9. Sequence Stratigraphy

Rather than being based either on correlation of rocks using lithology, fossils or other stratigraphical techniques, or on facies analysis to construct past sedimentary environments and systems, sequence stratigraphy combines the two approaches and recognizes packages of strata each of which was deposited during a cycle of relative sea-level change and/or changing sediment supply.

The packages of strata are bounded by chronostratigraphical surfaces. These surfaces include unconformities formed during relative sea-level fall and flooding surfaces formed during relative sea-level rise.

Advantages of sequence stratigraphic analysis:

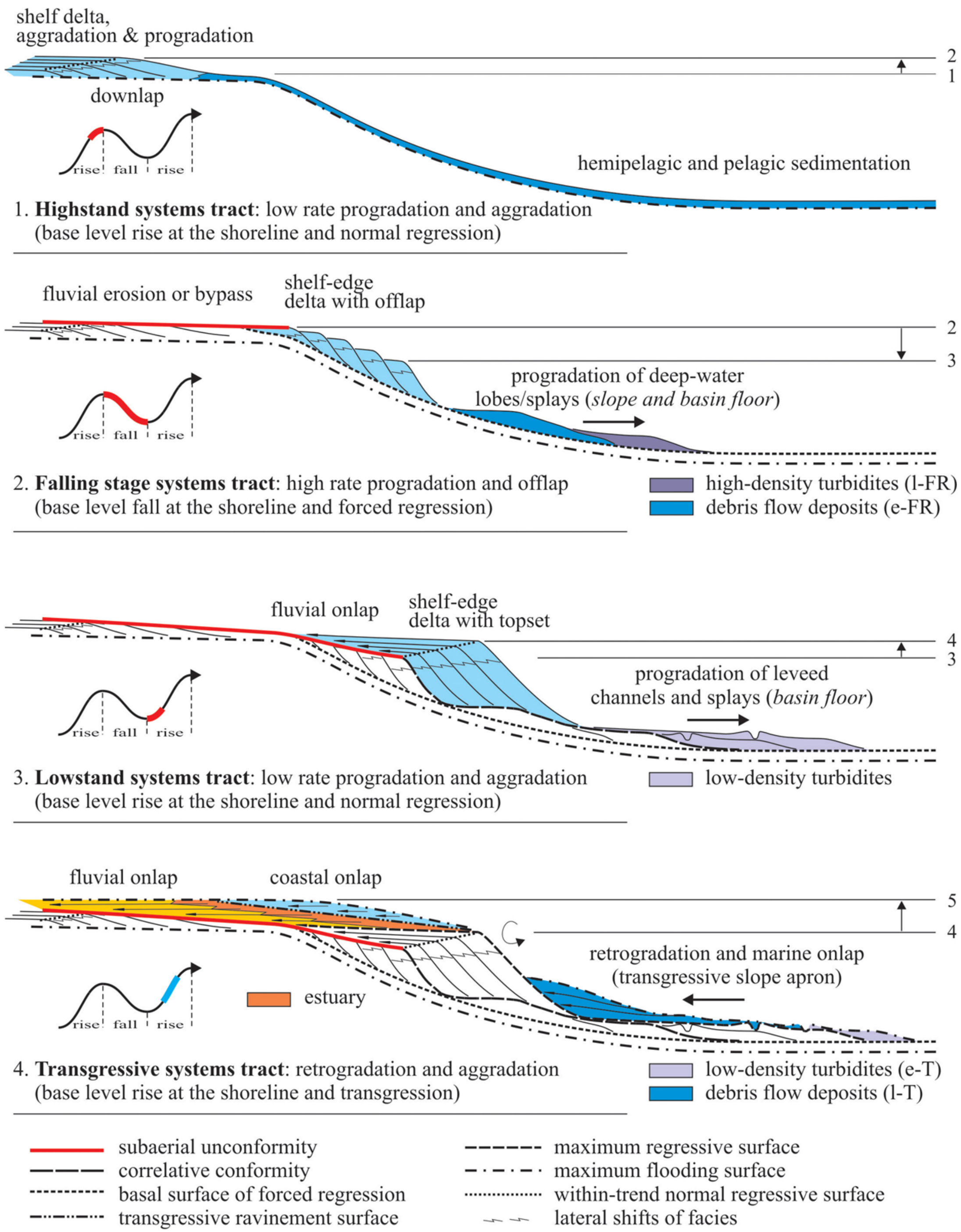
- To try to understand and predict gaps (unconformities) in the sedimentary record.
- To divide the sedimentary record into time-related genetic units, which are useful for stratigraphical correlation and prediction of facies.
- To obtain a holistic view of the distribution of sedimentary facies in time and space.
- To determine the amplitude and rates of past changes in sea-level, and so aid our understanding of the nature of crustal (e.g. fault movement, isostasy, ocean-floor spreading) and climatic processes operating in the past.
- To help identify, classify and understand the complex hierarchy of sedimentary cycles in the stratigraphical record. Sequence stratigraphy is useful for analyzing cycles that range, in duration, from the 10 ka to >50 Ma scale.

Sequence Stratigraphy

Material for this chapter are mainly from the following articles.

- Catuneanu, O., 2002. Sequence stratigraphy of clastic systems: concepts, merits, and pitfalls. Journal of African Earth Sciences 35 (1), 1–43.
- Catuneanu, O. (2006) *Principles of Sequence Stratigraphy*. Elsevier, 375 pp.
- Catuneanu, O. and 27 others (2009) Towards the standardization of sequence stratigraphy. Earth-Science Reviews 92, 1-33.
- Coe, A. L., 2003. The Sedimentary Record of Sea-Level Change. Cambridge University Press, 287pp.

Regional architecture of depositional systems, systems tracts, and stratigraphic surfaces



The systems tract nomenclature follows the scheme of Hunt and Tucker (1992). Systems tracts are defined by stratal stacking patterns and bounding surfaces, with an inferred timing relative to the base-level curve at the shoreline. Note that on seismic lines, downlapping clinoforms are concave-up, whereas transgressive 'healing phase' strata associated with coastal and marine onlap tend to be convex-up. Abbreviations: e-FR—early forced regression; l-FR—late forced regression; e-T—early transgression; l-T—late transgression.

Key concepts of sequence stratigraphy.

Depositional systems (Galloway, 1989): three-dimensional assemblages of process-related facies that record major paleo-geomorphic elements.

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.

Depositional systems represent the sedimentary product of associated depositional environments. They grade laterally into coeval systems, forming logical associations of paleo-geomorphic elements (cf., systems tracts).

Systems tract (Brown and Fisher, 1977): a linkage of contemporaneous depositional systems, forming the subdivision of a sequence.

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.

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

Sequences and systems tracts are bounded by key stratigraphic surfaces that signify specific events in the depositional history of the basin. Such surfaces may be conformable or unconformable, and mark changes in the sedimentation regime across the boundary.

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.

The concepts of sequence, systems tracts, and stratigraphic surfaces are independent of scale, i.e. time for formation, thickness, or lateral extent. Same sequence stratigraphic terminology can be applied to different orders of cyclicity, via the concept of hierarchy. Well log signatures are not part of the definition of sequence stratigraphic concepts, although general trends may be inferred from the predictable stacking patterns of systems tracts. The magnitude of the log deflections will vary with the magnitude/importance of the mapped surfaces and stratal units.

Catuneanu (2002)

Definitions of sequence stratigraphy

Sequence stratigraphy (Posamentier et al., 1988; Van Wagoner, 1995): the study of rock relationships within a time-stratigraphic framework of repetitive, genetically related strata bounded by surfaces of erosion or nondeposition, or their correlative conformities.

Sequence stratigraphy (Galloway, 1989): the analysis of repetitive genetically related depositional units bounded in part by surfaces of nondeposition or erosion.

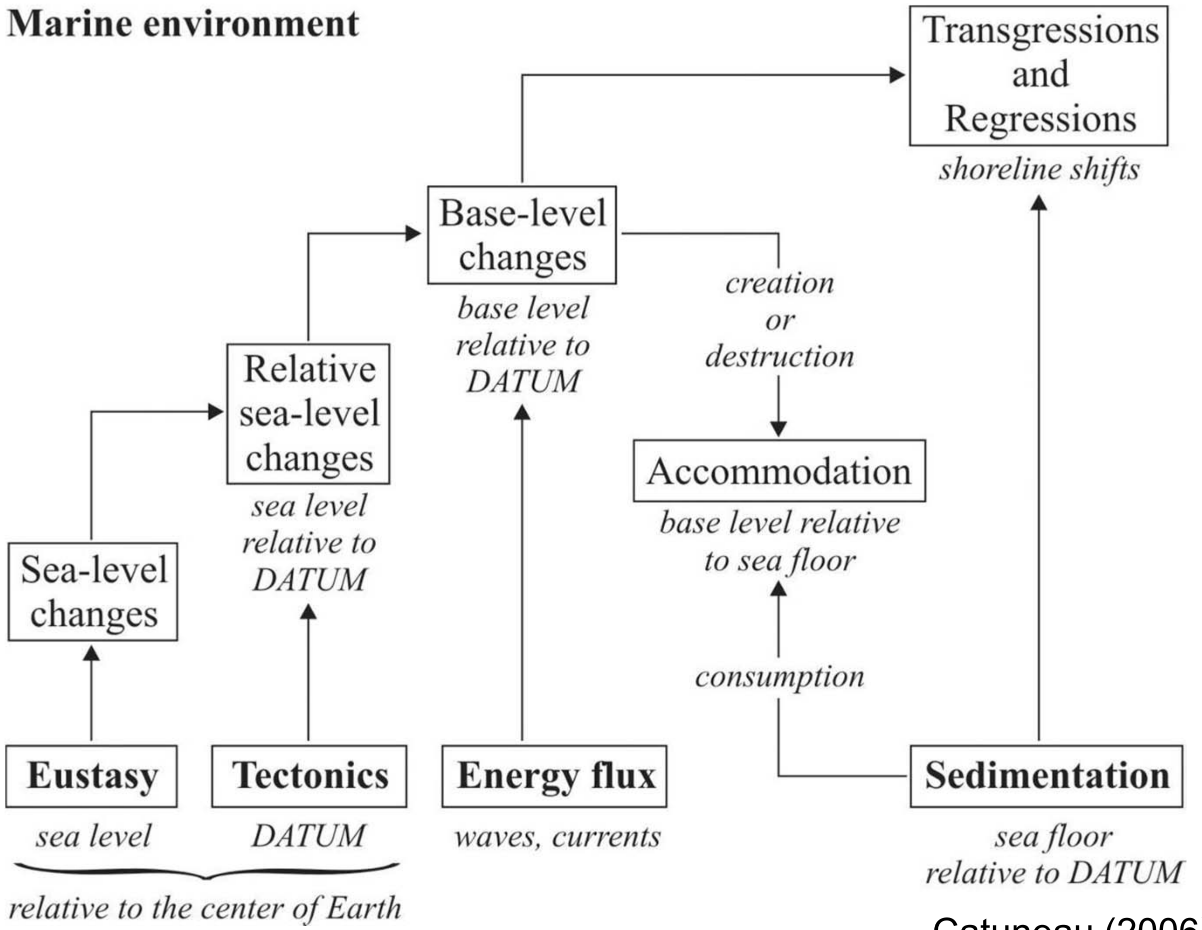
Sequence stratigraphy (Posamentier and Allen, 1999): the analysis of cyclic sedimentation patterns that are present in stratigraphic successions, as they develop in response to variations in sediment supply and space available for sediment to accumulate.

Sequence stratigraphy (Catuneanu, 2006): the analysis of the sedimentary response to changes in base level, and the depositional trends that emerge from the interplay of accommodation (space available for sediments to fill) and sedimentation.

In the simplest sense, sequence stratigraphy studies stratal stacking patterns and changes thereof in a temporal framework.

Controls on accommodation and shoreline shifts in a marine environment

This diagram also applies to lacustrine environments by substituting sea level with lake level. The energy flux lowers the base level *via* the effects of waves, wave-generated currents, tidal currents, contour currents, or gravity flows. Short-term climatic changes (seasonal to sub-seasonal time scales) are accounted for under energy flux, whereas the longer-term climatic changes (e.g., Milankovitch type) are built into eustasy.



Catuneau (2006) p.87

The ‘energy flux’ box stands for the dynamic balance between environmental energy and sediment supply, as an increase in energy *relative to sediment supply* leads to base-level fall (loss of accommodation), and a decrease in energy *relative to sediment supply* leads to base-level rise (gain of accommodation). Note the difference between ‘sediment supply’ (load moved by a transport agent) and ‘sedimentation’ (amount of vertical aggradation). For example, depending on energy flux conditions, high sediment supply does not necessarily result in high sedimentation rates. Base-level changes depend on sediment supply, but are measured independently of sedimentation. In contrast, relative sea-level changes are independent of both sediment supply and sedimentation.

The concept of base level

Base level (Twenhofel, 1939): highest level to which a sedimentary succession can be built.

Base level (Sloss, 1962): an imaginary and dynamic equilibrium surface above which a particle cannot come to rest and below which deposition and burial is possible.

Base level (Schumm, 1993): the imaginary surface to which subaerial erosion proceeds. It is effectively sea level, although rivers erode slightly below it.

Base level (Cross, 1991): a surface of equilibrium between erosion and deposition.

Base level (Cross and Lessenger, 1998): a descriptor of the interactions between processes that create and remove accommodation space and surficial processes that bring sediment or that remove sediment from that space.

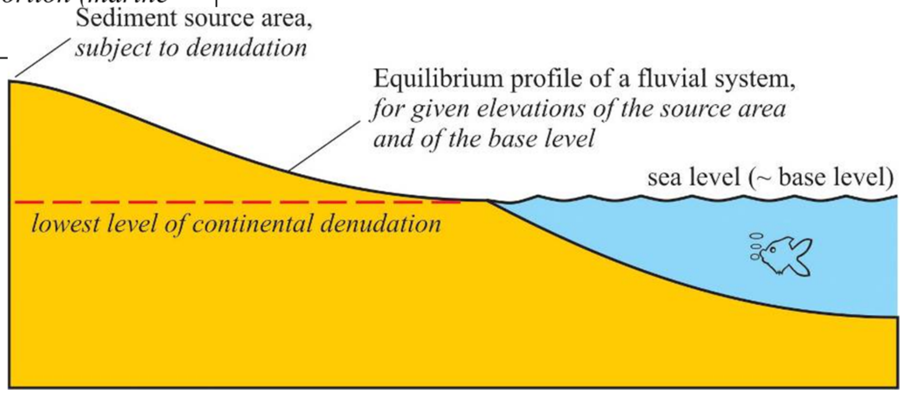
There are two schools of thought regarding the concept of base level:

(1) Base level is more or less the sea level, although usually below it due to the action of waves and currents. The extension of this surface into the subsurface of continents defines the ultimate level of continental denudation. On the continents, processes of aggradation versus incision are regulated via the concept of graded fluvial profile. Graded fluvial profiles meet the base level at the shoreline (Fig. 6).

(2) The concept of base level is generalized to define the surface of balance between erosion and sedimentation within both marine and continental areas (the "stratigraphic" base level of Cross and Lessenger, 1997). In this acceptance, the concept of graded fluvial profile becomes incorporated within the concept of base level. The stratigraphic base level will thus include a continental portion (fluvial base level = graded fluvial profile) and a marine portion (marine base level = sea level).

Defined as the lowest level of continental denudation (modified from Plummer and McGeary, 1996). Graded (equilibrium) fluvial profiles meet the base level at the shoreline. As the elevation of source areas changes in response to denudation or tectonic forces, graded fluvial profiles adjust accordingly. Graded profiles also respond to changes in base level.

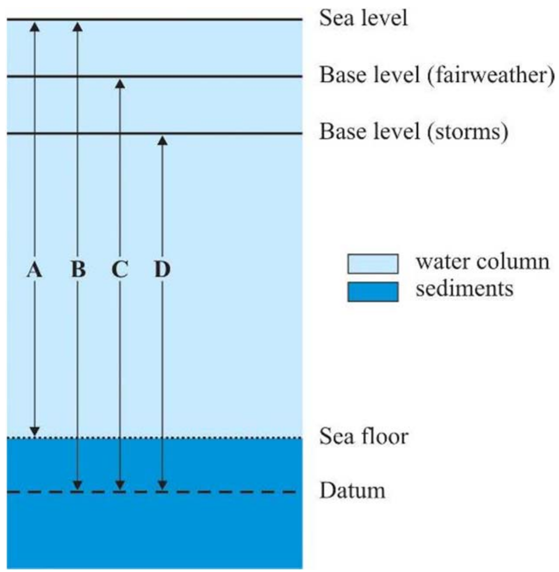
In Catuneau (2006), the fluvial base level is referred to as the fluvial graded profile, and the marine base level is simply referred to as the base level.



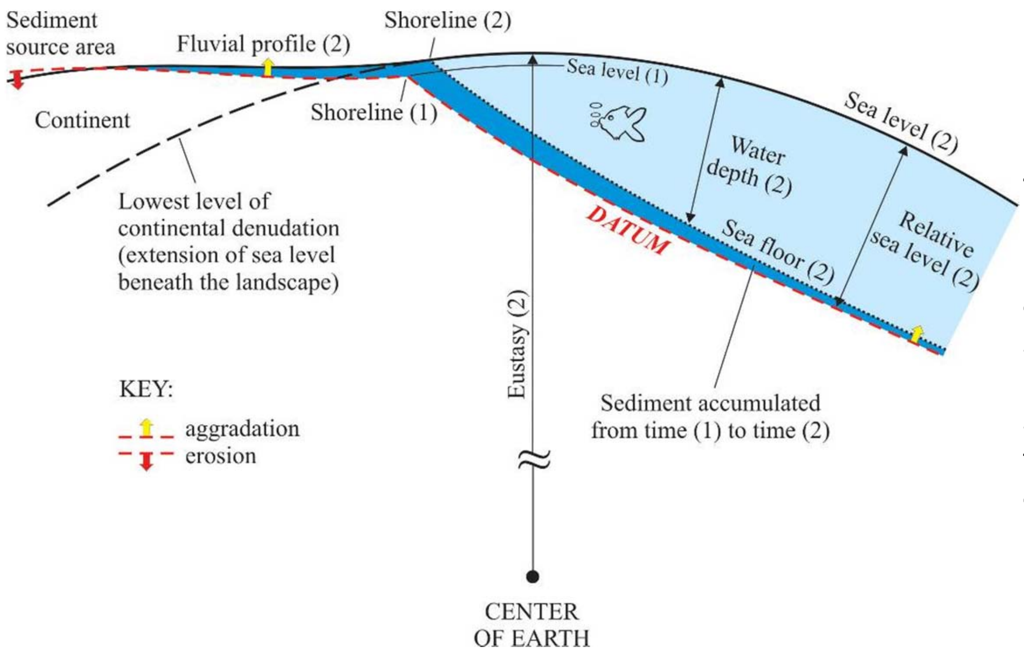
Concepts of water depth, sea level, relative sea level, and base level

Changes in distances A, B, and C/D reflect water-depth (bathymetric) changes, relative sea-level changes, and base-level changes, respectively. Note that the position of the base level is a function of environmental energy, which marks the difference between the concepts of relative sea-level and base-level changes (see also Fig. 3.15). Sea-level changes are independent of datum, seafloor, and sedimentation, and are measured relative to the center of Earth.

Catuneau (2006) p.292

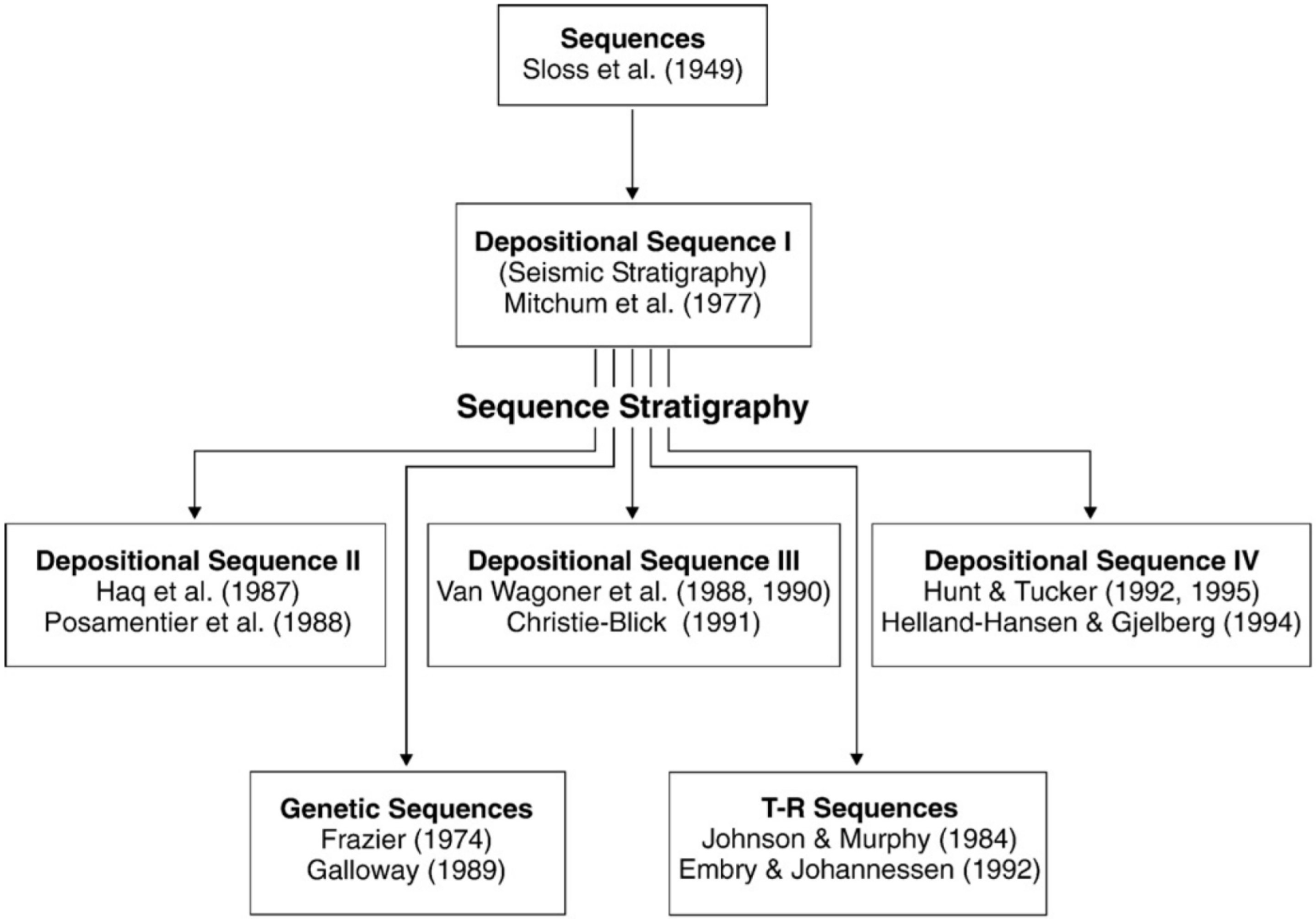


Eustasy, relative sea level, and water depth as a function of sea level, seafloor, and datum reference surfaces



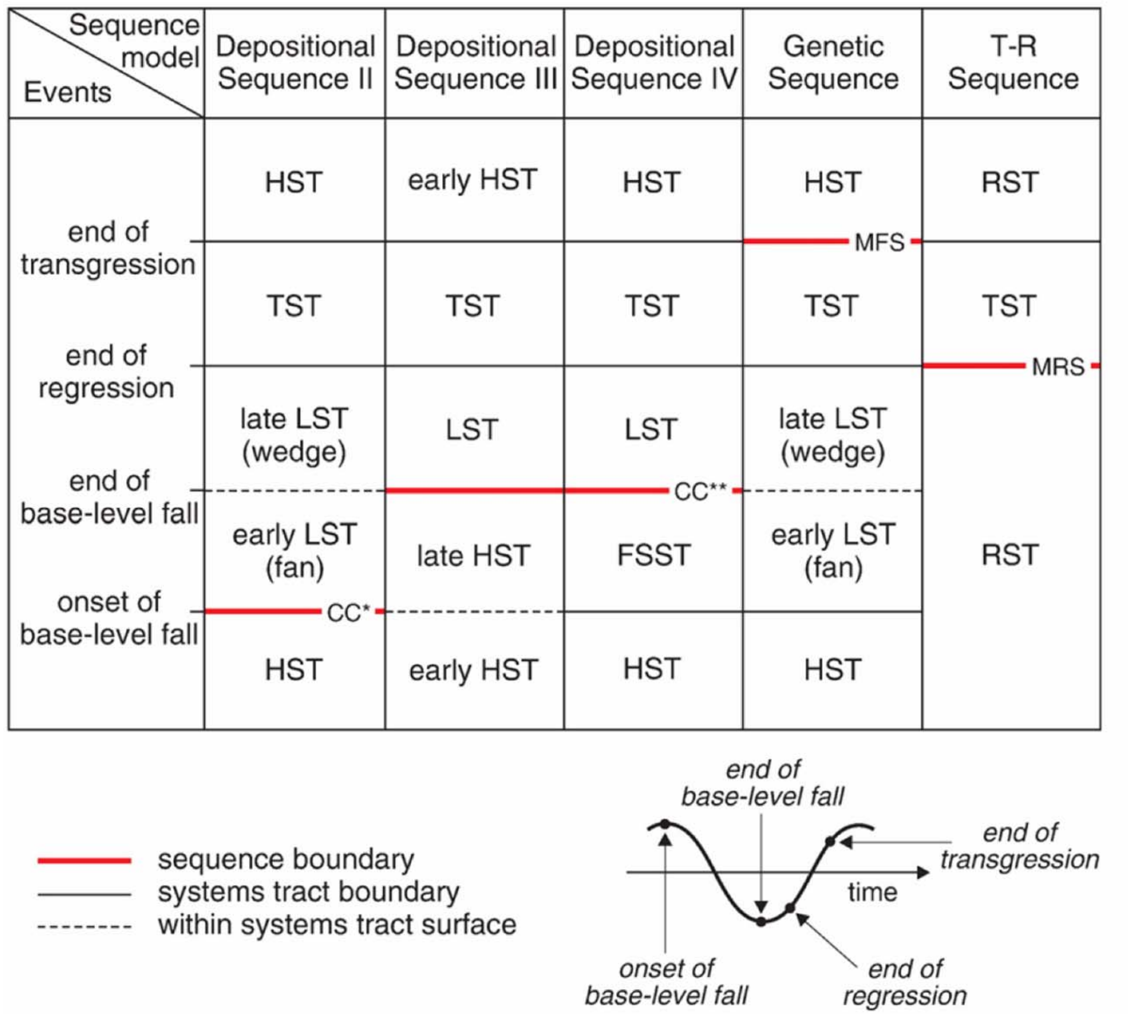
The datum is a subsurface reference horizon that monitors the amount of total subsidence or uplift relative to the center of Earth. In this diagram, the datum corresponds to the ground surface (subaerial and subaqueous) at time (1). Sedimentation (from time 1 to time 2 in this diagram) buries the datum, which, at any particular location, may be visualized as a G.P.S. that monitors changes in elevation through time (i.e., distance relative to the center of Earth).

Sequence stratigraphic models



(from Catuneanu, 2006; modified after Donovan, 2001).

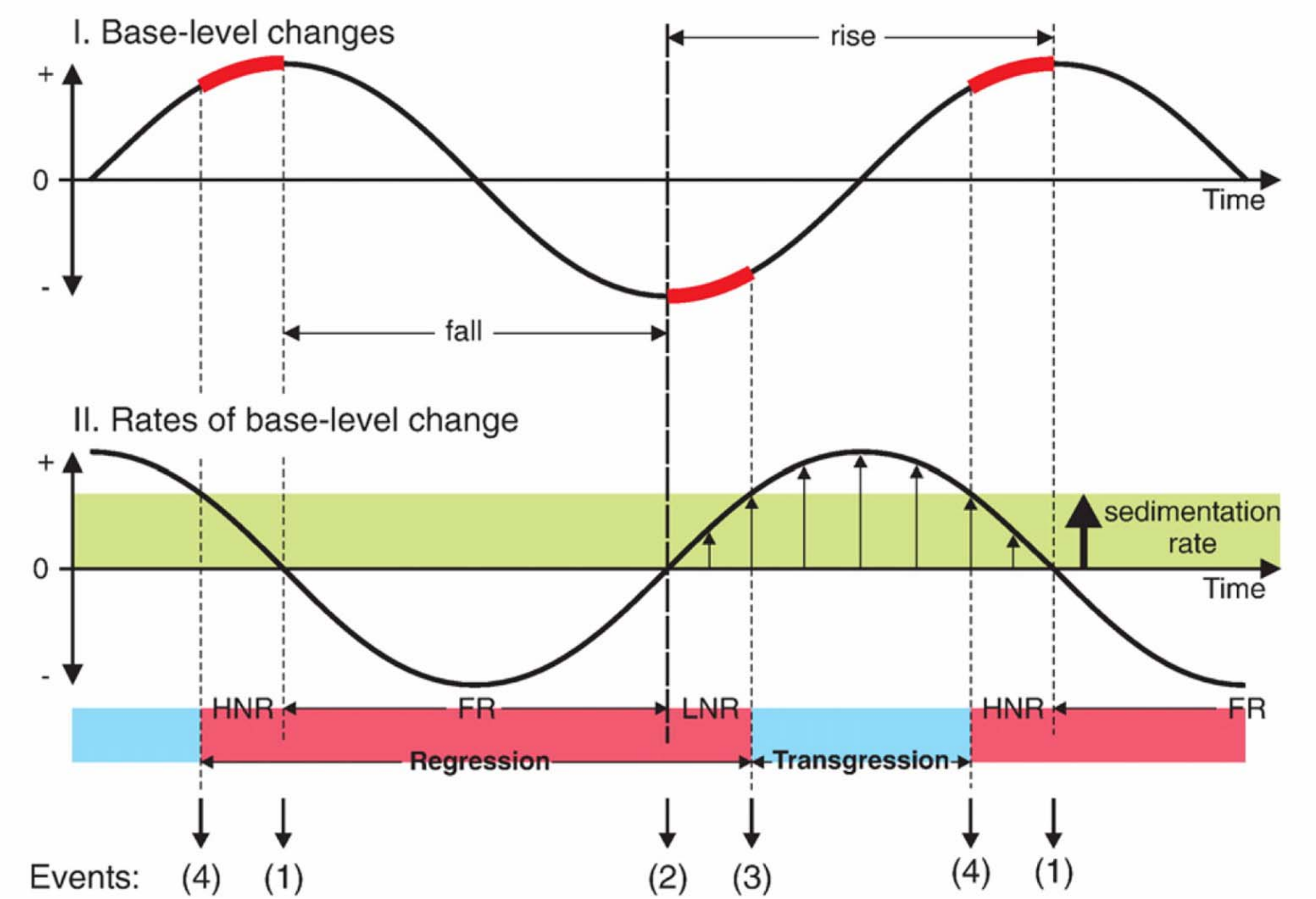
Nomenclature of systems tracts and timing of sequence boundaries for the existing sequence stratigraphic models



Catuneanu et al, (2009)

Abbreviations: LST — lowstand systems tract; TST — transgressive systems tract; HST — highstand systems tract; FSST — falling-stage systems tract; RST — regressive systems tract; T–R — transgressive–regressive; CC*—correlative conformity sensu Posamentier and Allen (1999); CC** — correlative conformity sensu Hunt and Tucker (1992); MFS — maximum flooding surface; MRS — maximum regressive surface.

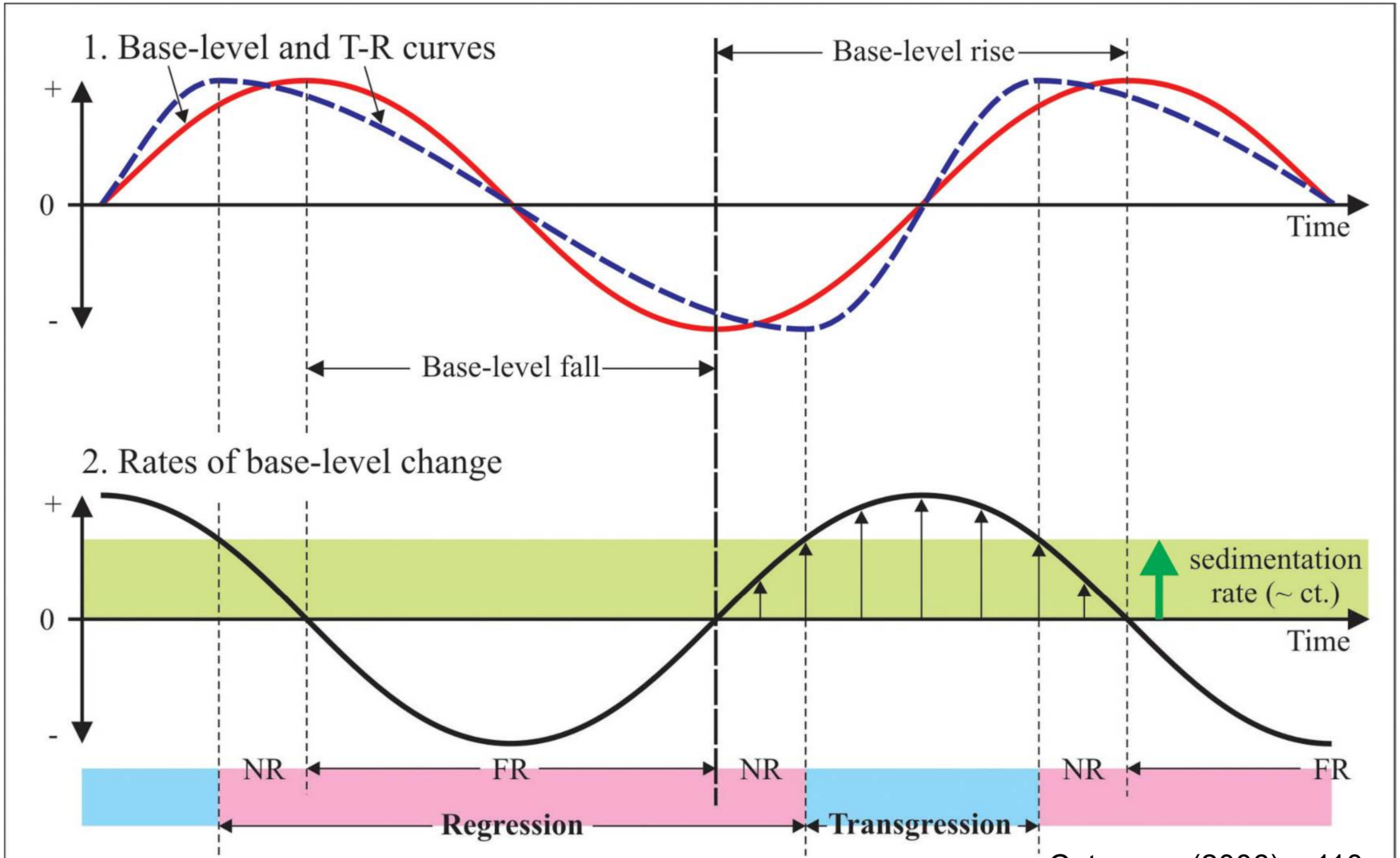
Concepts of transgression, normal regression, and forced regression, as defined by the interplay of base-level changes and sedimentation at the shoreline



Abbreviations:
FR— forced regression;
LNR — lowstand normal regression;
HNR— highstand normal regression.
(1) onset of forced regression;
(2) end of forced regression;
(3) end of regression;
(4) end of transgression.

The top sine curve shows the magnitude of base-level changes through time. The thicker portions on this curve indicate early and late stages of base-level rise, when the rates of base-level rise are outpaced by sedimentation rates. The sine curve below shows the rates of base-level changes. The rates of base-level change are the highest at the inflection points on the top curve. Transgressions occur when the rates of base-level rise outpace the sedimentation rates. For simplicity, the sedimentation rates are kept constant during the cycle of base-level shifts.

Base-level and transgressive–regressive (T–R) curves

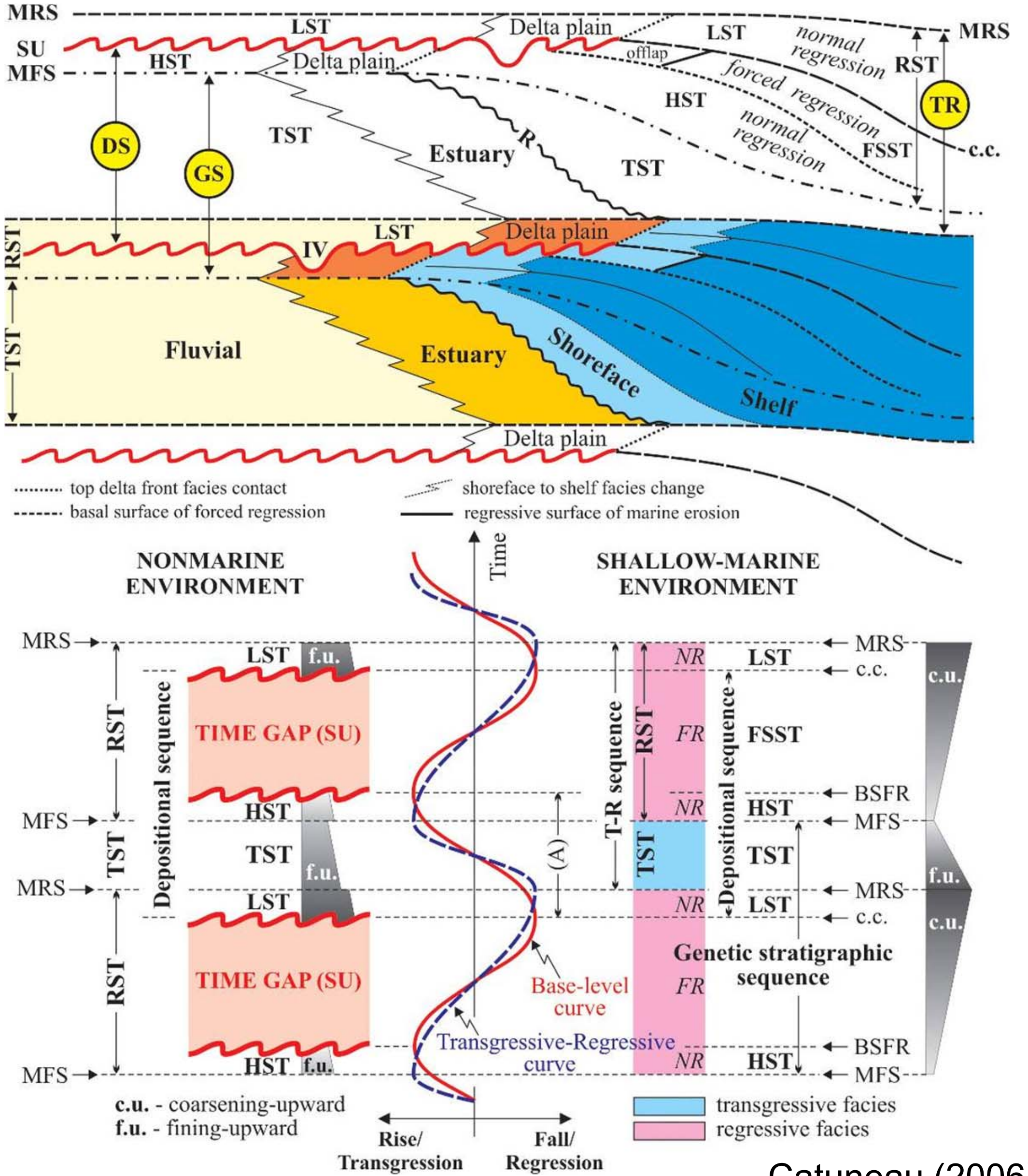


Catuneau (2006) p.110

Sequence stratigraphic surfaces, and systems tracts, are all defined relative to these curves. The T–R curve, describing the shoreline shifts, is the result of the interplay between sedimentation and base-level changes *at the shoreline*. Abbreviations: FR—forced regression; NR—normal regression.

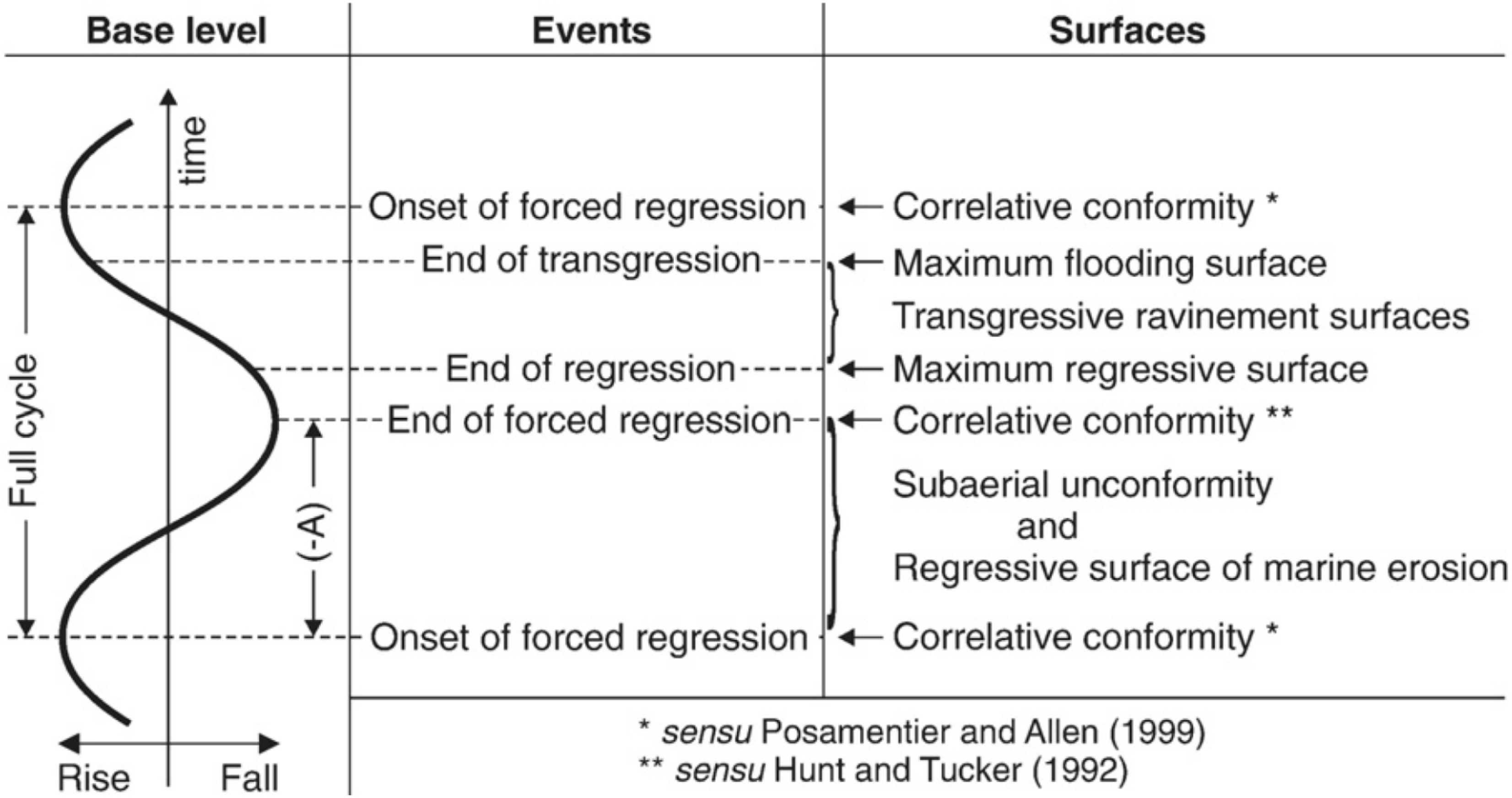
Sequences, systems tracts, and stratigraphic surfaces defined in relation to the base-level and the transgressive–regressive curves

Abbreviations:
SU—subaerial unconformity;
c.c.—correlative conformity (*sensu* Hunt and Tucker, 1992); BSFR—basal surface of forced regression (= correlative conformity *sensu* Posamentier *et al*., 1988);
MRS—maximum regressive surface;
MFS—maximum flooding surface;
R—transgressive wave-ravinement surface;
IV—incised valley;
(A)—positive accommodation (base-level rise);
NR—normal regression;
FR—forced regression;
LST—lowstand systems tract (*sensu* Hunt and Tucker, 1992);
TST—transgressive systems tract;
HST—highstand systems tract;
FSST—falling-stage systems tract;
RST—regressive systems tract;
DS—depositional sequence;
GS—genetic stratigraphic sequence;
TR—transgressive–regressive sequence.



Catuneau (2006) p.111

Timing of the seven surfaces of sequence stratigraphy relative to the four events of the base-level cycle



The reference curve of base-level change reflects fluctuations in base level along the coastline. The timing of the four events is unique along each dip line, but it may change along strike due to variations in sediment supply and/or subsidence rates. Although a symmetrical reference curve is used here (and in Fig. 16) for illustrative purposes, the actual curve may be either symmetrical or asymmetrical, depending on the interplay between the various driving mechanism(s) responsible for the fluctuations in base level. The erosion that generates transgressive ravinement surfaces may be triggered by waves or tides (hence the usage of plural). Abbreviation: (−A) — negative accommodation.

Types of stratigraphic surfaces

The top seven surfaces are proper sequence stratigraphic surfaces that may be used, at least in part, as *systems tract or sequence boundaries*. The bottom three represent facies contacts developed *within* systems tracts. Such within-trend facies contacts may be marked on a sequence stratigraphic cross-section only after the sequence stratigraphic framework has been constructed. The transgressive ravinement surfaces include a pair of *wave*- and *tidal*-ravinement surfaces, which are often superimposed, especially in open shoreline settings. Notes: *—*sensu* Hunt and Tucker, 1992; **—correlative conformity *sensu* Posamentier *et al*., 1988. Abbreviations: MRS—maximum regressive surface; MFS–– maximum flooding surface; RS—transgressive ravinement surfaces; NR—normal regressive; FR—forced regressive.

Surfaces of Sequence Stratigraphy

Base-level fall	Base-level rise
1, 2. Subaerial unconformity, and its correlative conformity *	5. Maximum regressive surface
3. Basal surface of forced regression **	6. Maximum flooding surface
4. Regressive surface of marine erosion	7. Ravinement surfaces (transgressive)

Within-trend facies contacts

Regression	Transgression
1. Within-trend NR surface 2. Within-trend FR surface	3. Flooding surface (other than MRS, MFS, or RS)

Sequence stratigraphic surfaces may be used, at least in part, as systems tract boundaries or sequence boundaries. This is their fundamental attribute that separates them from any other type of mappable surface.

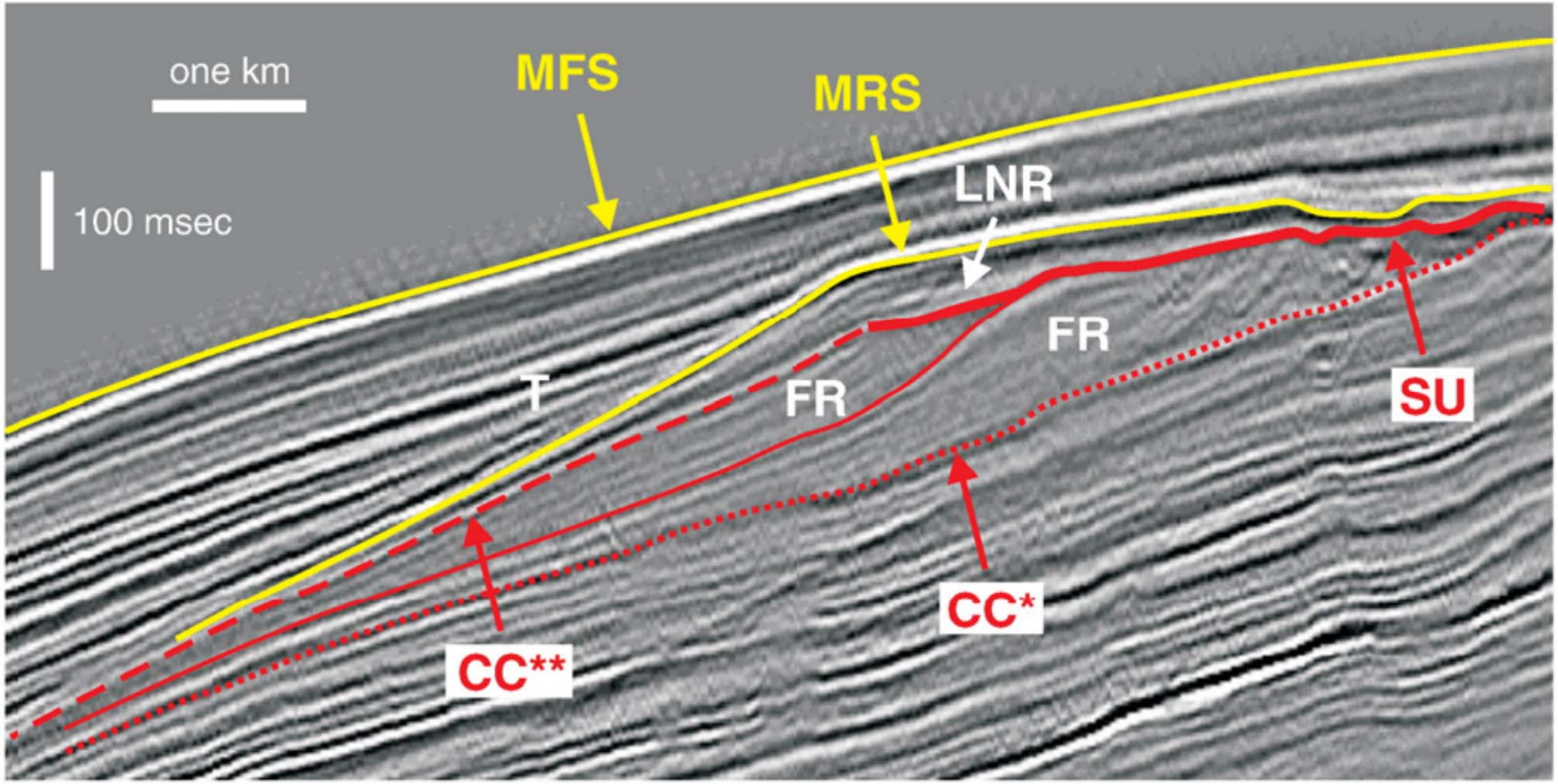
Within-trend facies contacts are lithological discontinuities within *systems tracts. Such surfaces may have a strong physical expression in outcrop or subsurface, but are more suitable for lithostratigraphic or allostratigraphic analyses.*

Catuneau (2006) p.112

Sequence stratigraphic surfaces as a function of depositional setting

Events	Sequence stratigraphic surfaces	Depositional setting		
		Nonmarine	Coastal to Shallow-Water	Deep-Water (1)
End of transgression	MFS	Present	Present	Present
	TRS	Absent	Present	Absent
End of regression	MRS	Present	Present	Present
End of FR	CC **	Absent	Present	Present
	RSME	Absent	Present	Absent
	SU	Present	Present (2)	Absent
Onset of FR	CC *	Absent	Present	Present

Each surface that exists in a depositional setting may be mappable or cryptic, depending on the types of data that are available for analysis and the way in which accommodation and sedimentation interacted at the time of formation. Abbreviations: FR — forced regression; CC —correlative conformities: * sensu Posamentier and Allen (1999), ** sensu Hunt and Tucker (1992); SU— subaerial unconformity; RSME — regressive surface of marine erosion; MRS — maximum regressive surface; TRS — transgressive ravinement surface; MFS — maximum flooding surface; (1) — submarine fan complex; (2) — if overlain by nonmarine facies.

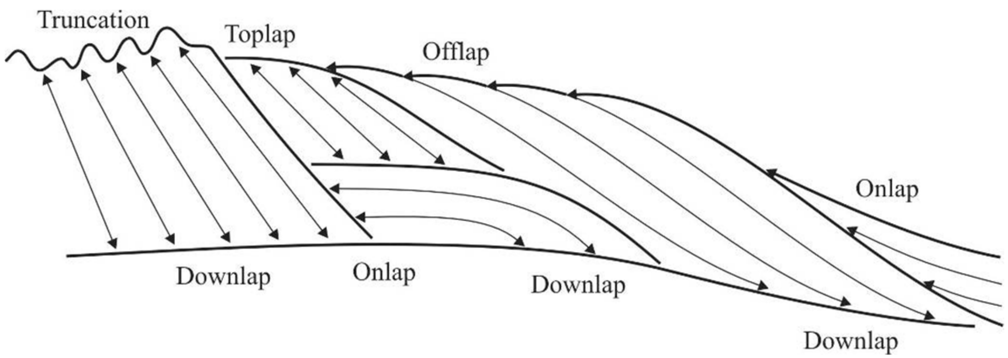


Seismic line in the Gulf of Mexico showing different genetic types of deposits (forced regressive, normal regressive, transgressive) and stratigraphic surfaces that may serve as sequence boundaries according to different sequence stratigraphic models (modified from Posamentier and Kolla, 2003). Abbreviations: FR — forced regressive; LNR — lowstand normal regressive; T — transgressive; SU — subaerial unconformity; CC* — correlative conformity sensu Posamentier and Allen, 1999 (=basal surface of forced regression); CC** — correlative conformity sensu Hunt and Tucker, 1992; MRS — maximum regressive surface; MFS — maximum flooding surface. The line displays the typical stacking patterns and stratal terminations associated with forced regression (offlap, downlap, toplap, truncation), normal regression (downlap, topset), and transgression (onlap).

Catuneanu et al, (2009)

Interpretation of stratal terminations in terms of syndepositional shoreline shifts and base-level changes

Types of stratal terminations



Note that tectonic tilt may cause confusion between onlap and downlap, due to the change in ratio between the dip of the strata and the dip of the stratigraphic surface against which they terminate.

Catuneau (2006) p.106

Stratal termination	Shoreline shift	Base level
Truncation, fluvial	FR	Fall
Truncation, marine	FR, T	Fall, Rise
Toplap	R	Stillstand
Apparent toplap	NR, FR	Rise, Fall
Offlap	FR	Fall
Onlap, fluvial	NR, T	Rise
Onlap, coastal	T	Rise
Onlap, marine	T	Rise
Downlap	NR, FR	Rise, Fall

Exceptions from these general trends are, however, known to occur, as for example fluvial incision (truncation) may also take place during base-level rise and transgression. Abbreviations: R—regression; FR—forced regression; NR—normal regression; T—transgression.

Catuneau (2006) p.108

Types of stratal terminations

Truncation: termination of strata against an overlying erosional surface. *Toplap* may develop into truncation, but truncation is more extreme than toplap and implies either the development of erosional relief or the development of an angular unconformity.

Toplap: termination of inclined strata (clinoforms) against an overlying lower angle surface, mainly as a result of nondeposition (sediment bypass), ± minor erosion. Strata lap out in a landward direction at the top of the unit, but the successive terminations lie progressively seaward. The toplap surface represents the proximal depositional limit of the sedimentary unit. In seismic stratigraphy, the *topset* of a deltaic system (delta plain deposits) may be too thin to be "seen" on the seismic profiles as a separate unit (thickness below the seismic resolution). In this case, the topset may be confused with toplap (i.e., *apparent toplap*).

Onlap: termination of low-angle strata against a steeper stratigraphic surface. Onlap may also be referred to as *lapout*, and marks the lateral termination of a sedimentary unit at its depositional limit. Onlap type of stratal terminations may develop in marine, coastal, and nonmarine settings:

- marine onlap: develops on continental slopes during transgressions (*slope aprons*, Galloway, 1989; *healing-phase deposits*, Posamentier and Allen, 1993), when deep-water transgressive strata onlap onto the maximum regressive surface.

- coastal onlap: refers to transgressive coastal to shallow-water strata onlapping onto the transgressive (tidal, wave) ravinement surfaces.

- fluvial onlap: refers to the landward shift of the upstream end of the aggradation area within a fluvial system during base-level rise (normal regressions and transgression), when fluvial strata onlap onto the subaerial unconformity.

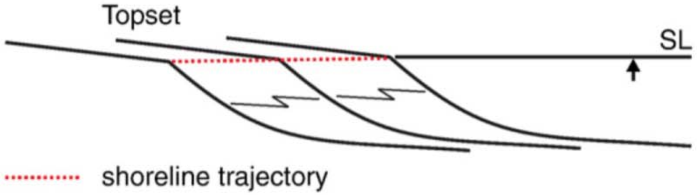
Downlap: termination of inclined strata against a lower-angle surface. Downlap may also be referred to as *baselap*, and marks the base of a sedimentary unit at its depositional limit. Downlap is commonly seen at the base of prograding clinoforms, either in shallow-marine or deep-marine environments. It is uncommon to generate downlap in nonmarine settings, excepting for lacustrine environments. Downlap therefore represents a change from marine (or lacustrine) slope deposition to marine (or lacustrine) condensation or nondeposition.

Offlap: the progressive offshore shift of the updip terminations of the sedimentary units within a conformable sequence of rocks in which each successively younger unit leaves exposed a portion of the older unit on which it lies. Offlap is the product of base-level fall, so it is diagnostic for forced regressions.

Catuneau (2006) p.107

Genetic types of deposits: normal regressive, forced regressive, transgressive

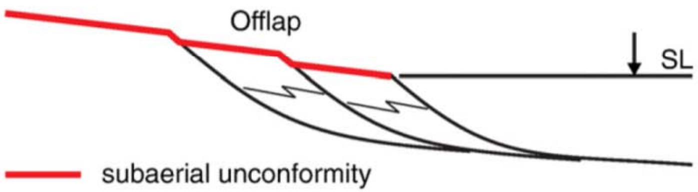
Normal regression



Definition: progradation driven by sediment supply. Sedimentation rates outpace the rates of base-level rise at the coastline.

Depositional trend: progradation with aggradation.

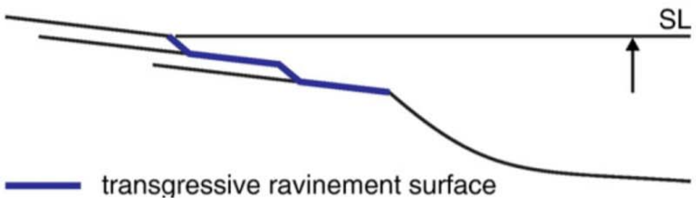
Forced regression



Definition: progradation driven by base-level fall. The coastline is forced to regress, irrespective of sediment supply.

Depositional trend: progradation with downstepping.

Transgression



Definition: retrogradation (backstepping) driven by base-level rise. The rates of base-level rise outpace the sedimentation rates at the coastline.

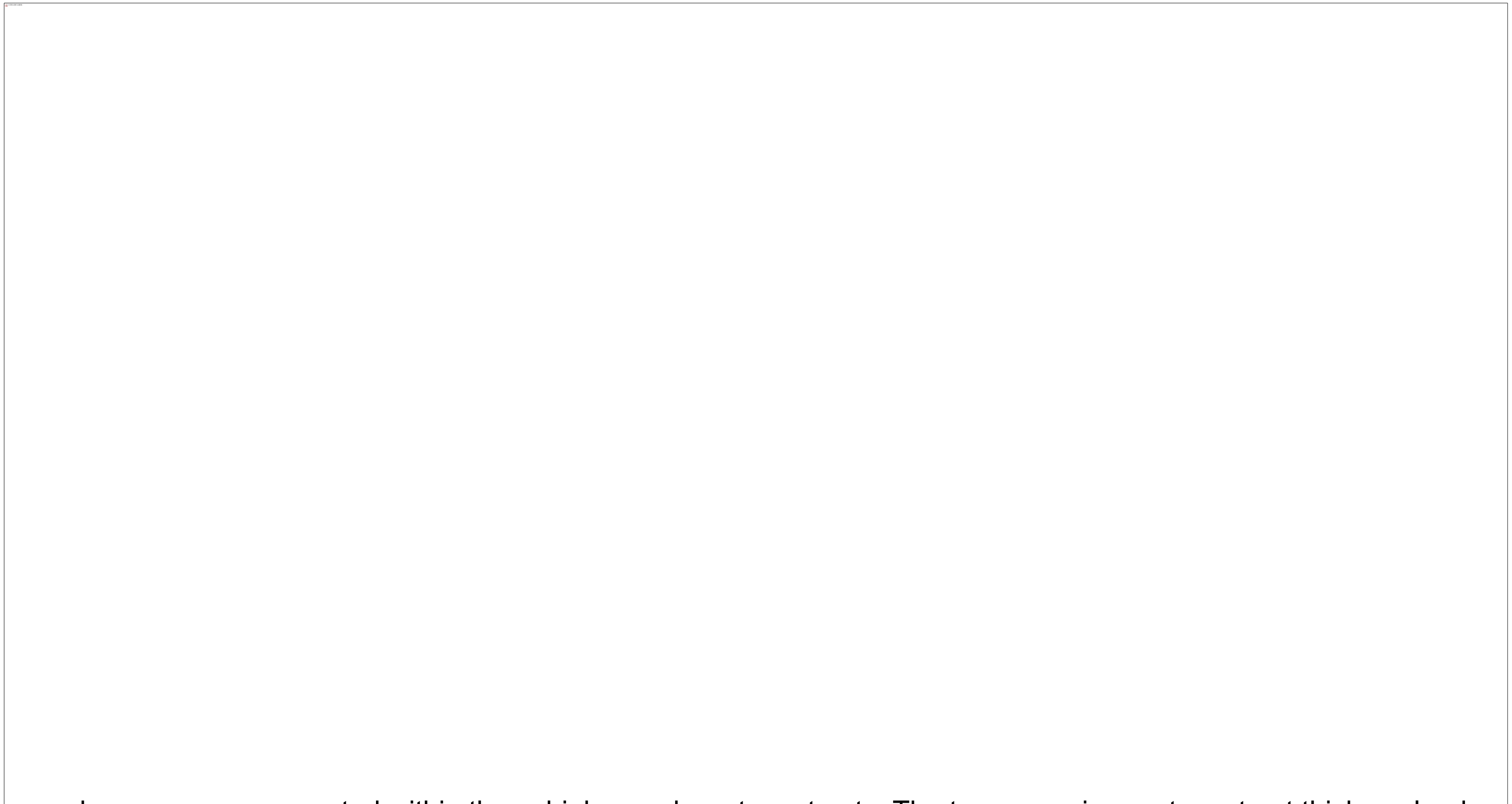
Depositional trend: retrogradation.

Zigzag lines indicate lateral changes of facies within the same sedimentary bodies (e.g., individual prograding lobes). The diagram shows the possible types of shoreline trajectory during changes (rise or fall) in base level. During a stillstand of base level (not shown), the shoreline may undergo sediment-driven progradation (normal regression, where the topset is replaced by toplap), erosional transgression, or no movement at all. However, due to the complexity of independent variables that interplay to control base-level changes, it is unlikely to maintain stillstand conditions for any extended period of time.

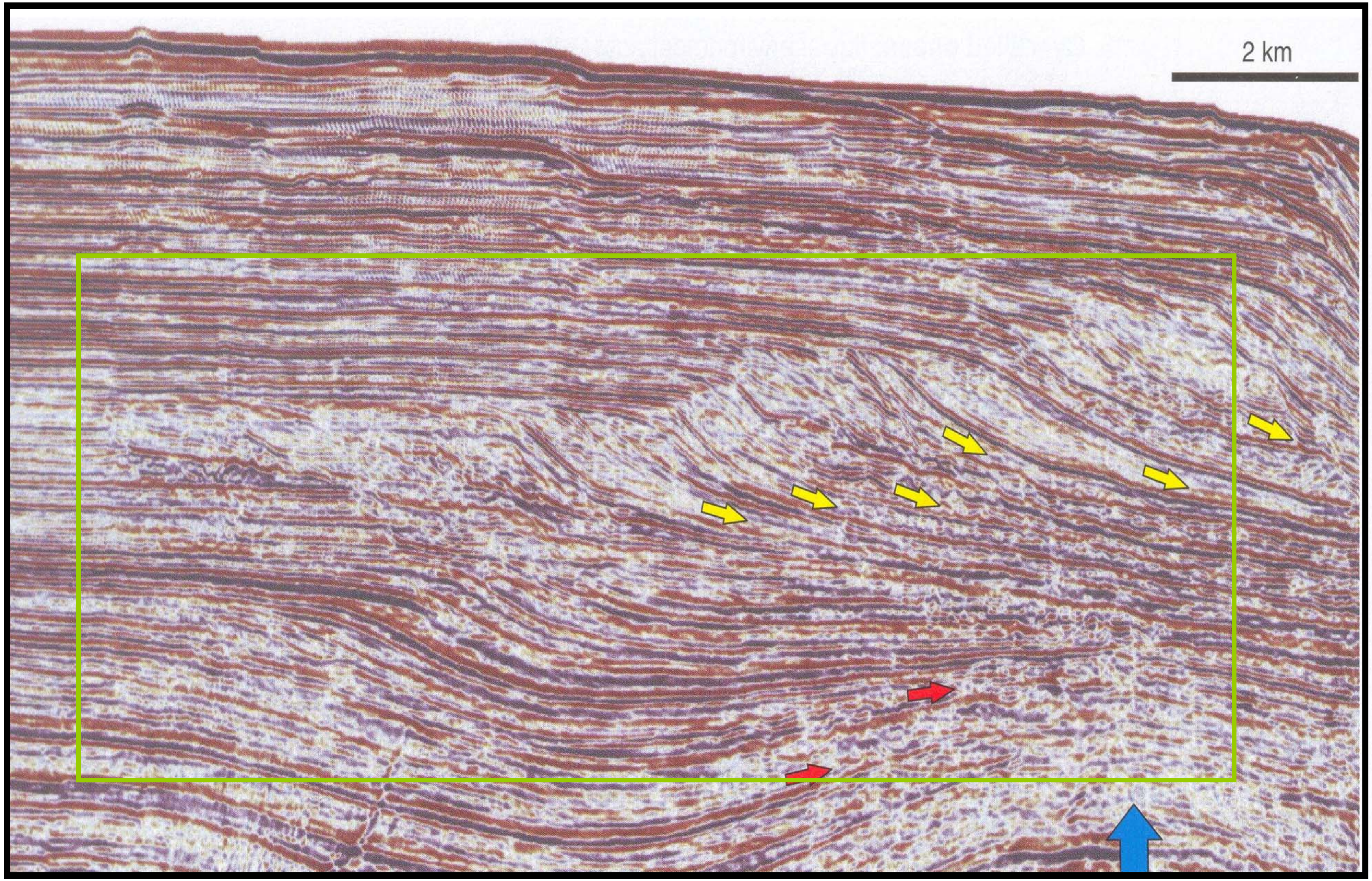
Stratal stacking patterns of ‘lowstand’ and ‘highstand’ normal regressions

In both cases progradation is driven by sediment supply: sedimentation rates outpace the rates of base-level rise at the shoreline. Lowstand normal regressions record a change in depositional trends from dominantly progradational to dominantly aggradational (concave up shoreline trajectory). In contrast, highstand normal regressions record a change from aggradation to progradation (convex up shoreline trajectory). These depositional trends reflect the pattern of change in the rates of creation of accommodation during the two types of normal regression.

Dip regional seismic profile from the Pelotas Basin, southern Brazil, showing large-scale (high-rank) lowstand normal regressive (LNR),transgressive (T) and highstand normal regressive (HNR) systems tracts.



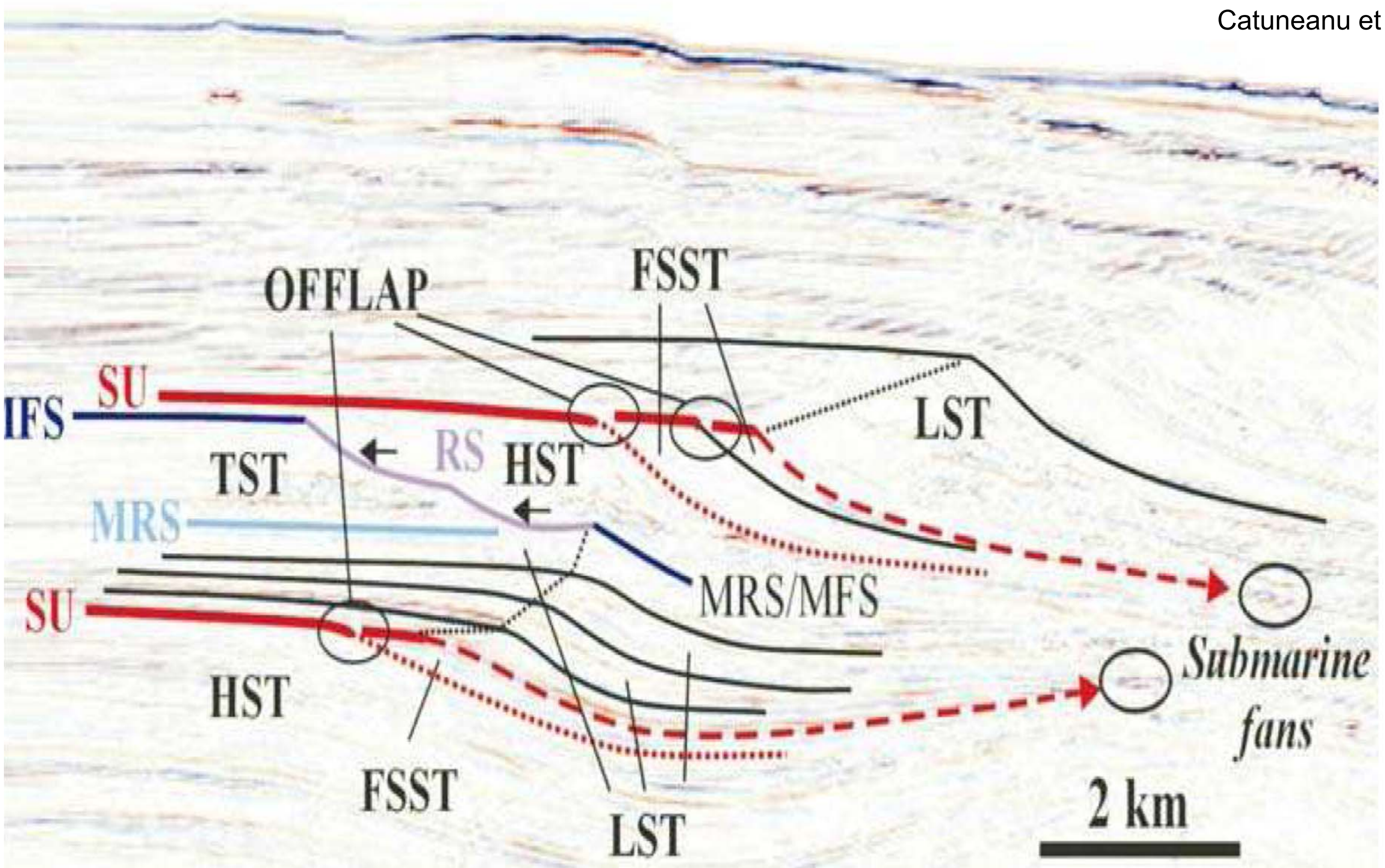
Lower rank sequences are nested within these higher rank systems tracts. The transgressive systems tract thickens landward, which reflects the direction of shift of the depocenter. Individual backstepping parasequences are difficult to observe within the transgressive systems tract due to the limitation imposed by vertical seismic resolution. Such backstepping parasequences are often easier to observe on well-log cross sections. The shoreline trajectory and the shelf-edge trajectory may coincide during lowstand normal regression, but are separate during transgression and highstand normal regression. The change in depositional trends from dominantly progradational to dominantly aggradational is typical for lowstand normal regressions. Conversely, the change in depositional trends from dominantly aggradational to dominantly progradational is typical for highstand normal regressions. Horizontal scale: approximately 50 km. Vertical scale: 2 seconds two-way travel time



Practical: 2D seismic section showing the overall progradation of a divergent continental margin. Use the stratigraphic terminations and parasequence stacking pattern to define major stratigraphic surfaces (e.g., RSME, SU, CC, MRS, MFS) and systems tracts (e.g., LST, TST, HST, FSST) within the box. The blue arrow indicates salt diapirism; red arrows indicate onlap; yellow arrows indicate downlap.

Catuneanu et al, (2009), p.66

Catuneanu et al, (2009), p.192



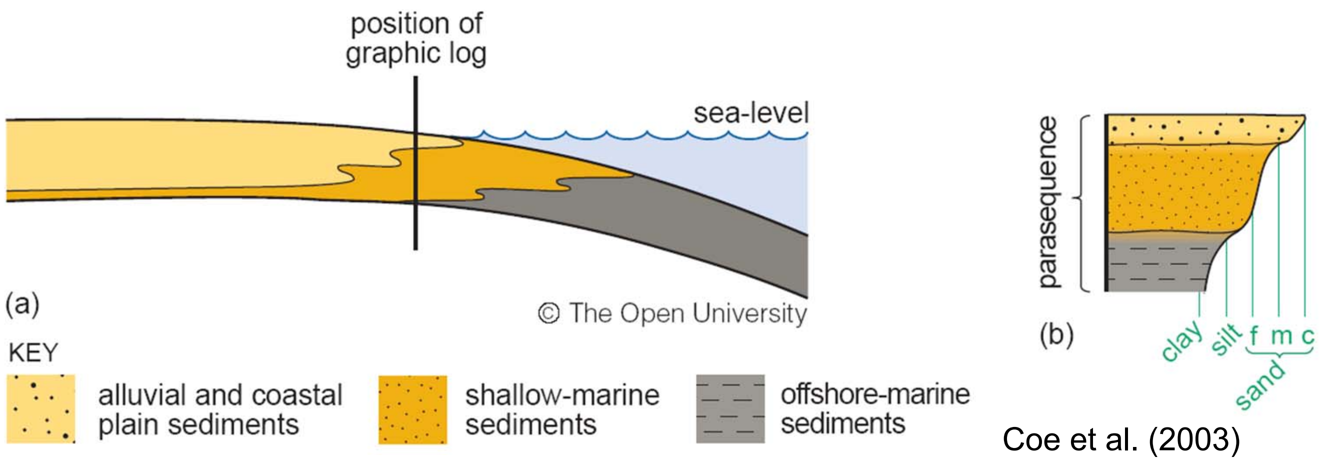
Interpreted seismic line showing the location of the best deep-water reservoirs in a sequence stratigraphic framework. The offlap type of stratal termination is highly significant for deep-water exploration because the youngest clinoform associated with offlap (i.e., the correlative conformity *sensu* Hunt and Tucker, 1992—dashed line in the figure) leads to the top of the coarsest deep-water facies. Abbreviations: FSST— falling-stage systems tract; LST—lowstand systems tract; TST—transgressive systems tract; HST—highstand systems tract; SU—subaerial unconformity; RS—transgressive ravinement surface; MRS—maximum regressive surface; MFS—maximum flooding surface.

Development of parasequences and parasequence stacking pattern

Considering a coastal environment where
the rate of increase of accommodation space < the rate of sediment supply.

A parasequence is a small-scale succession of relatively conformable beds or bed sets bounded by **flooding surfaces**. The facies within a parasequence will represent conformable deposits that accumulated through time in progressively shallower water depths, and thus any vertical succession through the parasequence is **shallowing-upward** and **usually** (but not necessary) **coarsening-upward**, as higher, younger sediments are deposited under progressively more proximal, higher-energy conditions They are the smallest bed-scale cycle (rather than laminar scale) commonly observed in the sedimentary record and the smallest unit usually considered in sequence stratigraphical analysis.

Parasequence results from a small-amplitude, short-term oscillation in the balance between sediment supply and accommodation space.



Coe et al. (2003)

Figure 4.4 (a) Cross-section showing progradation of a coastal succession due to the rate of increase in accommodation space being less than the rate of sediment supply. (b) A simplified graphic log of the resultant coarsening-upward succession termed a parasequence.

Parasequence thickness is highly variable, ranging from less than a metre to a few tens of metres. The lateral extent of parasequences varies between tens to thousands of square kilometres, depending on the geometry of the depositional area and the characteristics of the particular sedimentary system.

the rate of increase of accommodation space > the rate of sediment supply

This causes transgression of the sea. In the majority of cases, this transgression event is marked either by a much thinner set of facies representing transgression or, more often, by a distinct surface which caps the shallowing-upward succession, termed a ***flooding surface***. Following transgression, a new parasequence will start to build out on top of the first one

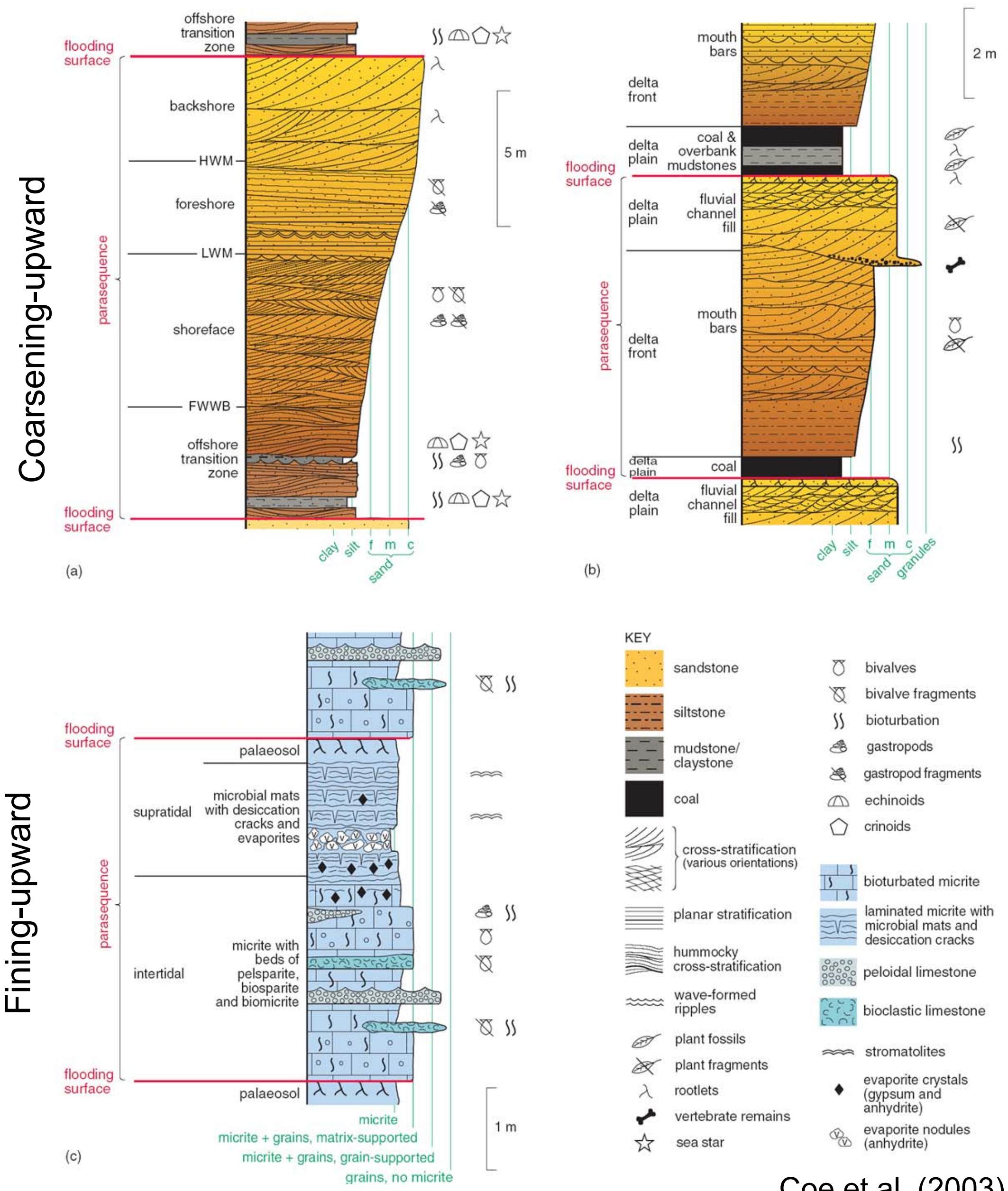
Why sediments representing small-scale short-term transgressions are not preserved:

1. During deepening in shallow-marine areas, wave processes will transport marine sediment landward, thus the sediment will be trapped in more proximal areas and not deposited until the following stillstand or shallowing.

2. rivers that previously supplied sediment to the area will not incise and produce sediment because of flooding.

3. in highly tectonically active areas: increase in accommodation space is greatly enhanced by the subsidence due to faulting. In this case, the sedimentary system does not have a fast enough response time to keep up with rise so no sediments are deposited.

Example coastal parasequences (all shallowing-upward, generally coarsening-upward, few fining-upward)



Coe et al. (2003)

(a) a strandplain succession of conformable beds representing the offshore transition zone, shoreface, foreshore and backshore might form a parasequence

(b) coarsening-upward succession of delta front mouth bar sandstones overlain by the fluvial channel fills of the delta plain

(c) a fining-upward succession of intertidal and supratidal carbonates.

Example fining-upward parasequences, nevertheless these cycles still represent shallowing upwards: (1) in estuarine depositional setting; (2) a muddy tidal flat to subtidal environment (Figure 4.5c);

Figure 4.5 Parasequences from a range of sedimentary environments: (a) a siliciclastic strandplain succession; (b) a deltaic succession; (c) an intertidal to supratidal carbonate ramp succession.

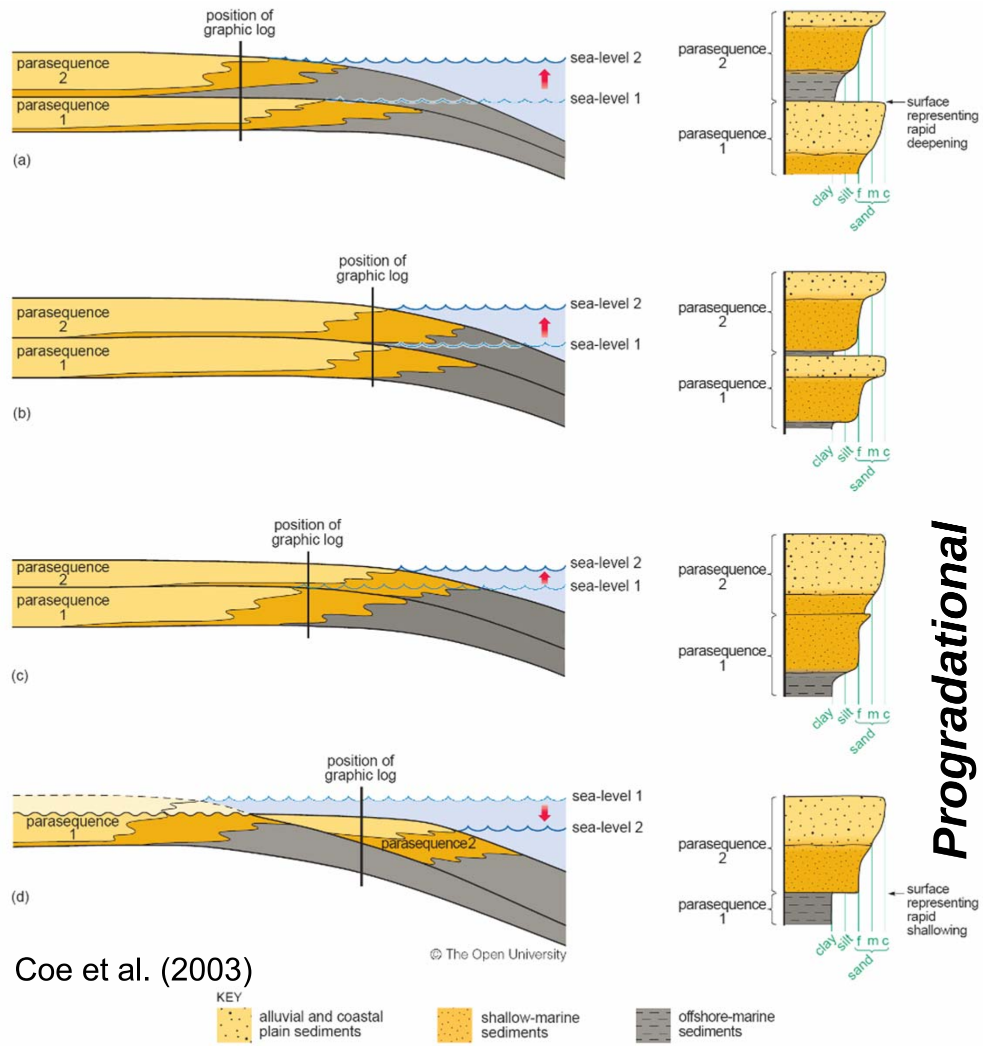
Parasequence sets, progradation, aggradation and retrogradation

Parasequence sets

Succession of genetically related parasequences that have the same stacking pattern (aggradational, progradational or retrogradational), and typically bounded by major marine flooding surfaces and their correlative surfaces.

Long-term change over two parasequences

Retrogradational parasequence set



Coe et al. (2003)

Aggradational parasequence set

Figure 4.6 Cross-sections and graphic logs showing the effects of long-term changes over two parasequences of: (a) an increase in the rate of creation of accommodation space (note that parasequence 2 is thicker than parasequence 1 on the left-hand side); (b) no change in the rate of creation of accommodation space; (c) a decrease in the rate of creation of accommodation space (parasequences 1 and 2 are the same thickness on the left-hand side); (d) a decrease in the amount of accommodation space (parasequence 2 is thicker than parasequence 1 on the left-hand side). Note that, if the accommodation space continues to decrease, it is unlikely that alluvial and coastal plain sediments will accumulate. The rate of sediment supply is assumed to be constant in each case.

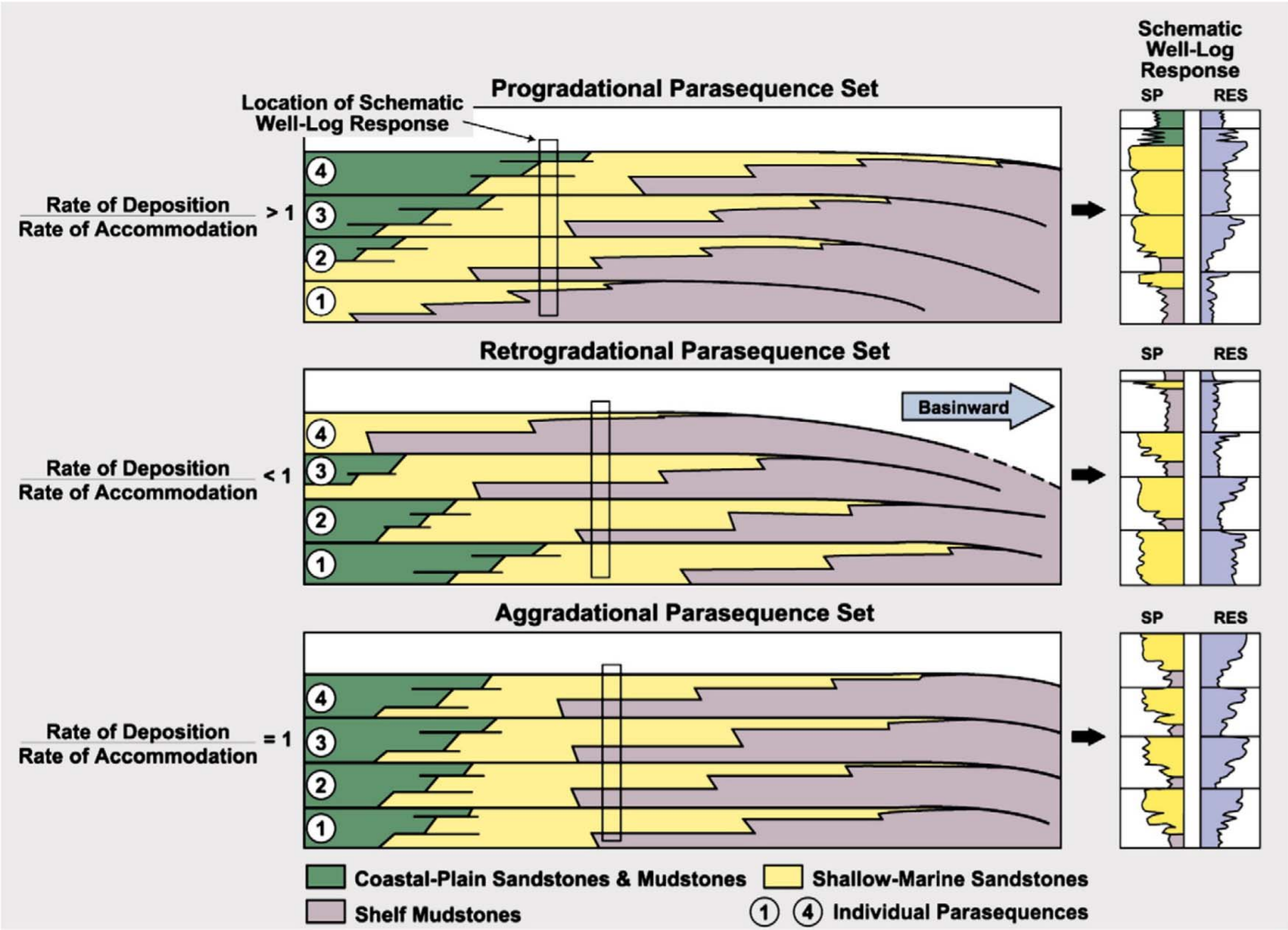
Retrogradation: The movement of coastline landward in response to a transgression. This can occur during a sea-level rise with low sediment flux. A **retrogradational parasequence set** is a parasequence set in which successively younger parasequences are deposited farther landward in a backstepping pattern. Overall, the rate of deposition is less that the rate of accommodation. Note that individual parasequences still prograde.

Aggradation: Vertical build up of a sedimentary sequence. Usually occurs when there is a relative rise in sea level produced by subsidence and/or eustatic sea-level rise, and the rate of sediment influx is sufficient to maintain the depositional surface at or near sea level (i.e. carbonate keep-up in a HST or clastic HST). Occurs when sediment flux = rate of sea-level rise. Produces aggradational stacking patterns in parasequences when the patterns of facies at the top of each parasequence are essentially the same (e.g., facies of shoreline stays in the same position).

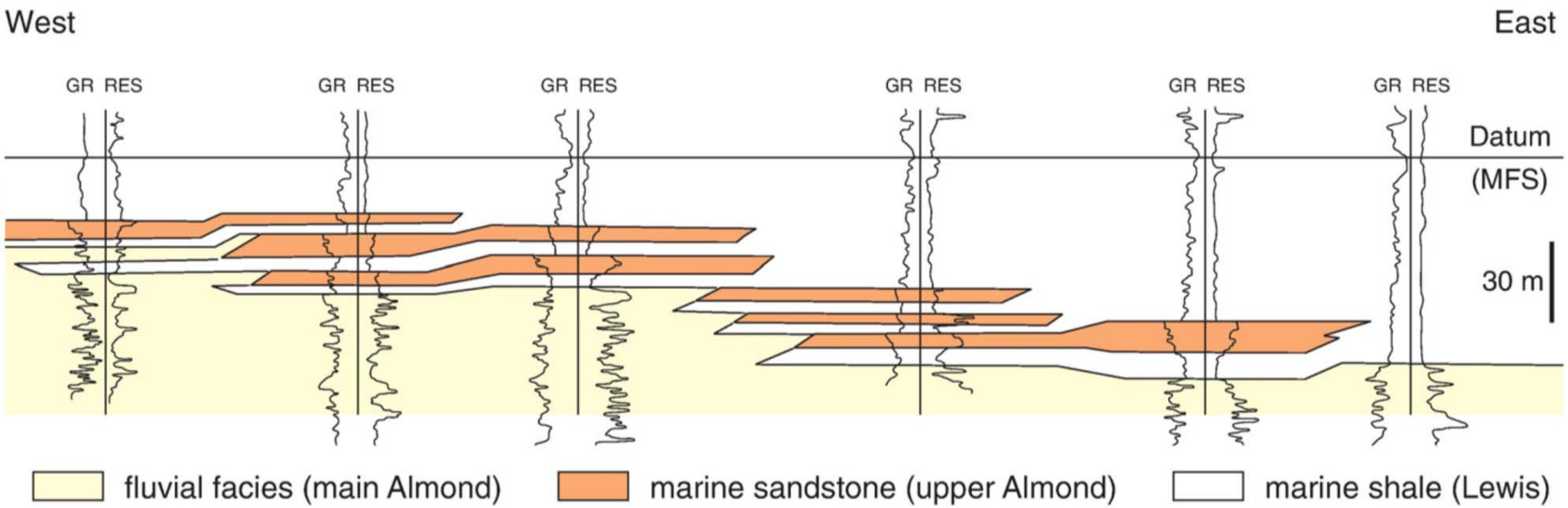
Progradation: Lateral outbuilding, or progradation, of strata in a seaward direction. A **progradational parasequence set** is a parasequence set in which successively younger parasequences are deposited farther basinward; overall the rate of deposition is greater than the rate of accommodation.

Question: What are the relative contributions of accommodation space and sediment supply to the progradational geometry in Figure 4.7e compared to Figure 4.7g?
Answer: In Figure 4.7e, the rate of sediment supply is greater than the rate of increase in accommodation space in order for the parasequence set to prograde and for each parasequence to have the same thickness in the proximal area and a greater thickness in the distal area. However, in Figure 4.7g, there is a decrease in the amount of accommodation space because of a relative sea-level fall. This is independent of the amount of sediment supply.
In fact, Figure 4.7g is the only one to show a relative sea-level fall (a decrease in accommodation space). This leads us on to an important concept, which is the distinction between two types of regression, as explained later.

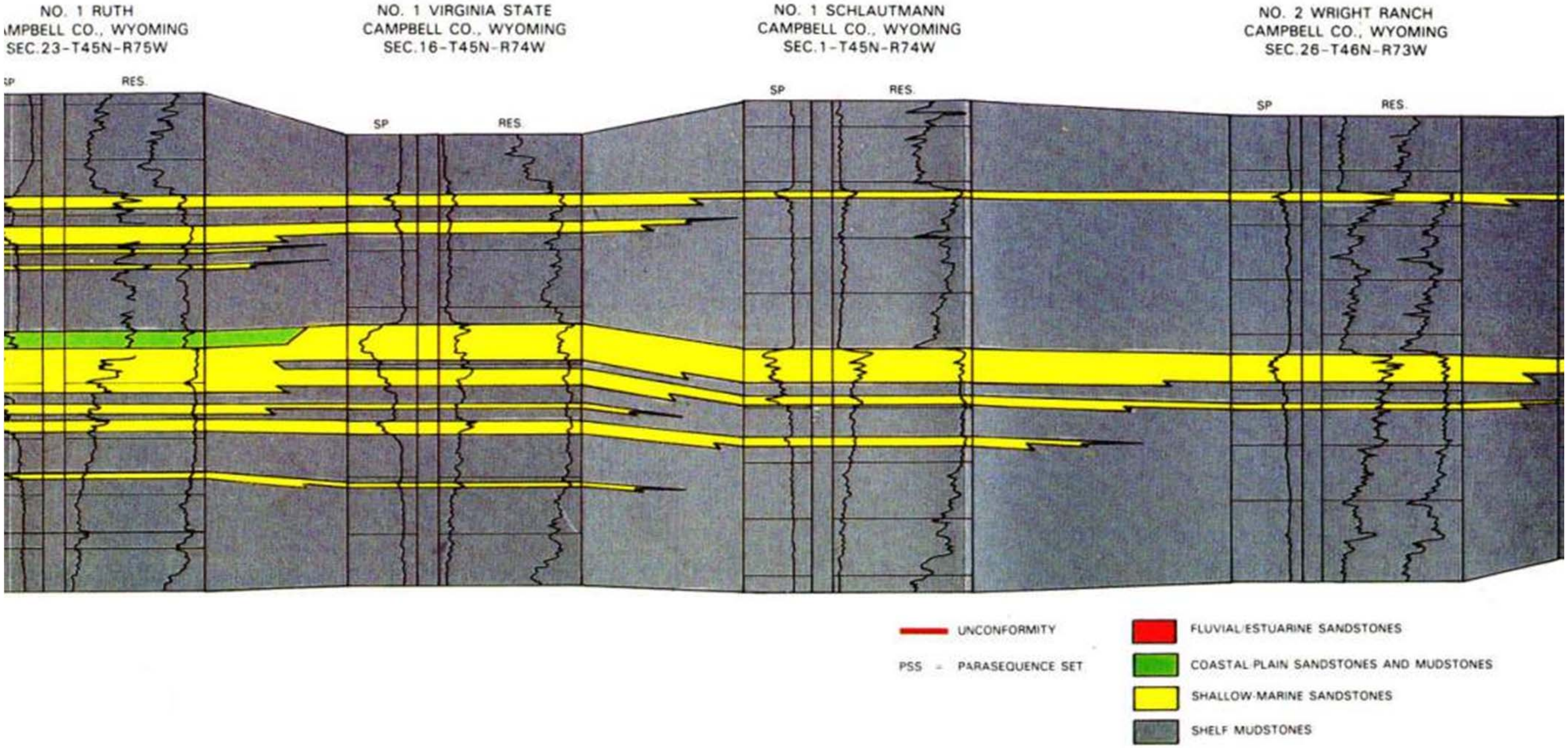
Vertical stacking of parasequence sets (from Van Wagoner et al., 1990).



Example transgressive systems tract showing retrogradational and backstepping parasequences

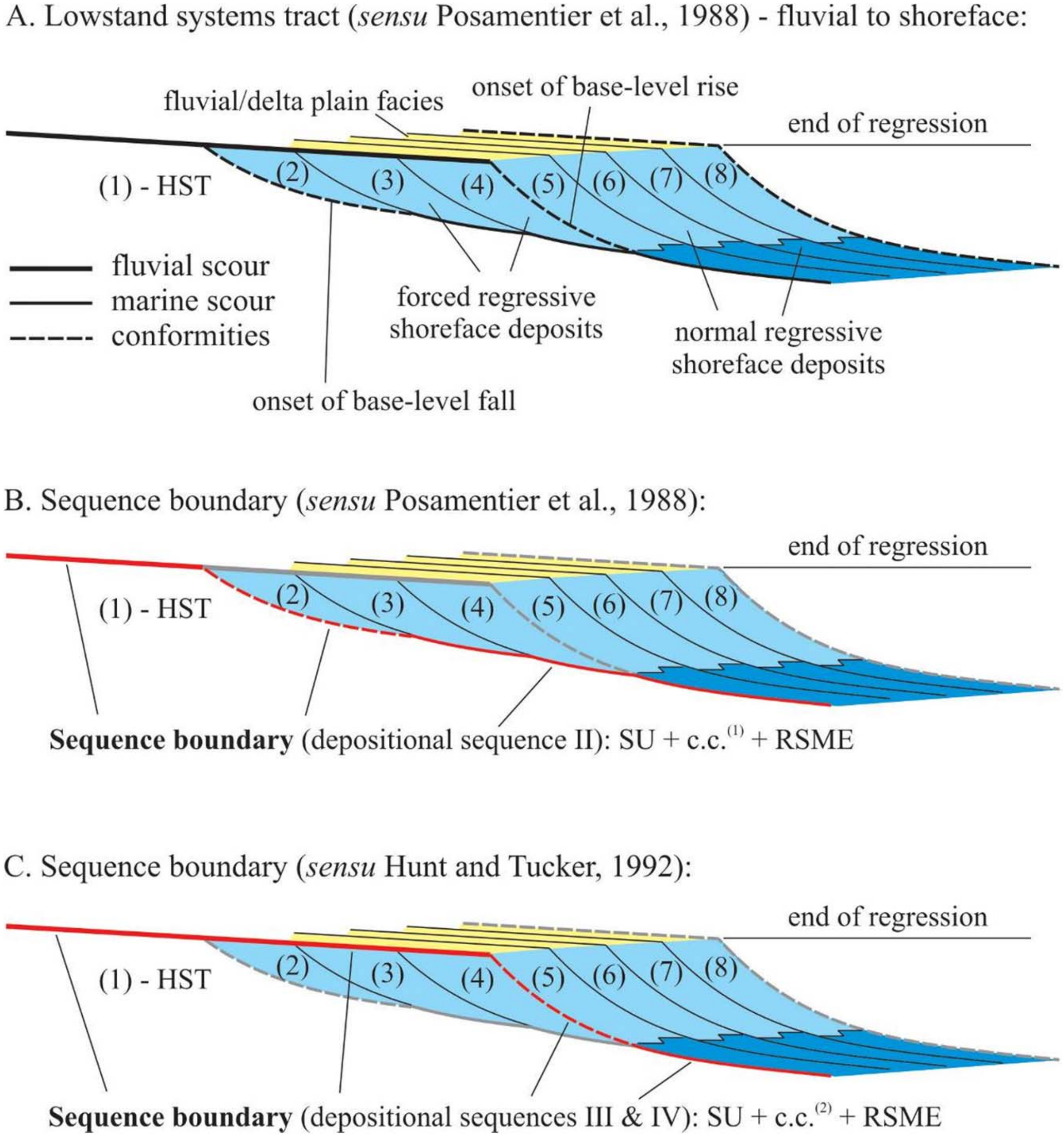


Regional well-log cross-section of the Almond Formation in the Washakie Basin, Wyoming. The backstepping stacking pattern of parasequences records the westward transgression of the Western Interior Campanian Seaway. The cross-section is approximately 65 km long. Well logs shown: gamma ray (GR) and resistivity (RES).


NO. 1 RUTH
CAMPBELL CO., WYOMING
SEC.23-T45N-R75W
SP
RES.
NO. 1 VIRGINIA STATE
CAMPBELL CO., WYOMING
SEC.16-T45N-R74W
SP
RES.
NO. 1 SCHLAUTMANN
CAMPBELL CO., WYOMING
SEC.1-T45N-R74W
SP
RES.
NO. 2 WRIGHT RANCH
CAMPBELL CO., WYOMING
SEC.26-T46N-R73W
SP
RES.
UNCONFORMITY
PSS = PARASEQUENCE SET
FLUVIAL/ESTUARINE SANDSTONES
COASTAL-PLAIN SANDSTONES AND MUDSTONES
SHALLOW-MARINE SANDSTONES
SHELF MUDSTONES

Methods of delineation of the depositional sequence boundary within the region of fluvial to shoreface facies transition

Cross section A shows the architecture of forced and normal regressive deposits, and the nature of their associated bounding surfaces. Cross-sections B and C indicate the sequence boundary position in the view of the different depositional sequence models. Note that the regressive surface of marine erosion may be part of the sequence boundary in either model, where it replaces the correlative conformity.
Abbreviations:
HST—highstand systems tract;
SU—subaerial unconformity;
RSME—regressive surface of marine erosion;
c.c.(1)—correlative conformity, *sensu* Posamentier *et al*.
(1988);
c.c.(2)—correlative conformity, *sensu* Hunt and Tucker (1992).



Catuneau (2006) p.238

Example of forced regression and its sequence stratigraphic interpretation

A. Sedimentary facies. As constrained by outcrop and core studies, the contact between the fluvial and the underlying shoreface facies is unconformable in wells (1), (2), (3) and (4), and conformable in well (5). B. Sequence stratigraphic interpretation. Correlative conformities are difficult to detect on well logs, within regressive successions of coarsening-upward shallow-marine facies. Correlative conformities are easier to detect on seismic lines, where stacking patterns such as offlap can be observed. Note the downstepping of the subaerial unconformity during forced regression; the thinning of sharp-based shoreface deposits toward the basin margin; and the aggradation recorded by the lowstand normal regressive strata. In this example, gradationally-based shoreface deposits indicate normal regression (highstand to the left; lowstand to the right), whereas sharp-based shoreface deposits are diagnostic for forced regression. This criterion allows the separation between normal and forced regressive deposits even in the absence of seismic data. Abbreviations:
FR — forced regressive; HNR — highstand normal regressive; LNR — lowstand normal regressive.