST)

The LST contains a set of progradationally stacked parasequences, that is, parasequences that progressively build basinwards and that form a net shallowing-upward succession. The lowstand systems tract is underlain by a sequence boundary (sb) and overlain by the transgressive surface (ts), the first major flooding surface of the sequence. The LST is deposited during a slow relative rise in sea immediately following a relative fall in sea level.

• The basal system tract in a type 1 depositional sequence Fig. 6.
• It is deposited during an interval of relative sea-level fall at the offlap break, and subsequent slow relative sea-level rise.
• Falling relative sea-level at the offlap break of a shelf-break margin will have an extreme effect on the river system.
• The river incises into the previous deposited topsets.

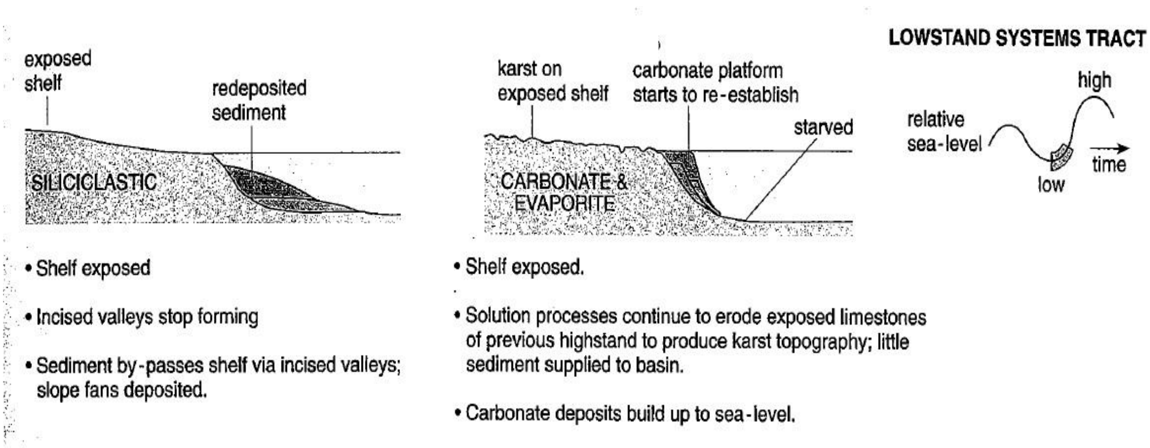

Fig. 6 Lowstand system tract.

• These rewroked sediments, and the fluvial load from the land, are delivered directly on to the previous highstand clinoform.
• Because the river is not free to avulse, the sediments are focused towards the same point in the slope.
• Because instability the sedimentation processes are dominated by large scale slope failure resulting in bypass of the slope and deposition of submarine fans in the basin Fig. 7.

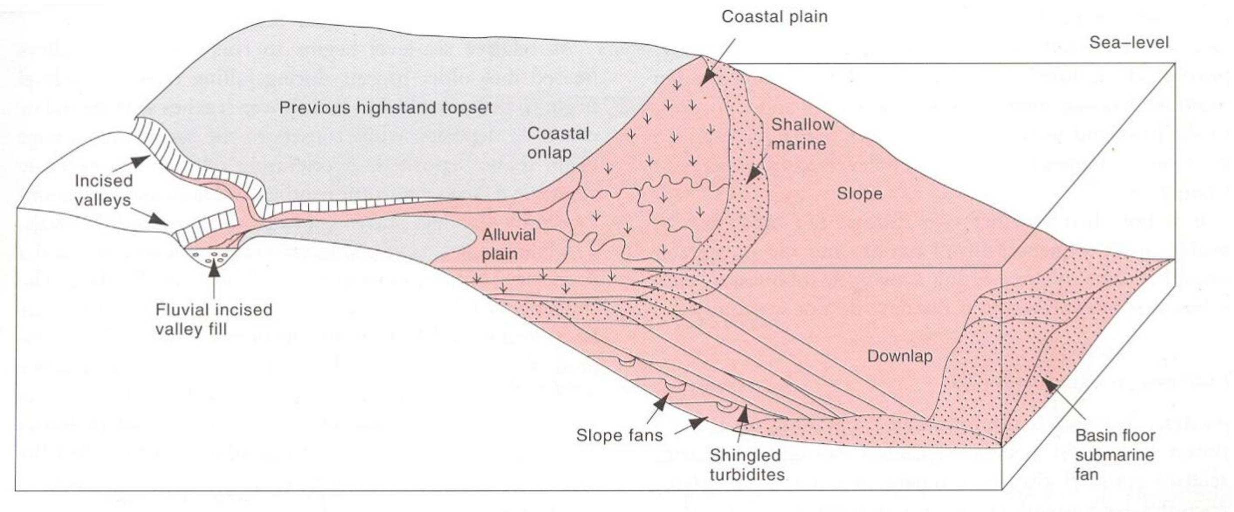

Fig. 7 Components of the Lowstand system tract on a shelf break margin . These include basin floor fan, and a slope fan, but the diagram shows the active systems of the lowstand wedge; namely valley fill, alluvial and coastal plain topsets, a shallow marine belt and an active slope system, which in its early stages my contain shingled turbidities .

3-2-1 Low stand submarine fans

- Two distinctive fan units can be recognized within the lowstand submarine fan; an initial basin floor fan unit, detached from the foot of the slope, and a subsequent slope fan unit, abutting the slope, occasionally referred to as slope front fill.
- Submarine fan deposits on the lower slope or basin.
- Associated with erosion of canyons into the slope.
- Turbidites and debris flow.

3-2-2 Lowstand prograding wedge

- Topset clinoform system deposited during accelerating relative sea-level rise.
- It is separated from the overlying transgressive system tract by a maximun prograding surface.

3-3 Transgressive Systems Tract (TST)

The TST is built from a set of retrogradationally stacked parasequences, that is, a set of parasequences that progressively step landward and that forms a net deepening-upward succession. The TST is underlain by the transgressive surface (ts) and overlain by the maximum flooding surface (mfs), which records the deepest-water conditions within the sequence. The TST contains the most prominent flooding surfaces within the sequence. This systems tract forms during a relative rise in sea level that is rapid enough to outpace the rate of sediment accumulation.

• It is the middle systems tract of both type 1 and type 2 sequences.
• It is deposited during the part of the relative sea-level rise cycle when topset accomodation volume is increasing faster than the rate of sediment supply fig. 8.

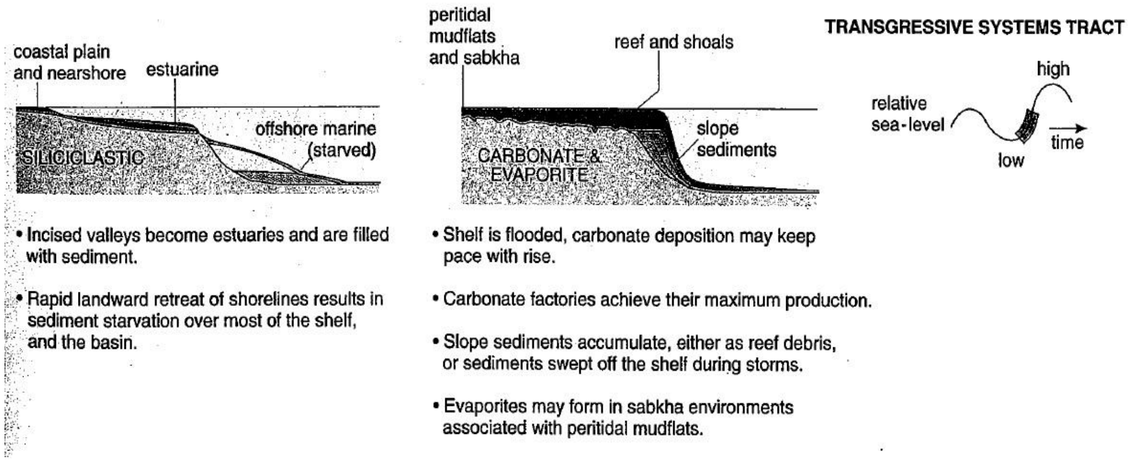

Fig. 8 Transgressive system tract

• It contain mostly topsets, with few associated clinoforms, and is entirely retrogradational.
• The active depositional systems are topset systems:
– alluvial,
– paralic (coal deposits formed along the margin of the sea),
– coastal plains
– shelfal.
• Wide shelf area are characteristic of transgressive systems tract.
• The Transgressive Systems Tract passes distantlly into a condensed

section characterized by extremely low rates of deposition and the development of condensed facies such as glauconitic, organic reach and/or phosphatic shales, or pelagic carbonates fig. 9.

- The ***maximum rate of rise of sealevel*** occurs some time within the transgressive systems tract, and the end of the systems tract occurs when the ***rate of topset accomodation*** volume ***decreases*** to a point where it just matches sediment supply, and progradation begins again This point is known as ***Maximum Flooding Surface***.
- Topsets of the TST tend to have a lower sand percentage than those of other systems tracts, because little of the mud-grade sediment bypasses the topsets.
- TST can therefore often hast sealing horizons to topset reservoirs, and also source beds.
- Present-day depositional systems over much of the glove form a TST.

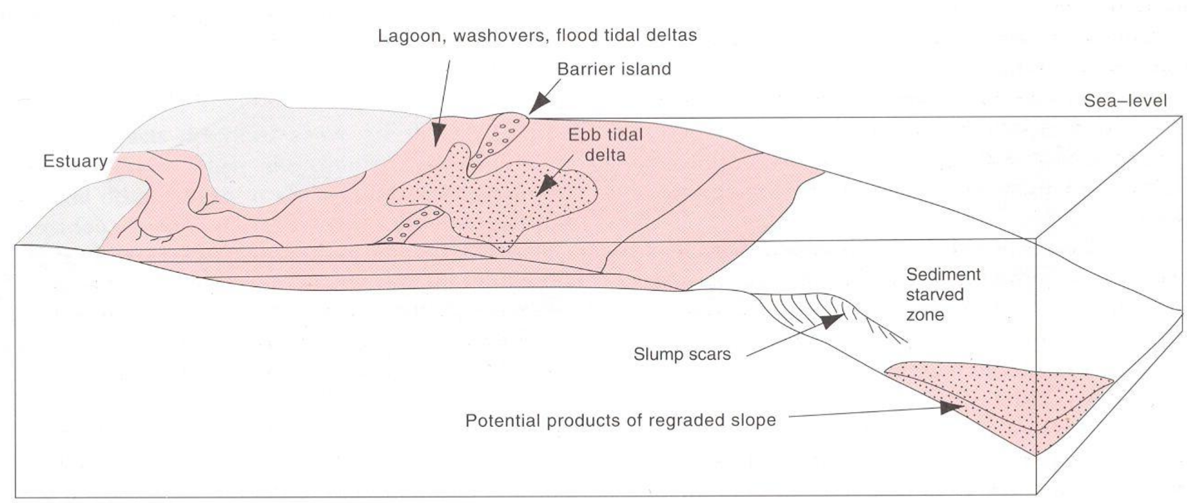

Fig. 9 Components of the Transgressive system tract. These are all topset systems, here are shown to have significant tidal influence, due to the wide shelfal area of the drowned lowstand topsets. Depostion includes estuarine, lagoonal, barrer and tidal depostional systems, wich pass seaward into a shelfal condensed zone.

3-4 Highstant Systems Tract (HST)

The HST contains a progradational set of parasequences, like the LST, but occurs in topographically higher setting, hence its name. The HST is underlain by the maximum flooding surface (mfs) and displays net upward shallowing to its upper bounding surface, the basal surface of forced regression (bsfr) or its correlative surface. The HST accumulates during a slow relative rise in sea level. Because the rate of sea-leve rise declines during the HST, coastal plain systems transition from mudstone-dominated with single-story fluvial channels in the lower HST to sandstone-dominated with multi-story fluvial channels in the upper HST. The HST is commonly capped by an unconformity at the sequence boundary (sb), which records prolonged subaerial exposure and erosion.

• The HST is the youngest sytems tract in either a type 1 or a type 2 sequence.
• It represent the progradational topset clinoform system deposited after maximum transgression, and before a sequence boundary, when the rate of creation of accommodation is less than the rate of sediment supply fig. 10.

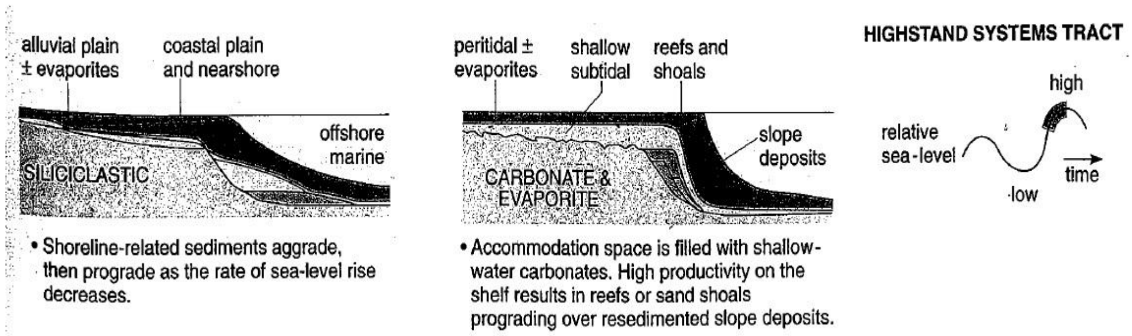

Fig. 10 Highstand system tract

• Deposits are similar initially to those of TST, but the infill of shelf areas by progradation, and the decrease in the rate of sea-level rise, may lead to a decrease in tidal influence and adecrease in the amount of coal, and of overbanks, laggonal and lacustrine shales fig. 11.

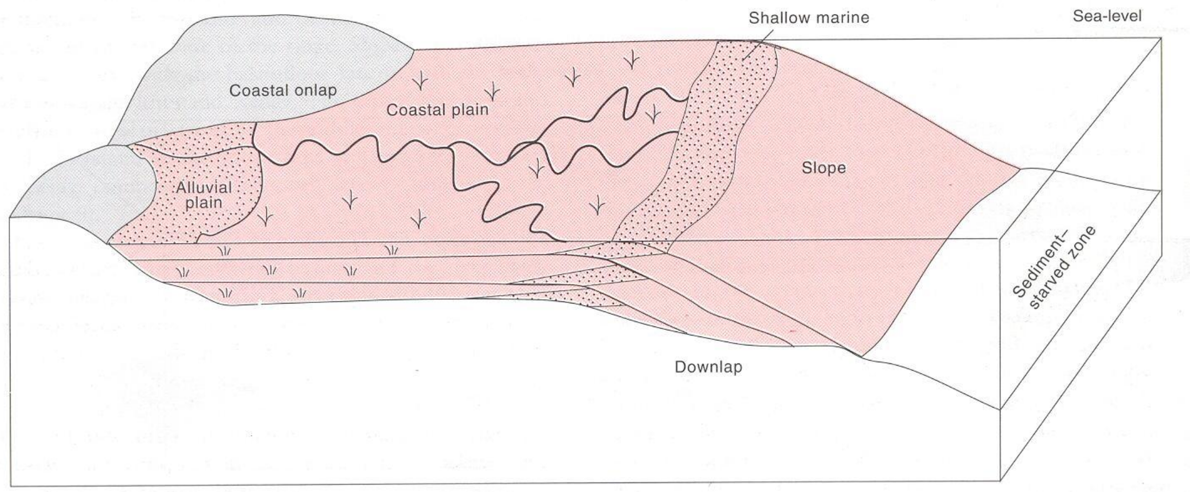

Fig. 11 Components of the Highstand system tract on a shelf break margin . These include (alluvial , coastal), shallow marine and slope systems.

4- Sequence stratigraphy of wireline logs
4-1 Sedimentological interpretation of wireline logs

It is common for the interpretation of subsurface formations to be based very largely on wireline log data, with only a limited amount of core information being available.

Certain lithologies have very distinctive log responses that allow them to be readily distinguished in a stratigraphic succession. Coal, for example, has a low density that makes it easily recognisable in a succession of higher density sandstones and mudstones fig. 12.

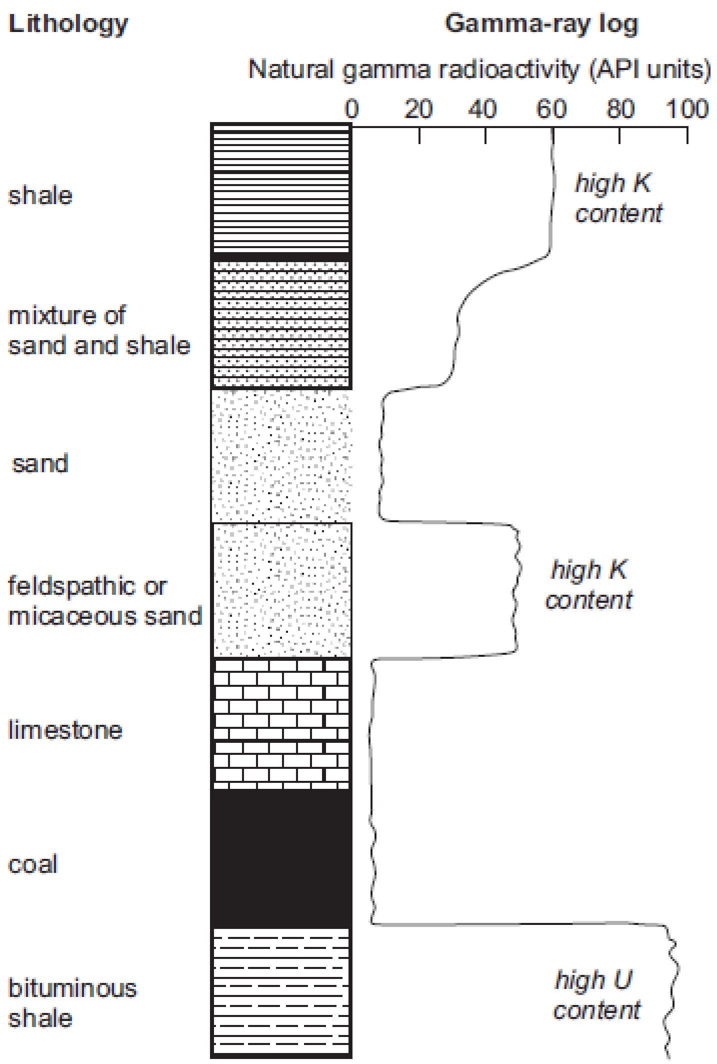

Fig. 12 Determination of lithology using information provided by a gamma-ray logging tool(From Rider 2002.)

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A bed of halite may also be picked out from a succession of other evaporite deposits and limestones because it is also relatively low density. Igneous rocks such as basalt lavas have markedly higher densities than other strata. Organic-rich mudrocks have high natural gamma radioactivity that allows them to be distinguished from other beds, especially if a spectral gamma-ray tool is used to pick out the high uranium content. However, many common lithologies cannot easily be separated from each lithologies cannot easily be separated from each lithologies cannot easily be separated from each and limestone, which have similar densities, natural radioactivity and electrical properties. Information from cuttings and core is therefore often an essential component of any lithological analysis.

The gamma-ray log is the most useful tool for subsurface facies analysis as it can be used to pick out trends in lithologies Fig. 13. An increase in gamma value upwards suggests that the formation is becoming more clay-rich upwards, and this may be interpreted as a fining-up trend, such as a channel fill in a fluvial, tidal or submarine fan environment.

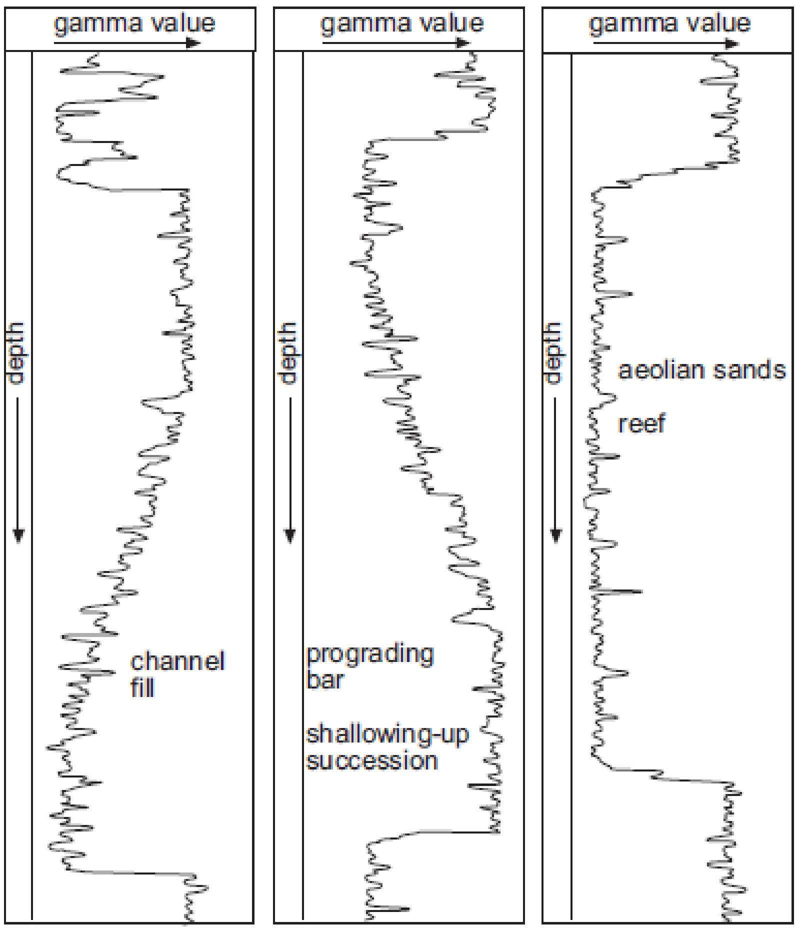

Fig.14 Trends in gamma-ray traces can be interpreted in terms of depositional environment provided that there is sufficient corroborative evidence from cuttings and cores (From Cant 1992.).

A coarsening-up pattern, as seen in prograding clastic shorelines, shoaling carbonate successions and submarine fan lobes may be recorded as a decrease in natural gamma radiation upwards. A drawback of using these trends is that they are not unique to particular depositional settings and other information will be required to identify individual environments.

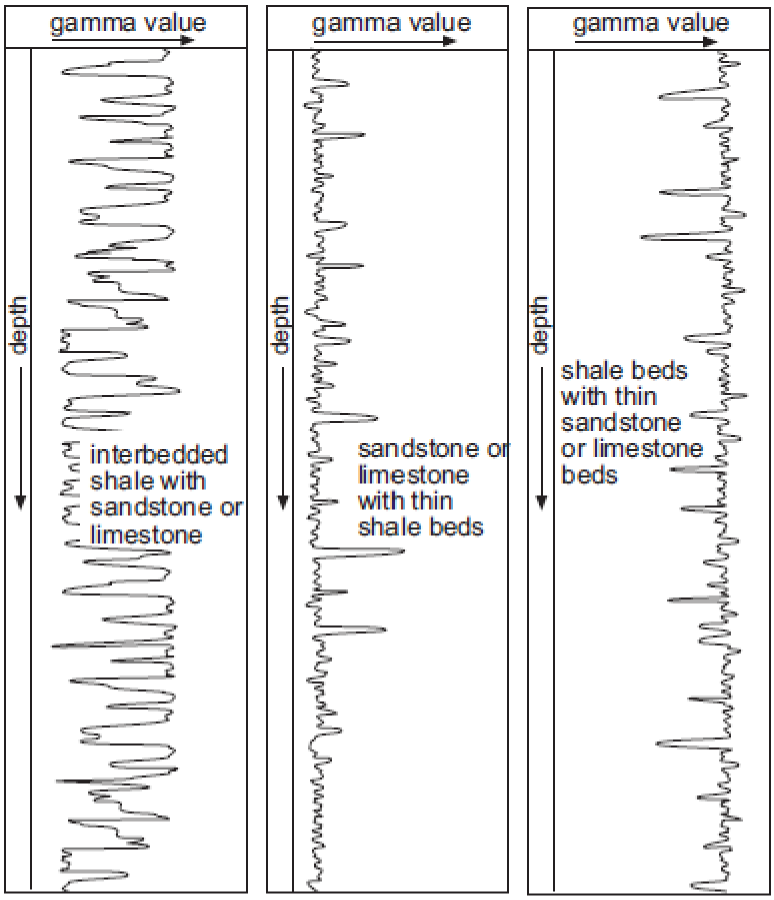

Fig.15 Trends in gamma-ray traces can be interpreted in terms of depositional environment provided that there is sufficient corroborative evidence from cuttings and cores (From Cant 1992.).

Detailed facies analysis can therefore be carried out using these tools, although patterns are not always easy to interpret and the most reliable interpretations can be made if there is also some core with which to make comparisons.

4-2 Log trand used in sequence stratigraphy

Log response may be used to estimate lithology, subject to the caveats above. Trends in log response (at any scale) therefore may equate with trends in depositional energy, and thus with patterns of sedimentary infill. In shallow marine successions, for example, increasing depositional energy is related directly to decreasing water depth.

A number of distinctive trends are recognized frequently on wireline logs, and generally are described from their gamma-log expression. Log trends may be observed as a change in the average log reading, or from shifts in the sand or shale base line (where the sand base line on a gamma log is the line marking the minimum gamma locus of the curve over an interval, and the shale base line is the line marking the maximum gamma locus)fig. 15 .

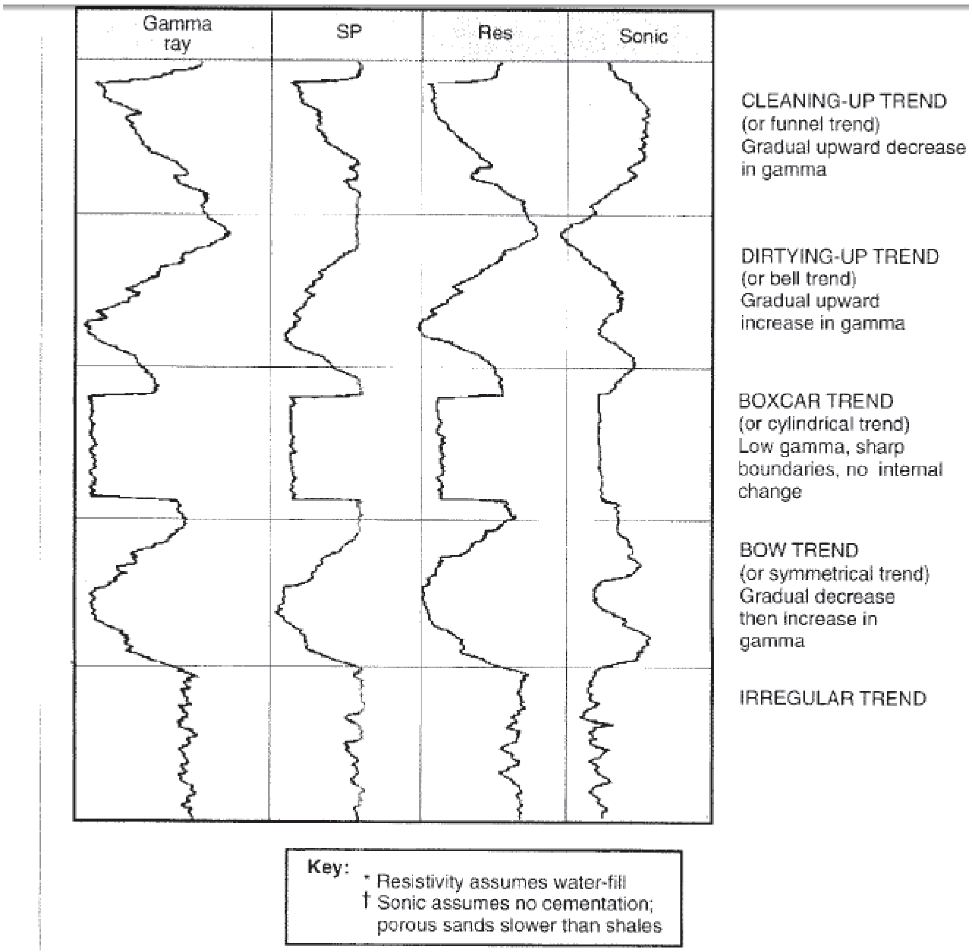

Fig.15 Idealized log trends

The Cleaning-up trend shows a progressive upward decrease in the gamma reading, representing a gradual upward change in clay-mineral content.

In shallow marine settings the cleaning-up motif is usually related to an upward transition from shale-rich to shale-free lithologies, owing to an upward increase in depositional energy, upward shallowing and upward coarsening or to progradation of a depositional system.

The 'dirtying-up' trend shows a progressive upward increase in the gamma reading related to a gradual upward change in the clay-mineral component.

Upward-fining predominates within meandering or tidal channel deposits, where it represents an upward decrease in fluid velocity, and thus energy, within the channel. Larger fining-up units are commonly recorded in coarse fluvial successions and in estuarine fill (Chapter 8). Channel deposits often have a basal lag, which may affect the gamma response if the lag contains shale clasts or heavy minerals.

Boxcar log trends (also known as the cylindrical motif) are sharp-based low-gamma units with an internally relatively constant gamma reading, set within a higher gamma background unit. The boundaries with the overlying and underlying shales are abrupt. The sonic reading from the sands may be either a higher or a lower transit time than from the shales, depending on cementation and compaction.

The interbedding of the two contrasting log units implies the existence of two contrasting depositional energies, and an abrupt switching from one to the other. Boxcar log trends are typical of some types of fluvial channel sands, turbidites, and aeolian sands.

The Bow trend (also known as barrel trends, symmetrical trends) consists of a cleaning-up trend, overlain by a dirtying-up trend of similar thickness and with no sharp break between the two. A bow trend is generally the result of a waxing and waning of clastic sedimentation rate in a basinal setting, where the sediments are unconstrained by base level, as for example during the progradation and retrogradation of a mud-rich fan system.

Irregular trends have no systematic change in either base line, and lack the clean character of the boxcar trend. They represent aggradation of a shaley or silty lithology, and may be typical of shelfal or deep water settings, a lacustrine succession, or muddy alluvial overbank facies.

4-3 Estimation of depositional control and sequence stratigraphy

A sequence analysis of a well-log suite is concerned with the identification of periods of basin-margin progradation and retrogradation, and the recognition of variations of relative sea-level. The logging suite shown on Fig. 4.6 is interpreted in Fig. 4.13, using the sequence stratigraphic methodology described in this chapter.

Progradation can be recognized from either a clinoform log response (large-scale cleaning- and shallowing-up unit), or from the progradational stacking of topset parasequences (as in Fig. 2.25). Evidence of basin-margin progradation will be found only within basin-margin units (topsets, clinoforms and toesets). Basinal logs may record only a time-equivalent condensed section.

Retrogradation of the basin margin is recognized from retrogradational stacking of topset parasequences, or from interpretation of a log unit implying significant upward-deepening

The response of a prograding unit, with constant sediment supply, to accelerating relative sea-level rise is a gradual upward change from progradation to aggradation, leading eventually to transgression. This may result in a log motif that changes from cleaning-up to aggradational, typical of many lowstand prograding wedges. Decelerating relative sea-level rise is suggested by a thinning-up stack of parasequences that aggrade to base level, especially if this is regionally recognizable.