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Sequence stratigraphy of clastic systems: concepts, merits, and pitfalls

Octavian Catuneanu *

Department of Earth and Atmospheric Sciences, University of Alberta, 1-26 Earth Sciences Building, Edmonton, Alta., Canada T6G 2E3

Abstract

Sequence stratigraphy is widely embraced as a new method of stratigraphic analysis by both academic and industry practitioners. This new method has considerably improved our insight into how sedimentary basins accumulate and preserve sediments, and has become a highly successful exploration technique in the search for natural resources. The different sequence stratigraphic models that are currently in use, i.e. three varieties of depositional sequences, a genetic stratigraphic sequence, and a transgressive–regressive sequence, all have merits and limitations. Each model works best in particular tectonic settings, and no one model is applicable to the entire range of case studies. Flexibility is thus recommended for choosing the model that is the best match for a specific project. Having said that, the existing sequence models also have a lot in common, with the main difference being in the style of conceptual packaging of the same succession of strata (i.e., where to pick the sequence boundaries).

Sequence stratigraphic models are centered around *one* curve of base level fluctuations that describes the changes in accommodation *at the shoreline*. The interplay between sedimentation and *this* curve of base level changes controls the transgressive and regressive shifts of the shoreline, as well as the timing of all systems tract and sequence boundaries. Surfaces that can serve, at least in part, as systems tract boundaries, are sequence stratigraphic surfaces. Systems tract boundaries have low diachroneity rates along dip, which match the rates of sediment transport. These surfaces may be much more diachronous along strike, in relation to variations in subsidence and sedimentation rates. This paper presents the fundamental concepts of sequence stratigraphy, and discusses the merits and pitfalls of its theoretical framework. The deviations in the rock record from the predicted architecture of systems tracts and stratigraphic surfaces are also discussed.
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Keywords: Sequence stratigraphy; Eustasy and base level; Tectonic setting; Accommodation space; Architecture of systems tracts and stratigraphic surfaces

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* Tel.: +1-780-492-6569; fax: +1-780-492-7598.
E-mail address: octavian@ualberta.ca (O. Catuneanu).

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1. Introduction

1.1. Sequence stratigraphy: a new paradigm

Sequence stratigraphy is the most recent and revolutionary paradigm in the field of sedimentary geology, and completely revamps geological thinking and the methods of stratigraphic analysis. As opposed to the other, more conventional types of stratigraphy, such as biostratigraphy, lithostratigraphy, chemostratigraphy or magnetostratigraphy, which are mostly concerned with data collection, sequence stratigraphy has an important built-in interpretation component which addresses issues such as (i) the reconstruction of the allogenic controls at the time of sedimentation, and (ii) predictions of facies architecture in yet unexplored areas. The former issue sparked an intense debate, still ongoing, between the supporters of eustatic versus tectonic controls on sedimentation, which is highly important to the understanding of Earth history and the fundamental Earth processes. The latter issue provides the petroleum industry community with a new and powerful analytical and correlation tool for exploration and basin analysis.

This is not to say, however, that sequence stratigraphy is the triumph of interpretation over data, or that sequence stratigraphy developed in isolation from other geological disciplines. In fact sequence stratigraphy builds on many existing data sources, requires a good

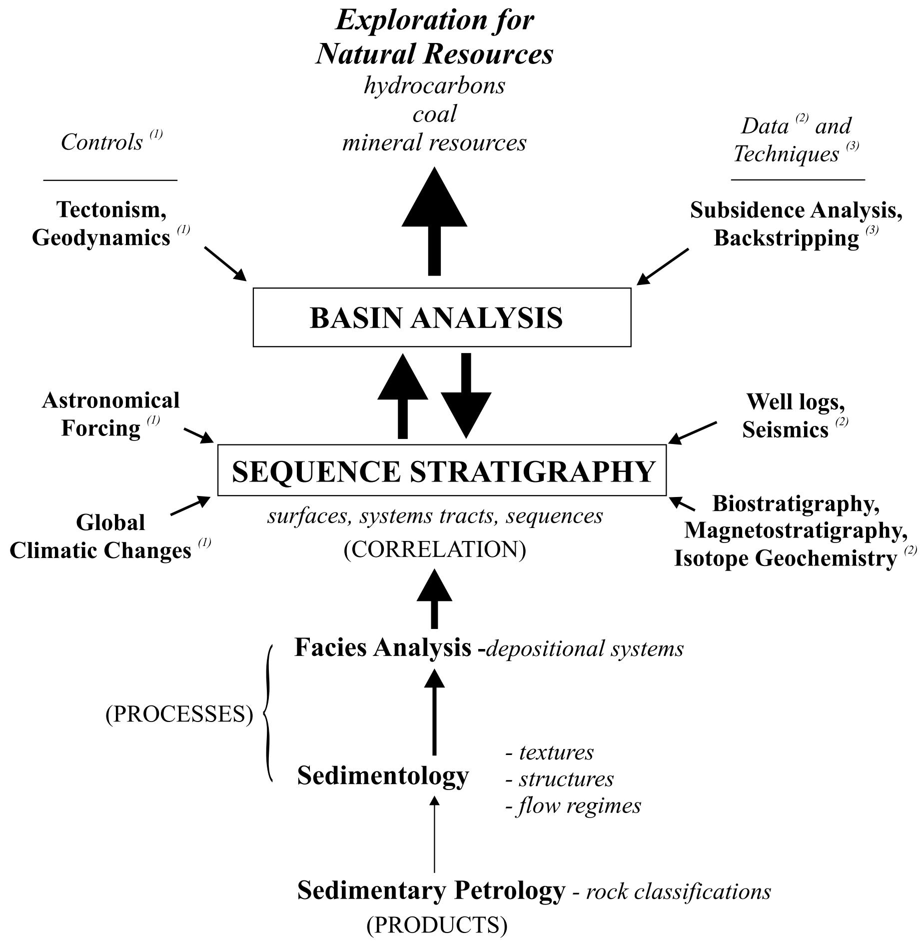

Fig. 1. Sequence stratigraphy in the context of interdisciplinary research.

knowledge of sedimentology and facies analysis, and fills the gap between sedimentology, basin analysis, and the various types of conventional stratigraphy (Figs. 1 and 2).

Stratigraphy	**Property**
Lithostratigraphy	lithology
Biostratigraphy	fossils
Magnetostratigraphy	magnetic polarity
Chemostratigraphy	chemical properties
Allostratigraphy	discontinuities
Seismic stratigraphy	seismic data
Sequence stratigraphy	depositional trends

Depositional trends refer to aggradation versus erosion, and progradation versus retrogradation. Changes in depositional trends are controlled by the interplay between sedimentation and base level changes.

Fig. 2. Types of stratigraphy, defined on the basis of the property they analyze.

1.2. Historical developments

Sequence stratigraphy is generally regarded as stemming from the seismic stratigraphy of the 1970s. In fact, major studies investigating the relationship between sedimentation, unconformities, and changes in base level, which are directly relevant to sequence stratigraphy, were published prior to the birth of seismic stratigraphy (e.g., Grabau, 1913; Barrell, 1917; Sloss et al., 1949; Sloss, 1962, 1963; Wheeler and Murray, 1957; Wheeler, 1958, 1959, 1964; Curray, 1964; Frazier, 1974).

The term "sequence" was introduced by Sloss et al. (1949) to designate a stratigraphic unit bounded by subaerial unconformities. Sloss emphasized the importance of such sequence-bounding unconformities, and subsequently subdivided the entire Phanerozoic succession of the interior craton of North America into six major sequences (Sloss, 1963). Sloss also emphasized the importance of tectonism in the generation of sequences and bounding unconformities, an idea which is widely accepted today but was largely ignored by the proponents of seismic stratigraphy.

Seismic stratigraphy emerged in the 1970s with the work of Vail (1975) and Vail et al. (1977). This new method for analyzing seismic-reflection data stimulated a revolution in stratigraphy, with an impact on the geological community as important as the introduction of the flow regime concept in the late 1950s–early 1960s and the plate tectonics theory in the 1960s (Miall, 1995). The concepts of seismic stratigraphy were published together with the global cycle chart (Vail et al., 1977), based on the underlying assumption that eustasy is the main driving force behind sequence formation at all levels of stratigraphic cyclicity. Seismic stratigraphy and the global cycle chart were thus introduced to the geological community as an inseparable package of new stratigraphic methodology. These ideas were then passed on to sequence stratigraphy in its early years, as seismic stratigraphy evolved into sequence stratigraphy with the incorporation of outcrop and well data (Posamentier et al., 1988; Posamentier and Vail, 1988; Van Wagoner et al., 1990). The global-eustasy model posed two challenges to the practitioners of "conventional" stratigraphy: (1) that sequence stratigraphy, as linked to the global cycle chart, constitutes a superior standard of geological time to that assembled from conventional chronostratigraphic evidence, and (2) that stratigraphic processes are dominated by the effects of eustasy, to the exclusion of other allogenic mechanisms, including tectonism (Miall and Miall, 2001). Although the global cycle chart is now under intense scrutiny and criticism (e.g., Miall, 1992), the global-eustasy model is still used for sequence stratigraphic analysis in some recent publications (e.g., de Gracianski et al., 1998).

In parallel to the eustasy-driven sequence stratigraphy, which held by far the largest share of the market, other researchers went to the opposite end of the spectrum by suggesting a methodology that favored tectonism as the main drive of stratigraphic cyclicity. This version of sequence stratigraphy was introduced as "tectonostratigraphy" (e.g., Winter, 1984). The major weakness of both schools of thought is that an a priori interpretation of the main allogenic control on accommodation was automatically attached to any sequence delineation, which gave the impression that sequence stratigraphy is more of an interpretation artifact than an empirical, data-based method. This a priori interpretation facet of sequence stratigraphy attracted considerable criticism and placed an unwanted shade on a method that otherwise represents a truly important advance in the science of stratigraphy. Fixing the damaged image of sequence stratigraphy only requires the basic understanding that base level changes can be controlled by any combination of eustatic and tectonic forces, and that the dominance of any of these allogenic mechanisms should be assessed on a case by case basis. It became clear that sequence stratigraphy needs to be dissociated from the global-eustasy model, and that a more objective analysis should be based on empirical evidence that can actually be observed in outcrop or the subsurface. This realization came from inside the Exxon research group, where the global cycle chart originated in the first place: "Each stratal unit is defined and identified only by physical relationships of the strata, including lateral continuity and geometry of the surfaces bounding the units, vertical stacking patterns, and lateral geometry of the strata within the units. Thickness, time for formation, and interpretation of regional or global origin are not used to define stratal units…, [which]… can be identified in well logs, cores, or outcrops and used to construct a stratigraphic framework regardless of their interpreted relationship to changes in eustasy" (Van Wagoner et al., 1990).

The switch in emphasis from sea level changes to relative sea level changes in the early 1990s marked a major and positive turnaround in sequence stratigraphy. By doing so, no interpretation of specific eustatic or tectonic fluctuations was forced upon sequences, systems tracts, or stratigraphic surfaces. Instead, the key surfaces, and implicitly the stratal units between them, are inferred to have formed in relation to a more "neutral" curve of relative sea level (base level) changes that can accommodate any balance between the allogenic controls on accommodation.

1.3. Definitions and key concepts

Figs. 3 and 4 provide the most popular definitions for sequence stratigraphy and the key sequence stratigraphic concepts. In contrast with all other types of stratigraphy (including allostratigraphy), and in spite of becoming such a fashionable method of stratigraphic analysis, sequence stratigraphy has not yet made it into the North American Code of Stratigraphic Nomenclature. The reason for this is the lack of agreement on some basic sequence stratigraphic concepts, including the definition of a "sequence", and also the proliferation of an incredibly complex jargon that is next to impossible to standardize.

The fact that several different sequence models are currently in use does not make the task of finding a common ground easy, even for what a "sequence" should be. Part of the problem comes from the fact that the position of the sequence boundary (both in space and time) varies from one model to another, to the extent that any of the key stratigraphic surfaces may become the (or part of the) sequence boundary. Nevertheless, all versions of sequence boundaries include both unconformable and conformable portions, which means that the original definition of Mitchum(1977) (Fig. 4) still fits in most of the cases.

It is important to note that no scale is associated with the definition of sequence stratigraphic concepts (Figs. 3 and 4). This means that the same terminology can and should be applied for sequences, systems tracts, and surfaces that develop at different temporal and spatial

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 (Embry, 2001b): the recognition and correlation of stratigraphic surfaces which represent changes in depositional trends in sedimentary rocks. Such changes were generated by the interplay of sedimentation, erosion and oscillating base level and are now determined by sedimentological analysis and geometric relationships.

Note that <u>sedimentation</u> is separated from <u>base</u> <u>level</u> <u>changes</u>. Also note important keywords:
- *"cyclicity": a sequence is a cyclothem, i.e. it corresponds to a stratigraphic cycle;*
- *"time framework": in the early days of sequence stratigraphy, the bounding surfaces were taken as time lines, in the view of the global-eustasy model. Today, independent time control is necessary for large scale correlations;*
- *"genetically related strata": no major hiatuses are assumed within a sequence.*

Fig. 3. Definitions 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.

Fig. 4. Key concepts of sequence stratigraphy.

scales. The differences between the larger- and the smaller-scale sequences, systems tracts, and surfaces is resolved via the concept of hierarchy, by using modifiers such as first-order, second-order, third-order, etc., often in a relative sense. The advantage of using a consistent terminology regardless of scale is that the jargon is kept to a minimum, which makes sequence stratigraphy more user-friendly and easier to understand across a large spectrum of readership. At the same time, we often do not know the scale (duration, lateral extent, or thickness changes across the basin) of the surfaces and stratal units we deal with within a study area, so the use of specific names for specific scales may become very subjective.

Jargon is what makes sequence stratigraphy a hard undertaking for anybody who starts learning this discipline. All sequence models are used to describe the same rocks, but very often using different sets of terms. Beyond this terminology barrier, sequence stratigraphy is in fact a relatively easy method to use. As many of the sequence stratigraphic terms in the literature are synonymous, a careful analysis of the different models reveals a lot of common ground, with the main differences in the approach of conceptual packaging of the same succession of strata. Once these differences are understood, the practitioner has the flexibility of using whatever model works best for the particular circumstances of a specific case study. This paper reviews the existing sequence stratigraphic models, emphasizing their similarities, merits, and pitfalls.

2. Base level changes, transgressions, and regressions

2.1. Base level

Base level (of deposition or erosion) is generally regarded as a global reference surface to which continental denudation and marine aggradation tend to proceed. This surface is dynamic, moving up and down through time relative to the center of Earth in parallel with eustatic rises and falls in sea level. For simplicity, base level is often approximated 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. This spatial relationship between sea level and base level is also supported by the fact that rivers meeting the sea erode below sea level (Schumm, 1993), i.e. to the base level. Some of the more popular definitions of base level are presented in Fig. 5.

Fig. 6 shows a marine to continental area, in which base level is approximated with sea level. The base level may be projected into the subsurface of the continents, marking the lowest level of subaerial erosion (Plummer

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).

Fig. 5. Definitions of base level.

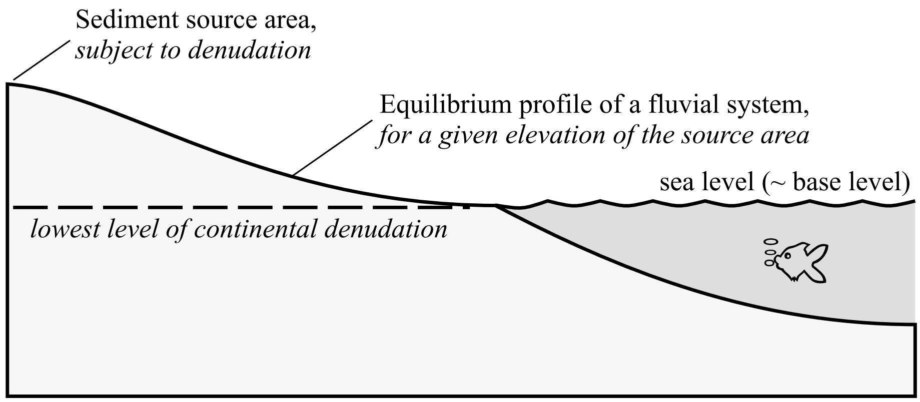

Fig. 6. The concept of base level, defined as the lowest level of continental denudation (modified from Plummer and McGeary (1996)). Graded (equilibrium) fluvial profiles meet the base level at the shoreline. As the elevation of the source areas changes in response to denudation or tectonic forces, the graded fluvial profiles adjust accordingly. See also Fig. 5 for alternative definitions of base level.

and McGeary, 1996). The surface topography tends to adjust to base level by long-term continental denudation. Between the source areas that are subject to denudation and the marine shorelines, a variety of processes of nonmarine aggradation may still take place when the amount of sediment load exceeds the transport capacity of any particular transport agent (gravity-, air- or water-flows).

Coupled with the concept of base level, fluvial equilibrium (graded) profiles are particularly important to understanding processes of sedimentation in continental areas. For any given elevation of the source area, rivers tend to develop a dynamic equilibrium in the form of a graded longitudinal profile (Miall, 1996, p. 353). This equilibrium profile is achieved when the river is able to transport its sediment load without aggradation or degradation of the channels (Leopold and Bull, 1979). Rivers that are out of equilibrium will aggrade or incise in an attempt to reach the graded profile (Butcher, 1990, p. 376). As the elevation of the source areas changes (due to factors such as denudation, subsidence, or tectonic uplift), rivers will start adjusting to new equilibrium profiles. An equilibrium profile may be below or above the land surface (triggering incision or aggradation respectively), and it merges with the base level in the marine shoreline areas (Fig. 6).

The marine base level (~sea level) and the fluvial graded profiles are sometimes used in conjunction to define a composite (stratigraphic) base level, which is the surface of equilibrium between erosion and deposition within both marine and continental areas (Cross, 1991; Cross and Lessenger, 1998; see discussion in Fig. 5). At any given location, the position of this irregular 3D surface is determined by the competing forces of sedimentation and erosion, and it may be placed either above the land surface/sea floor (where aggradation occurs), or below the land surface/sea floor (where subaerial/submarine erosion occurs).

Both schools of thought, i.e. one that keeps the concepts of graded profiles and base level separate and one that incorporates the graded profiles into the concept of base level (Fig. 5), are equally valid as they refer to the same processes just using a different terminology. Irrespective of how the base level concept is used, sequence stratigraphic models account for *one* curve of base level fluctuations that describes the changes in accommodation *at the shoreline*. The interplay between sedimentation and *this* curve of base level changes controls the transgressive and regressive shifts of the shoreline. Seaward, the magnitude and timing of base level shifts may change in response to the interplay between eustasy and differential subsidence (Catuneanu et al., 1998). Landward, the vertical shifts of the graded profiles (fluvial base level changes) are controlled by a combination of factors including climate, source area tectonism, and base level changes at the shoreline (Shanley and McCabe, 1994). The changes in base level at the shoreline are what the sequence models account for as the dominant control on fluvial processes, especially in the downstream reaches of river systems: a base level rise at the shoreline tends to trigger an upwards shift of the graded profiles (fluvial aggradation); a base level fall at the shoreline tends to trigger a downwards shift of the graded profiles (fluvial incision). This is a central theme of sequence stratigraphy, which allows for predictable architectures of stratal units and bounding surfaces to be inferred in the transition zone between the marine and nonmarine portions of the basin. The predictions of the theoretical models, e.g. the timing of fluvial incision and aggradation relative to the base level shifts at the shoreline, may sometimes be offset due to the interference of climate and source area tectonism (Blum, 1994, 2001; Leckie, 1994). The tectonic and climatic controls on fluvial base level changes are most important in the upstream reaches of fluvial systems, fading away downstream. The opposite is valid for the

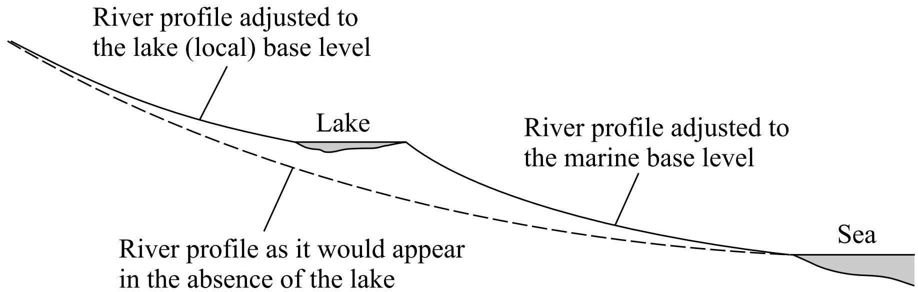

Fig. 7. Marine and local base levels as illustrated by a river flowing into a lake and from the lake into the sea (modified from Press and Siever (1986)). In each river segment, the graded profile adjusts to the lowest level it can reach.

control exerted by the base level changes at the shoreline (Shanley and McCabe, 1994).

In addition to the regional base level, sedimentation processes in inland basins may also respond to local base levels, such as lake levels (Fig. 7) or eolian deflation surfaces related to the level of the groundwater table (Kocurek, 1988; Shanley and McCabe, 1994).

2.2. Base level changes

At the core of sequence stratigraphic analysis is the sedimentary response to changes in accommodation. The concept of accommodation (Jervey, 1988) defines the space available for sediments to accumulate. This space can be created or destroyed by fluctuations in base level, and is gradually consumed by sedimentation.

Base level fluctuations are independent of sedimentation, and reflect changes in response to a number of external (eustatic, tectonic, climatic), diagenetic (sediment compaction), and environmental (wave and current energy) controls. The effects of climate are generally indirect, controlling accommodation via sea level changes (eustasy) or environmental energy.

The magnitude of eustatic fluctuations is measured relative to the centre of Earth. To evaluate the amount of vertical tectonics, as well as sedimentation and sediment compaction, we consider an imaginary reference horizon near the sea floor (datum in Fig. 8). The reason why we choose this datum not to coincide with the sea floor is because we want to separate the effects of tectonism, sedimentation, and sediment compaction. This datum will move down relative to the centre of Earth in response to tectonic subsidence, as well as in response to sediment compaction. The datum will move up relative to the centre of Earth in response to tectonic uplift. The sea floor moves up relative to the datum during times of sediment aggradation, and down relative to the datum during times of sea floor erosion. As compaction has the

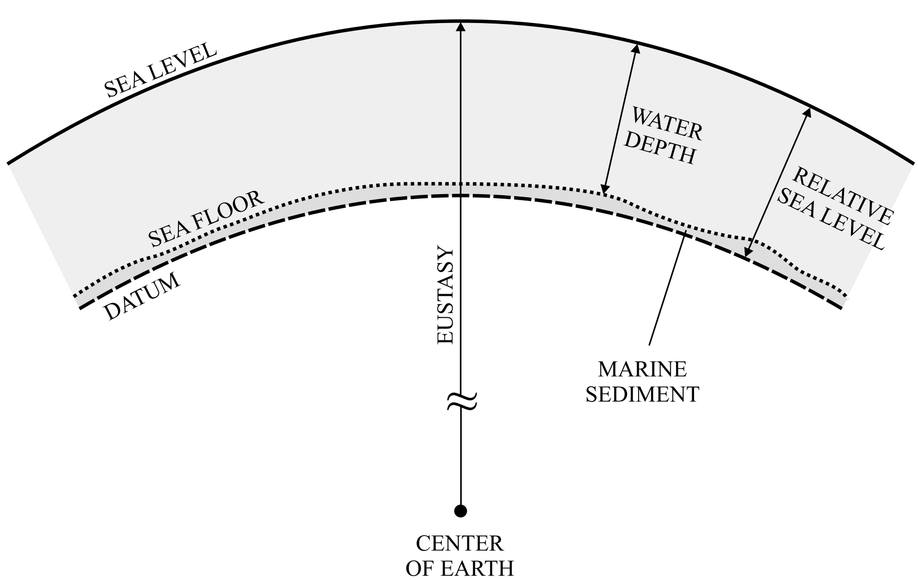

Fig. 8. Eustasy, relative sea level, and water depth as a function of sea level, sea floor, and datum reference surfaces (modified from Posamentier et al. (1988)). The datum is an imaginary, reference horizon taken just beneath the sea floor to monitor the magnitude of vertical tectonics (subsidence, uplift) relative to the centre of Earth. Many people have problems visualizing this datum: just think of a GPS buried in the unconsolidated sediment beneath the sea floor, which is able to monitor changes in elevation (i.e., distance relative to the centre of Earth).

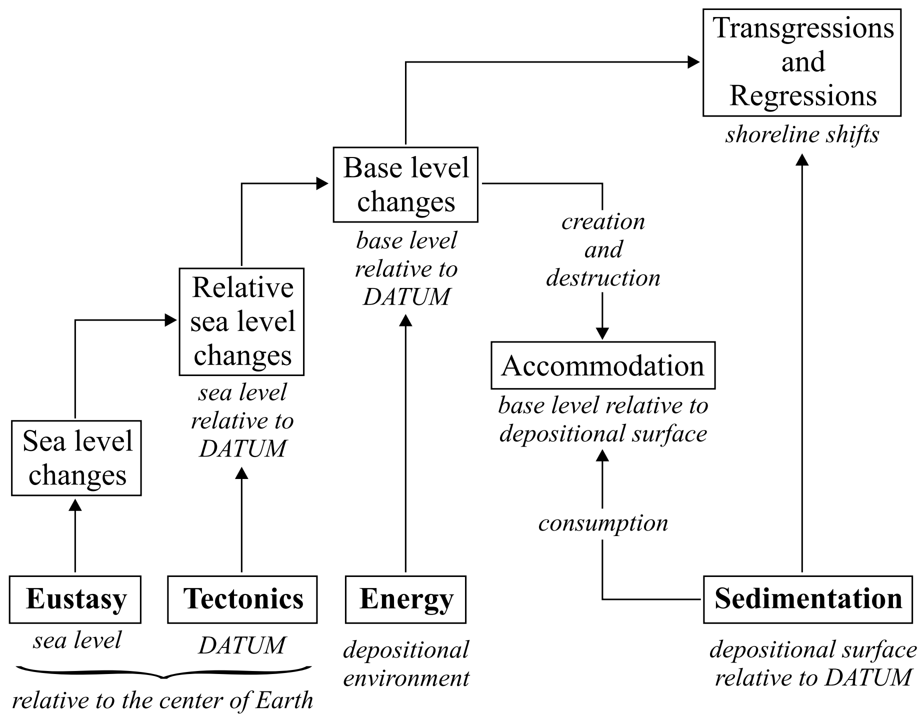

Fig. 9. Controls on base level changes, transgressions, and regressions. Note that the relative sea level changes account for the combined effects of eustasy and tectonics. Sediment compaction is included under "Tectonics", as it has the same effect on accommodation as the tectonic subsidence. As the base level is offset relative to the sea level due to the energy of the environment (waves, currents), the base level changes build on, but are not equal to, the relative sea level changes. Sea level changes, relative sea level changes, and base level changes are independent of sedimentation. The interplay between base level changes (combined effect of eustasy, tectonics, compaction, and environmental energy) and sedimentation controls the transgressive or regressive shifts of the shoreline. Accommodation is the space available for sediments to accumulate. This space is created or destroyed by base level changes, and it is consumed by sedimentation.

same effect on the position of the datum as tectonic subsidence, they are both incorporated under "Tectonics" in Fig. 9.

Sea level fluctuations relative to the datum are known as relative sea level changes. Different scenarios for rises and falls in relative sea level are illustrated in Figs. 10 and 11. Similarly, base level fluctuations *relative to the datum* define the concept of base level changes. As base level is not exactly coincident with sea level, due to the wave and current processes, the concepts of relative sea level changes and base level changes are not identical although they follow each other closely (Fig. 9).

A rise in base level (increasing vertical distance between base level and the datum) creates accommodation. Sedimentation during base level rise results in the consumption of the available accommodation at lower or higher rates relative to the rates at which accommodation is being created. The former situation implies water deepening, whereas the latter implies water shallowing. At any given time, the amount of accommodation that is still available for sediments to accumulate is measured by the vertical distance between the sea floor and the base level.

A fall in base level (decreasing vertical distance between base level and the datum) destroys accommodation. Almost invariably, such stages result in water shallowing irrespective of the depositional processes.

A common mistake among the practitioners of sequence stratigraphy is the confusion between base level changes and water depth changes. Base level changes are independent of sedimentation (base level relative to datum), whereas the water depth changes depend on sedimentation (sea level relative to the sea floor). For example, either water deepening or shallowing may occur during a stage of base level rise, as a function of the balance between the rates of creation and consumption of accommodation.

2.3. Transgressions and regressions

The interplay between base level changes and sedimentation controls the fluctuations in water depth, as well as the transgressive and regressive shifts of the shoreline (Fig. 9).

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 result in retrogradational stacking patters, e.g. marine facies shifting towards and overlying nonmarine

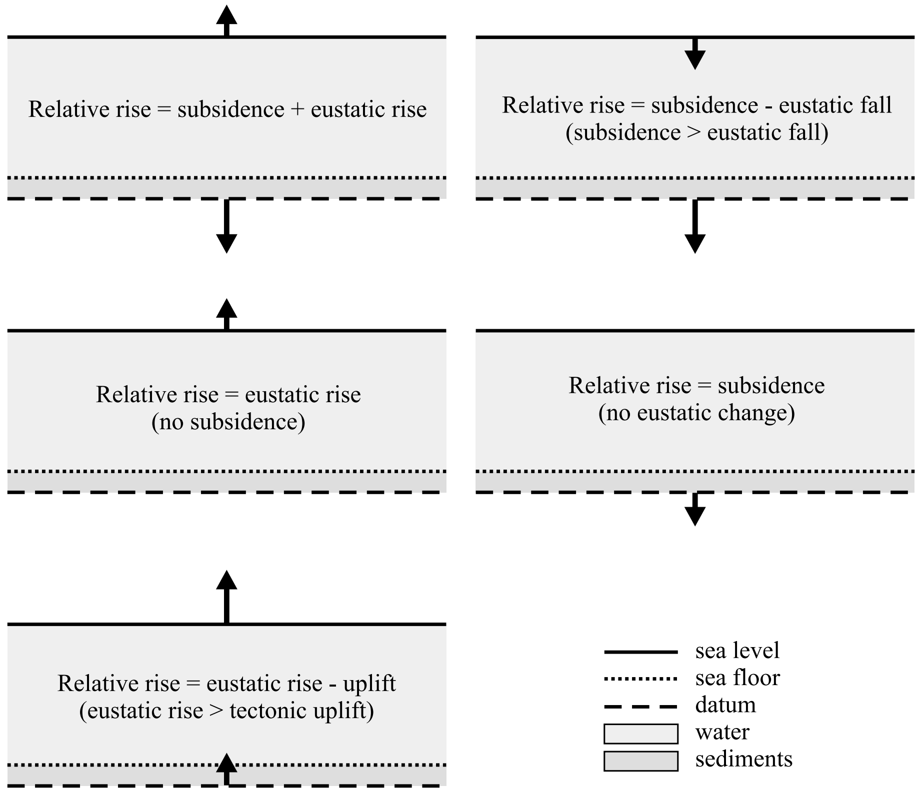

Fig. 10. Scenarios of relative sea level rise. If the base level is equated with the sea level for simplicity (by neglecting the energy of waves and currents), than the relative sea level rise becomes synonymous with the base level rise. Note that the newly created accommodation may be consumed by sedimentation at any rates, resulting in the shallowing or deepening of the water. The length of the arrows is proportional to the rates of vertical tectonics and eustatic changes.

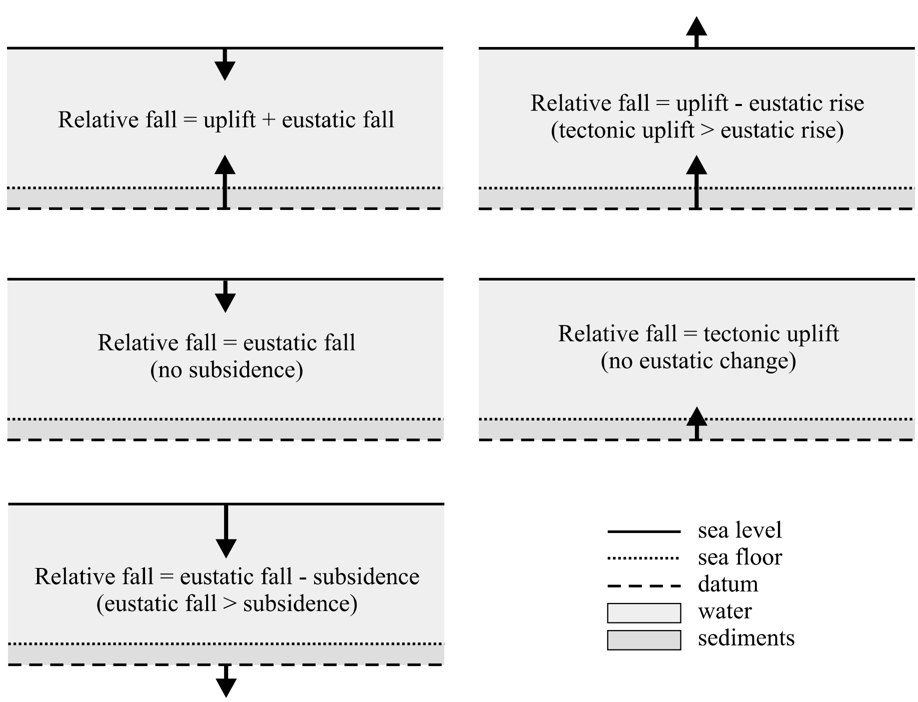

Fig. 11. Scenarios of relative sea level fall. If the base level is equated with the sea level for simplicity (by neglecting the energy of waves and currents), than the relative sea level fall becomes synonymous with the base level fall. Falling base level results in the destruction of existing accommodation, and almost invariably in the shallowing of the water. The length of the arrows is proportional to the rates of vertical tectonics and eustatic changes.

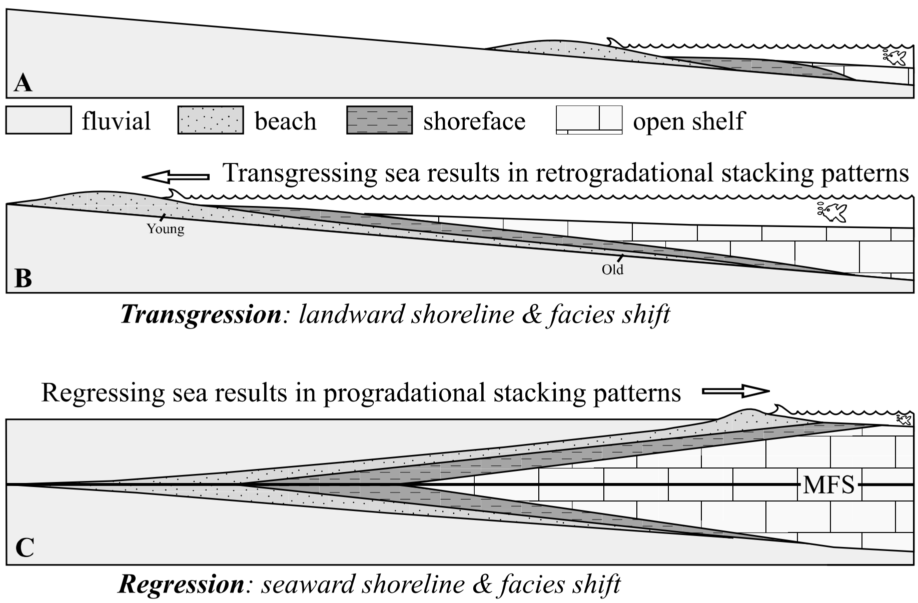

Fig. 12. Transgressions and regressions. Note the retrogradation and progradation (lateral shifts) of facies, as well as the surface that separates retrogradational from overlying progradational geometries. This surface is known as the maximum flooding surface (MFS).

facies (Fig. 12). Within the nonmarine side of the basin, the transgression is commonly indicated by the appearance of tidal influences in the fluvial succession, e.g. sigmoidal cross-bedding, tidal bedding (wavy, flaser and lenticular bedding), oyster beds and brackish to marine trace fossils (Shanley et al., 1992; Miall, 1997). Retrogradation is the diagnostic depositional trend for transgressions, and is defined as *the backward* (*landward*) *movement or retreat of a shoreline or of a coastline by wave erosion; it produces a steepening of the beach profile at the breaker line* (Bates and Jackson, 1987).

A regression is defined as the seaward migration of the shoreline. This migration triggers a corresponding seaward shift of facies, as well as a shallowing of the marine water *in the vicinity of the shoreline*. Regressions result in progradational stacking patterns, e.g. nonmarine facies shifting towards and overlying marine facies (Fig. 12). Progradation is the diagnostic depositional trend for regressions, and is defined as *the building forward or outward toward the sea of a shoreline or coastline (as of a beach, delta, or fan) by nearshore deposition of river-borne sediments or by continuous accumulation of beach material thrown up by waves or moved by longshore drifting* (Bates and Jackson, 1987).

The direct relationship between transgressions and regressions, on the one hand, and water deepening and shallowing, on the other hand, is safely valid for the shallow areas adjacent to the shoreline (see *italics* in the definitions of transgressions and regressions). In offshore areas, the deepening and shallowing of the water may be out of phase relative to the coeval shoreline movements, as subsidence and sedimentation rates vary along the dip of the basin. For example, the Mahakam delta in Indonesia (Verdier et al., 1980) provides a case study where the progradation (regression) of the shoreline is accompanied by a deepening of the water offshore, due to the interplay between sedimentation and higher subsidence rates. Also, the progradation of submarine fans during the rapid regression of the shoreline often occurs in deepening waters due to the high subsidence rates in the central parts of many extensional basins.

Transgressions, as well as two types of regressions may be defined as a function of the ratio between the rates of base level changes and the sedimentation rates at the shoreline (Plint, 1988; Posamentier et al., 1992; Fig. 13). The stratal geometries associated with these basic types of shoreline shifts are presented in Fig. 14.

Transgressions occur when accommodation is created more rapidly than it is consumed by sedimentation, i.e. the rates of base level rise outpace the sedimentation rates at the shoreline. This results in a retrogradation of facies. The scour surface cut by waves during the shoreline transgression is onlapped by the aggrading and retrograding shoreface deposits (Fig. 14).

Forced regressions occur during stages of base level fall, when the shoreline is forced to regress by the falling base level irrespective of the sediment supply. This triggers erosional processes in both the nonmarine and shallow marine environments adjacent to the coastline. Fluvial incision is accompanied by the progradation of offlapping shoreface deposits (Fig. 14).

Normal regressions occur in the early and late stages of base level rise, when the sedimentation rates outpace the low rates of base level rise at the shoreline. In this case, the newly created accommodation is totally

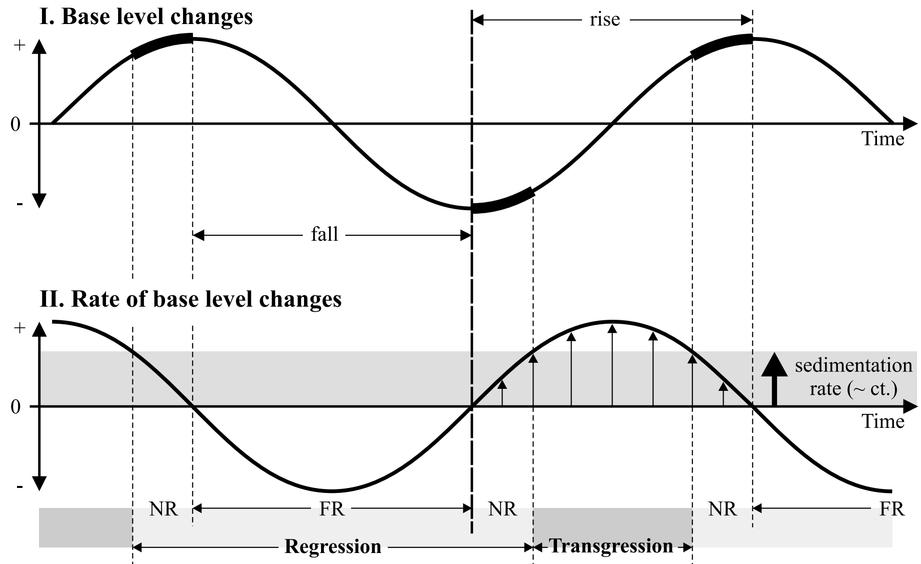

Fig. 13. Concepts of transgression, normal regression, and forced regression, as defined by the interplay between base level changes and sedimentation. The sine curve at the top shows the magnitude of base level changes through time. The thicker portions on this curve indicate early and late stages of base level rise, when the rates of base level rise (increasing from zero and decreasing to zero, respectively) are outpaced by the sedimentation rates. The sine curve below shows the rates of base level changes. Note that the rates of base level changes are zero at the end of base level rise and base level fall stages (the change from rise to fall and from fall to rise requires the motion to cease). The rates of base level changes are the highest at the inflection points on the top curve. For simplicity, the sedimentation rates are kept constant during the shown base level fluctuations. Transgressions occur when the rates of base level rise outpace the sedimentation rates. Abbreviations: FR = forced regression; NR = normal regression.

consumed by sedimentation, aggradation is accompanied by sediment bypass, and a progradation of facies occurs (Fig. 14).

Note that both transgressions and normal regressions may occur during base level rise, as a function of the balance between the rates at which accommodation is created and consumed (Fig. 13). This would make the transgressive stages shorter in time than the regressive stages (normal and forced), given a symmetrical curve of base level changes. The succession of transgressive and regressive shifts illustrated in Fig. 13 represents the most complete scenario of stratigraphic cyclicity. In practice, simplified versions of stratigraphic cyclicity may also be encountered, such as: (i) repetitive successions of transgressive and normal regressive facies, where continuous base level rise in the basin outpaces and is outpaced by sedimentation in a cyclic manner; (ii) repetitive successions of forced and normal regressions, where the high sediment input consistently outpaces the rates of base level rise (hence, no transgressions).

3. Stratigraphic surfaces

3.1. Types of stratal terminations

Stratal terminations are defined by the geometric relationship between strata and the stratigraphic surface against which they terminate. The main types of stratal terminations are described by truncation, toplap, onlap, downlap, and offlap (Fig. 15). Excepting for the truncation, the other concepts have been introduced with the development of seismic stratigraphy to define the architecture of seismic reflections (Mitchum and Vail, 1977; Mitchum et al., 1977). These terms have subsequently been incorporated into sequence stratigraphy in order to describe the stacking patterns of stratal units and to provide diagnostic features for the recognition of the various surfaces and systems tracts (e.g., Posamentier et al., 1988; Van Wagoner et al., 1988; Christie-Blick, 1991). The definitions of the key types of stratal terminations are provided in Fig. 16.

Stratal terminations also allow to infer the type of shoreline shifts, and implicitly the base level changes at the shoreline. For example, *coastal onlap* indicates transgression, *offlap* is diagnostic for forced regressions, and *downlap* may form in relation to normal or forced regressions. The preservation of *topset* packages (delta plain deposits) indicates aggradation coeval with progradation, hence base level rise and normal regression. The formation of *toplap* requires progradation of clinoforms (delta front) with perfect bypass in the delta plain. This means an ideal case where the base level at the shoreline does not change, as a base level rise would result in topset, and a base level fall would result in offlap. This ideal situation may only happen for relatively short periods of time, as the base level (controlled by the interplay of several independent factors) is hardly ever

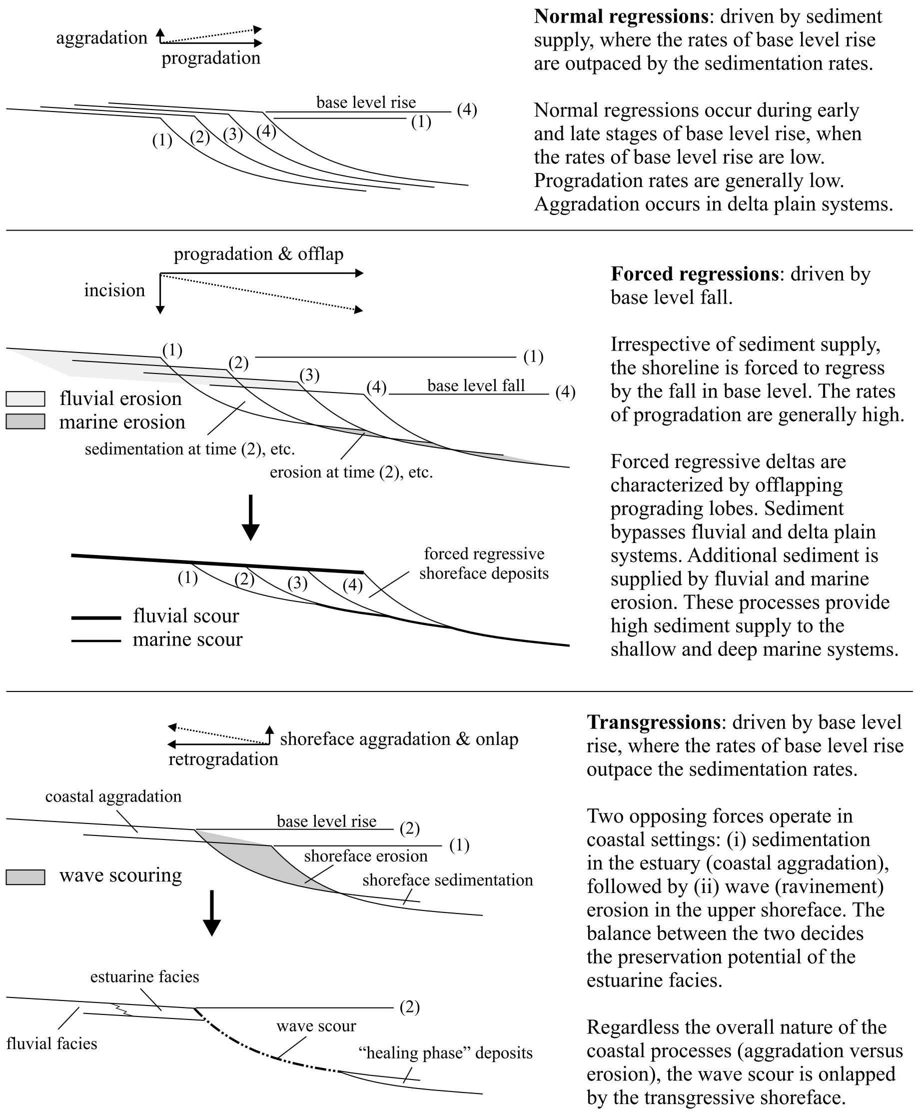

Fig. 14. Shoreline trajectories—normal regressions, forced regressions, and transgressions.

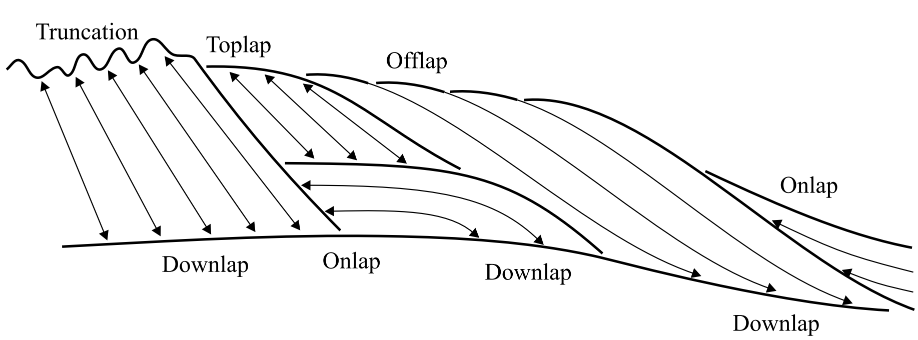

Fig. 15. Types of stratal terminations (modified from Emery and Myers (1996)). Note that tectonic tilt may cause confusion between onlap and downlap, due to the change in ratio between the dip of the strata and the dip of the stratigraphic surface against which they terminate.

stable. The concept of toplap was developed from the analysis of seismic data, where the thickness of the topset packages often falls below the seismic resolution, being reduced to a seismic interface (*apparent toplap*; Fig. 17).

3.2. Sequence stratigraphic surfaces

Sequence stratigraphic surfaces are defined relative to two curves; one describing the base level changes at the

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*; Fig. 17).

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, mainly during transgressions (*slope aprons*; Galloway, 1989) and forced regressions (*regressive slope onlap surfaces*; Embry, 2001), as a result of gravity flow processes.

- coastal onlap: refers to lower shoreface strata onlapping onto the ravinement surface during the shoreline transgression (Fig. 14).

- fluvial onlap: refers to the landward shift of the upstream end of the aggradation area within a fluvial system during base level rise (transgression or normal regression).

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.

Fig. 16. Types of stratal terminations (definitions from Mitchum(1977); Emery and Myers (1996)).

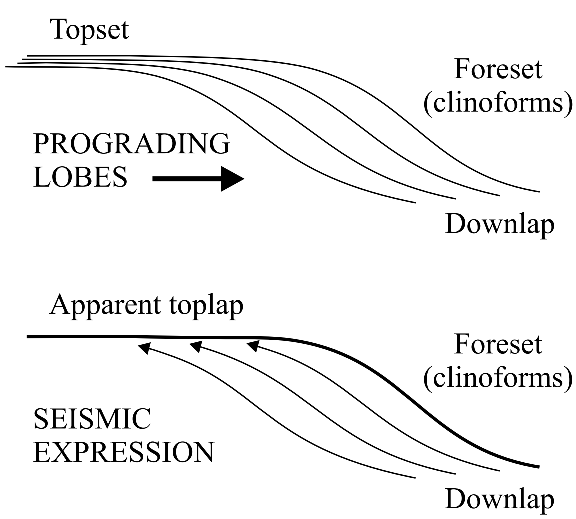

Fig. 17. Seismic expression of a topset package that is thin relative to the seismic resolution. The top diagram shows the stratal architecture of a deltaic system in a normal regressive setting. Note the possible confusion between topset and toplap due to the relatively low seismic resolution.

shoreline, and one describing the associated shoreline shifts (Fig. 18). The two curves are offset relative to one another with the duration of normal regressions (Fig. 13). The base level changes in Fig. 18 are idealized, as being defined by a symmetrical sine curve. This may not necessarily be the case in reality. Pleistocene examples from the Gulf of Mexico suggest longer stages of base level fall relative to base level rise in relation to glacio-eustatic climatic fluctuations, as it takes more time to build ice caps (base level fall) than to melt to ice (Blum, 2001). The tectonic control on base level changes may also generate asymmetrical base level curves. The case study of the Western Canada foreland system shows that stages of thrusting in the adjacent orogen, responsible for subsidence in the foredeep, were shorter in time relative to the stages of orogenic quiescence that triggered isostatic rebound and uplift in the foredeep (Catuneanu et al., 1997). Given the likely asymmetrical nature of the reference curve of base level changes, the

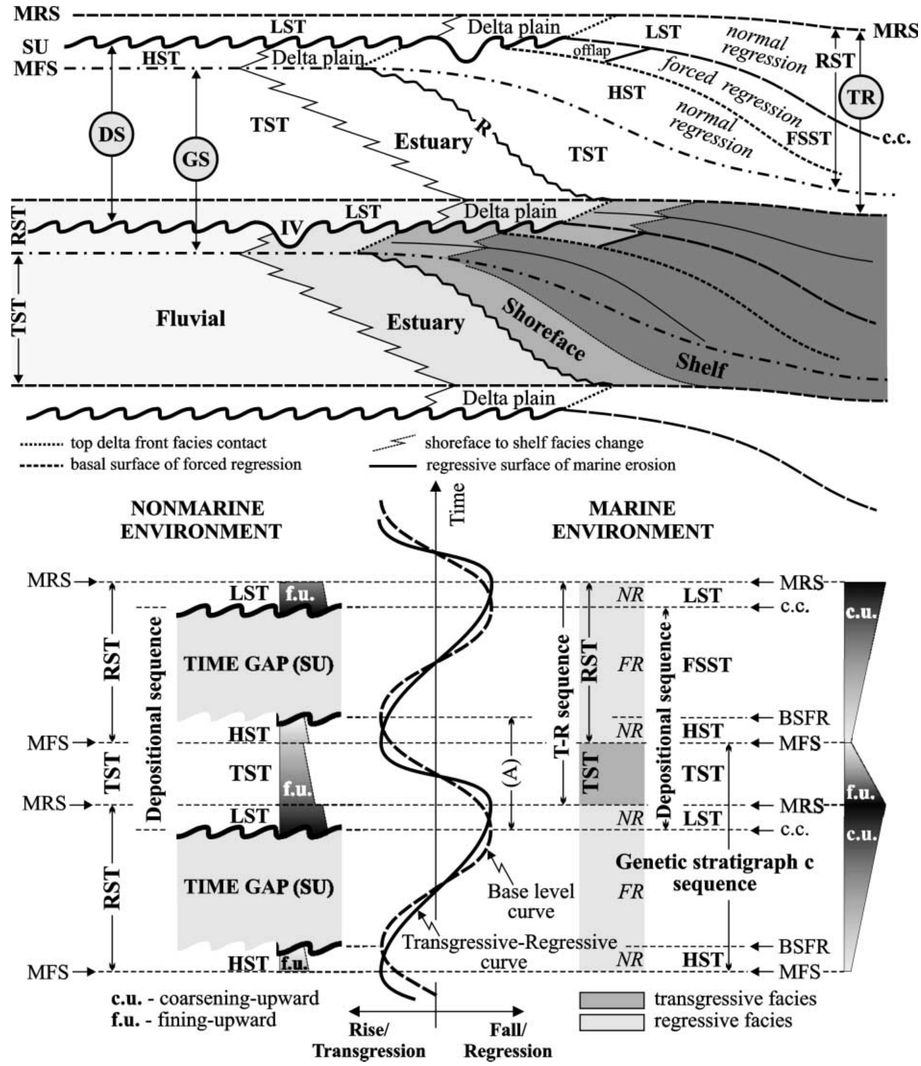

Fig. 18. Sequences, systems tracts, and stratigraphic surfaces defined in relation to the base level and the T–R curves. Abbreviations: SU—subaerial unconformity; c.c.—correlative conformity; BSFR—basal surface of forced regression; MRS—maximum regressive surface; MFS—maximum flooding surface; R—ravinement surface; IV—incised valley; (A)—positive accommodation (base level rise); NR—normal regression; FR—forced regression; LST—lowstand systems tract; 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.

associated transgressive–regressive (T–R) curve is bound to display an even more asymmetrical shape.

The main types of surfaces used in sequence stratigraphic analysis are presented in Fig. 19. The top six surfaces are proper sequence stratigraphic surfaces that may be used, at least in part, as *systems tract or sequence boundaries*. The bottom two represent facies contacts developed *within* systems tracts, which mark lithological discontinuities that are more appropriate for lithostratigraphic or allostratigraphic analyses.

3.2.1. Subaerial unconformity

The importance of subaerial unconformities as sequence-bounding surfaces was emphasized by Sloss et al. (1949). The subaerial unconformity is a surface of erosion or nondeposition created during base level fall by subaerial processes such as fluvial incision, wind degradation, sediment bypass, or pedogenesis. It gradually extends basinward during the forced regression of the shoreline and reaches its maximum extent at the end of the forced regression (Helland-Hansen and Martinsen, 1996: "seaward, the subaerial unconformity extends to the location of the shoreline at the end of fall"). Criteria for the recognition of subaerial unconformities in the field have been reviewed by Shanmugam (1988). The subaerial unconformity has a marine correlative conformity whose timing corresponds to the end of base level fall at the shoreline (Hunt and Tucker, 1992; Fig. 18).

Forced regressions require the fluvial systems to adjust to new (lower) graded profiles. A small base level fall at the shoreline may be accommodated by changes

Surfaces of Sequence Stratigraphy

Base level fall	Base level rise
1. Subaerial unconformity (and its correlative conformity)	1. Maximum regressive surface
2. Basal surface of forced regression	2. Maximum flooding surface
3. Regressive surface of marine erosion	3. Ravinement surface (transgressive)

Within-trend facies contacts

Normal regression	Transgression
1. Within-trend normal regressive surface	1. 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.*

Abbreviations: MRS - maximum regressive surface; MFS - maximum flooding surface; RS - ravinement surface.

Fig. 19. Types of stratigraphic surfaces (modified from Embry (2001a)).

in channel sinuosity, roughness and width, with only minor incision (Ethridge et al., 2001). The subaerial unconformity generated by such unincised fluvial systems is mainly related to the process of sediment bypass (Posamentier, 2001). A larger base level fall at the shoreline, such as the lowering of the base level below a major topographic break (e.g., the shelf break) results in fluvial downcutting and the formation of incised valleys (Ethridge et al., 2001; Posamentier, 2001). The interfluve areas are generally subject to sediment starvation and soil development. The subaerial unconformity can thus be traced at the top of paleosol horizons that are correlative to the unconformities generated in the channel subenvironment (Wright and Marriott, 1993). A synonymous term for the subaerial unconformity is the *regressive surface of fluvial erosion* (Plint and Nummedal, 2000).

3.2.2. Correlative conformity

The correlative conformity forms within the marine environment at the end of base level fall at the shoreline (Hunt and Tucker, 1992; Fig. 18). This is the paleo-sea floor at the end of forced regression, which correlates with the seaward termination of the subaerial unconformity. The correlative conformity was also defined as the paleo-sea floor at the onset of forced regression (Posamentier et al., 1988), but this choice was criticized because it allows the sequence boundary to be intercepted twice in the same vertical section within the area of forced regression (Hunt and Tucker, 1992). In this case, the correlative conformity (*sensu* Posamentier et al., 1988) does not correlate with the seaward termination of the subaerial unconformity.

The correlative conformity turned out to be a problem surface in sequence stratigraphy, surrounded by controversies regarding its timing and physical attributes. The main problem relates to the difficulty of recognizing it in most outcrop sections, cores, or wireline logs, although at the larger scale of seismic data it can be traced as the clinoform that correlates with the basinward termination of the subaerial unconformity. In this practice, the shallow marine portion of the correlative conformity separates rapidly prograding and offlapping forced regressive strata from the overlying aggradational normal regressive deposits. In the deep marine environment, the correlative conformity may be traced at the top of the prograding submarine fan complex (the "basin floor component" of Hunt and Tucker (1992)).

3.2.3. Basal surface of forced regression

The basal surface of forced regression was introduced by Hunt and Tucker (1992) to define the base of all deposits that accumulate in the marine environment during the forced regression of the shoreline. This replaces the correlative conformity of Posamentier et al. (1988), and it represents the paleo-sea floor at the onset of base level fall at the shoreline (Figs. 18, 20 and 21). In shallow marine successions, the basal surface of forced regression may be conformable, in which case it poses the same recognition problems as the correlative conformity, or it may be reworked by the regressive surface of marine erosion (Figs. 20 and 21). In the deep marine environment, the basal surface of forced regression may be traced at the base of the prograding submarine fan complex (Hunt and Tucker, 1992), as the scour cut by the earliest gravity flows associated with the forced regression of the shoreline. During the growth of the prograding submarine fan complex, individual submarine fans may gradually onlap the sediment-starved continental slope (Vail and Wornardt, 1990; Kolla, 1993; Embry, 1995). This portion of the basal surface of forced regression is also known as the *regressive slope onlap surface* (Embry, 2001a).

3.2.4. Regressive surface of marine erosion

The regressive surface of marine erosion is a scour cut by waves in the lower shoreface during the forced regression of the shoreline, as the shoreface attempts to preserve its concave-up profile that is in equilibrium with the wave energy (Bruun, 1962; Plint, 1988; Dominguez and Wanless, 1991; Plint and Nummedal,

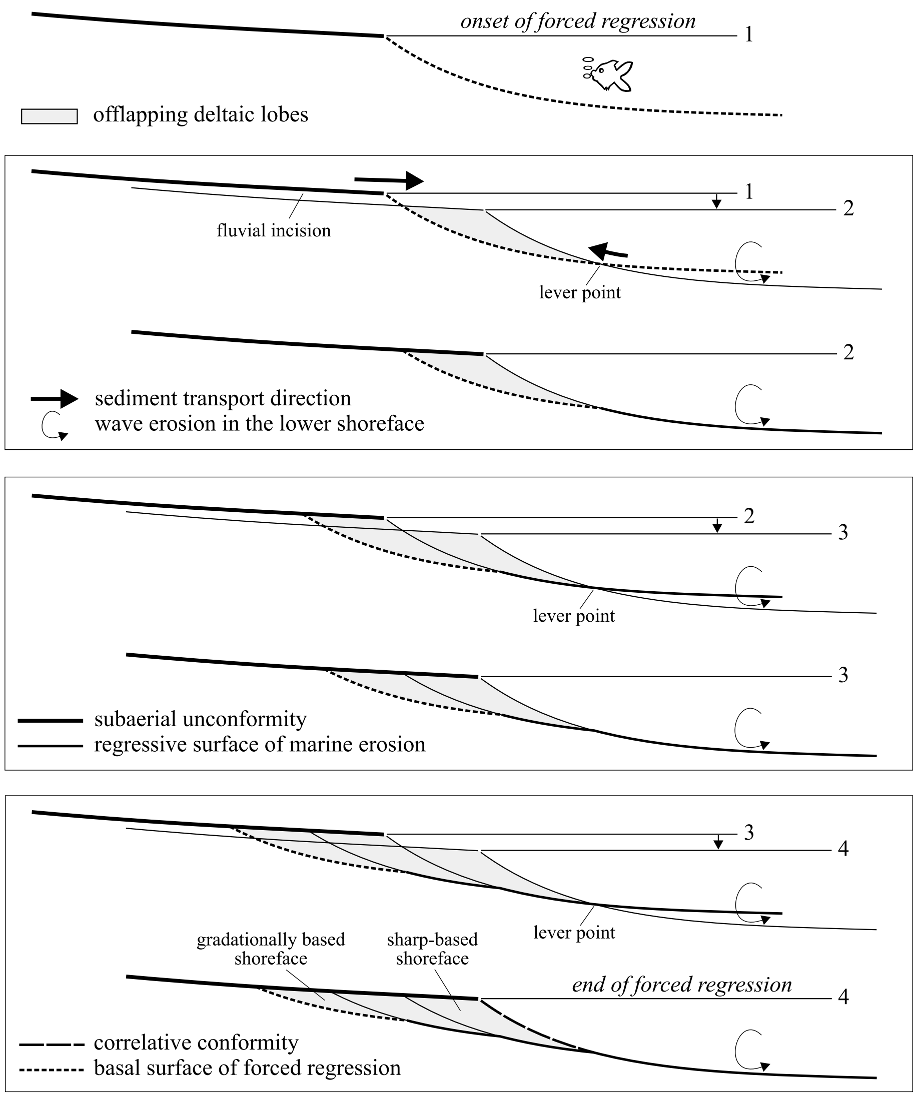

Fig. 20. Fluvial and shoreface processes in response to the forced regression of the shoreline in a shelf-type setting (modified from Bruun (1962); Plint (1988); Dominguez and Wanless (1991)). The shoreface profile is preserved during the forced regression via a combination of coeval sedimentation and erosion processes in the upper and lower shoreface respectively. The formation of the regressive surface of marine erosion requires the gradient of the sea floor to be shallower than the shoreface equilibrium profile. This is often the case in shelf-type settings. In ramp settings, where the gradient of the sea floor is steeper than the shoreface equilibrium profile, the offlapping shoreface clinoforms may prograde without erosion in the lower shoreface (Gilbert-type deltas). Note that the regressive surface of marine erosion may rework the basal surface of forced regression. The earliest falling stage shoreface deposits are gradationally based, where a conformable basal surface of forced regression is preserved.

2000). This surface (the ‘‘marine scour’’ associated with forced regressions in Fig. 14; Fig. 20) underlies sharp-based shoreface deposits (Plint, 1988), and may be separated from the basal surface of forced regression by forced regressive shelf sediments (Fig. 21). The landward portion of the regressive surface of marine erosion is likely to rework the basal surface of forced regression, in which case it becomes a systems tract boundary (Fig. 21).

The formation of the regressive surface of marine erosion requires a shallow gradient of the sea floor, smaller than the average gradient of the shoreface profile (~0.3°; Figs. 20 and 21). This is often the case in shelf settings, where the average gradient of the sea floor is about 0.03°. In contrast, slope settings have a steeper sea floor topography (~3°) relative to what is required by the shoreface to be in equilibrium with the wave energy, and hence no scouring is generated in the lower shoreface during forced regressions. These steep sea floor slopes are prograded by Gilbert-type deltas whose delta front facies are not sharp-based (*sensu* Plint, 1988). A synonymous term for the regressive surface of marine erosion is the *regressive ravinement surface* (Galloway, 2001).

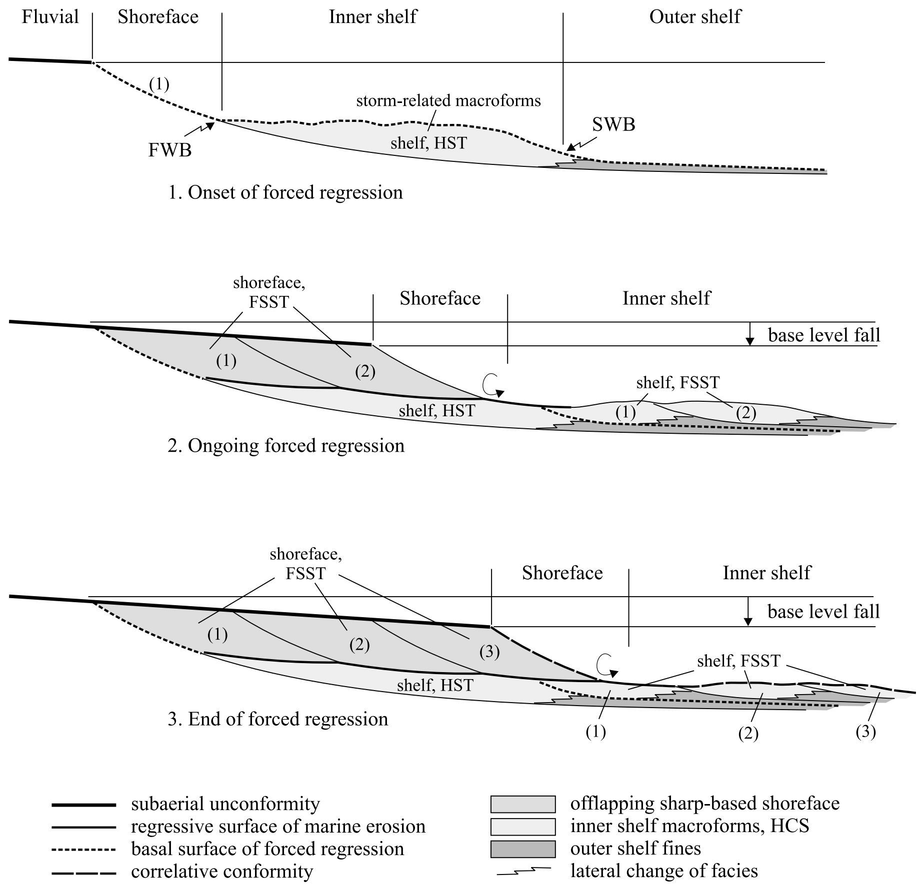

Fig. 21. Shallow marine deposits of the falling stage, in a shelf-type setting. The regressive surface of marine erosion and the basal surface of forced regression are distinct surfaces: the former underlies (sharp-based) shoreface deposits, the latter may underlie any type of marine facies. The basal surface of forced regression is the sea floor at the onset of forced regression. The two surfaces may occur in the same vertical profile, separated by falling stage shelf deposits. The regressive surface of marine erosion may become a systems tract boundary where it reworks the basal surface of forced regression. Abbreviations: HST—highstand systems tract; FSST—falling stage systems tract; HCS—hummocky cross-stratification; FWB—fair-weather wave base; SWB—storm wave base.

3.2.5. Maximum regressive surface

The maximum regressive surface (Helland-Hansen and Martinsen, 1996) is defined relative to the T–R curve, marking the point between regression and subsequent transgression (Fig. 18). Hence, this surface separates prograding strata below from retrograding strata above. The change from progradational to retrogradational stacking patterns takes place during the base level rise at the shoreline, when the rates of base level rise start outpacing the sedimentation rates. The maximum regressive surface is generally conformable, although the possibility of scouring associated with the change in the direction of shoreline shift at the onset of transgression is not excluded (Loutit et al., 1988; Galloway, 1989). The maximum regressive surface is also known as the *transgressive surface* (Posamentier and Vail, 1988), *initial transgressive surface* (Nummedal et al., 1993), or *conformable transgressive surface* (Embry, 1995).

In a shallow marine succession, the maximum regressive surface is easy to recognize at the top of coarsening-upward (regressive) deposits. In coastal settings, the maximum regressive surface underlies the earliest estuarine deposits (Fig. 18). The extension of this surface into the fluvial part of the basin is much more difficult to pinpoint, but at a regional scale it is identified with an abrupt decrease in fluvial energy, i.e. a change from amalgamated braided channel fills to overlying meandering systems (Kerr et al., 1999; Ye and Kerr, 2000). This change in fluvial style across the maximum regressive surface is marked by a grain size threshold in Fig. 18.

3.2.6. Maximum flooding surface

The maximum flooding surface (Frazier, 1974; Posamentier et al., 1988; Van Wagoner et al., 1988; Galloway, 1989) is also defined relative to the T–R curve, marking the end of shoreline transgression (Fig. 18). Hence, this surface separates retrograding strata below from prograding strata above. The presence of prograding strata above identifies the maximum flooding surface as a downlap surface on seismic data. The change from retrogradational to overlying progradational stacking patterns takes place during continued base level rise at the shoreline, when the sedimentation rates start to outpace the rates of base level rise. The maximum flooding surface is generally conformable, excepting for the outer shelf and upper slope regions where the lack of sediment supply may leave the sea floor exposed to erosional processes (Galloway, 1989). The maximum flooding surface is also known as the *maximum transgressive surface* (Helland-Hansen and Martinsen, 1996) or *final transgressive surface* (Nummedal et al., 1993).

In a marine succession, the maximum flooding surface is placed at the top of fining-upward (transgressive) deposits. In an offshore direction, the transgressive deposits may be reduced to a condensed section, or may even be missing. In the latter situation, the maximum flooding surface will be superimposed on and rework the maximum regressive surface. In coastal settings, the maximum flooding surface is placed at the top of the youngest estuarine facies (Fig. 18). Criteria for the recognition of the maximum flooding surface into the fluvial portion of the basin have been provided by Shanley et al. (1992), mainly based on the presence of tidal influences in fluvial sandstones. The position of this surface may also be indicated by an abrupt increase in fluvial energy, from meandering to overlying braided fluvial systems (Shanley et al., 1992), or by regionally extensive coal seams (Hamilton and Tadros, 1994). The change in fluvial styles across the maximum flooding surface is suggested by a grain size threshold in Fig. 18.

Tidal influences in fluvial strata may occur within a few tens of kilometers from the coeval shoreline (Shanley et al., 1992). Farther inland, the maximum flooding surface corresponds to the highest level of the watertable relative to the land surface, which, given a low sediment input and the right climatic conditions, may offer good conditions for peat accumulation at a regional scale.

3.2.7. Ravinement surface

The ravinement surface is a scour cut by waves in the upper shoreface during shoreline transgression (Bruun, 1962; Swift et al., 1972; Swift, 1975; Dominguez and Wanless, 1991; Figs. 14 and 18). This erosion may remove as much as 10–20 m of substrate (Demarest and Kraft, 1987), as a function of the wind regime and related wave energy in each particular region. The ravinement surface is onlapped during the retrogradational shift of facies by transgressive shoreface deposits (coastal onlap).

In a vertical profile that preserves the entire succession of facies, the ravinement surface separates coastal strata below (beach sands in an open shoreline setting, or estuarine facies in a river mouth setting) from shoreface and shelf deposits above. Where the transgressive coastal deposits are not preserved, the ravinement surface may rework the underlying regressive strata and the subaerial unconformity (Embry, 1995). In the latter case, the ravinement surface becomes part of the sequence boundary. Synonymous terms for the ravinement surface include the *transgressive ravinement surface* (Galloway, 2001), *wave-ravinement surface* (Swift, 1975), *shoreface ravinement* (Embry, 1995), and *transgressive surface of erosion* (Posamentier and Vail, 1988).

3.3. Within-trend facies contacts

3.3.1. Within-trend normal regressive surface

The within-trend normal regressive surface is a facies contact that develops during normal regressions at the top of prominent shoreline sands. These prominent coarser deposits may be represented by beach sands in an open shoreline setting, or by delta front sands in a river mouth setting (Fig. 22), and are usually overlain by alluvial deposits dominated by floodplain fines. This surface has a strong physical expression, being easy to identify in outcrop and subsurface. It may or may not connect with the landward termination of the

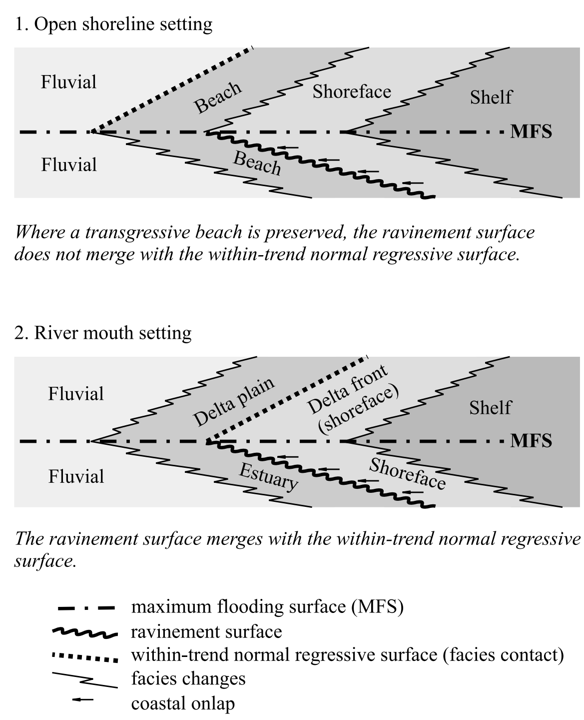

Fig. 22. Architecture of facies and stratigraphic surfaces at the point of maximum shoreline transgression. The position of the within-trend normal regressive surface varies with the type of coastline, between open shoreline and river mouth settings. The ravinement surface always sits at the base of the transgressive shoreface facies. The maximum flooding surface separates retrograding from overlying prograding geometries. Within the transgressive systems tract, the facies contact between shoreface sands and the overlying shelf shales defines the within-trend flooding surface.

ravinement surface, depending on the type of coastal setting (Fig. 22).

The within-trend normal regressive surface is conformable, as it forms during a time of coastal aggradation. This facies contact is a lithologic discontinuity that may be used in lithostratigraphic and allostratigraphic analyses, but it is not part of a systems tract boundary or of a sequence boundary. For this reason, the within-trend normal regressive surface is not a proper sequence stratigraphic surface (Fig. 19). It may however be used to fill in the internal facies details of sequences and systems tracts once the main sequence stratigraphic framework is outlined.

3.3.2. Flooding surface

The flooding surface is defined as "a surface separating younger from older strata across which there is evidence of an abrupt increase in water depth. This deepening is commonly accompanied by minor submarine erosion or nondeposition" (Van Wagoner, 1995). This definition is general enough to allow different types of surfaces to be candidates for flooding surfaces. The ravinement surface is often considered a "flooding surface" (Posamentier and Allen, 1999: "an overflowing of water onto land that is normally dry"), but other surfaces that form in fully marine successions satisfy the definition of a flooding surface as well: the maximum regressive surface (where the transgressive strata are thin and therefore the abrupt increase in water depth appears to happen across the maximum regressive surface), the maximum flooding surface (where the transgressive strata are missing and the maximum flooding surface reworks the maximum regressive surface), or a within-trend facies contact (where the transgressive strata are thicker) (Fig. 23).

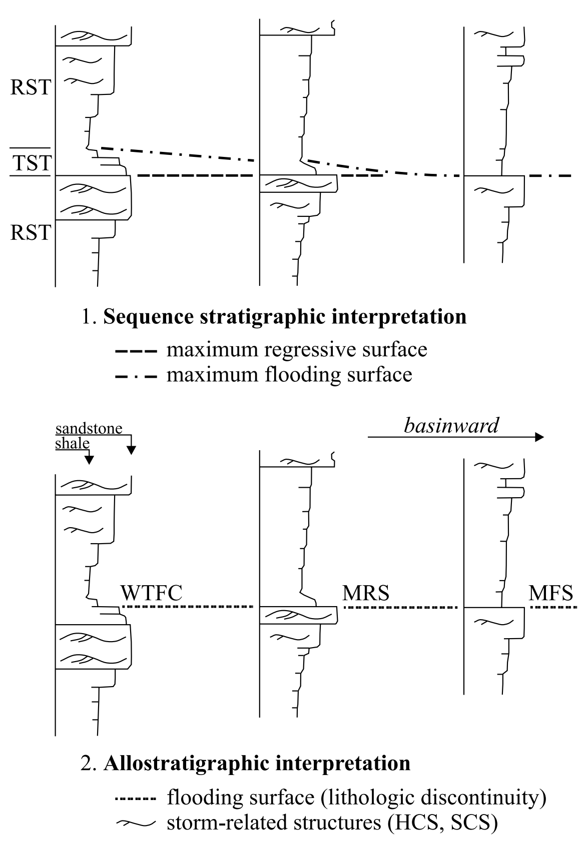

Fig. 23. Shallow marine (shoreface to shelf) succession of sands and shales interpreted in sequence stratigraphic and allostratigraphic terms. The thickness shown is about 12 m. Note that the transgressive facies thin basinward, to the point where the maximum flooding surface reworks the maximum regressive surface. The flooding surface is picked at the strongest lithological contrast. The example is from the Cardium Formation, Western Canada Basin. Abbreviations: WTFC—within-trend facies contact; MRS—maximum regressive surface; MFS—maximum flooding surface; TST—transgressive systems tract; RST—regressive systems tract.

As the ravinement, maximum regressive, and maximum flooding surfaces are already defined in an univocal manner, the within-trend type of flooding surface is the only new surface left to be considered. This facies contact between transgressive sands and the overlying transgressive shales is never in a position to serve as a systems tract or sequence boundary, which is why it is not a surface of sequence stratigraphy. Similar to the within-trend normal regressive surface, the within-trend flooding surface may however be used to resolve the internal facies architecture of a systems tract once the sequence stratigraphic framework is established.

4. Systems tracts

4.1. Methods of definition

The concept of systems tract was introduced to define a linkage of contemporaneous depositional systems (Brown and Fisher, 1977), which form the subdivision of a sequence. Systems tracts are interpreted based on stratal stacking patterns, position within the sequence, and types of bounding surfaces, and are assigned particular positions along an inferred curve of base level changes at the shoreline (Fig. 18). The definition of systems tracts was gradually refined from the earlier work of Exxon scientists (Vail, 1987; Posamentier et al., 1988; Posamentier and Vail, 1988; Van Wagoner et al., 1988, 1990) based on the contributions of Galloway (1989), Hunt and Tucker (1992), Embry and Johannessen (1992), Embry (1993, 1995), Posamentier and Allen (1999), and Plint and Nummedal (2000).

The early Exxon sequence model includes four systems tracts; the lowstand, transgressive, highstand, and shelf-margin systems tracts. These systems tracts were first defined relative to a curve of eustatic fluctuations (Posamentier et al., 1988; Posamentier and Vail, 1988), which was subsequently replaced with a curve of relative sea level (base level) changes. The lowstand and the shelf-margin systems tracts are similar concepts, as being related to the same portion of the sea level/base level curve, but they assume high versus low rates of sea level/base level fall in the shoreline area respectively. In addition to this, the lowstand systems tract was associated with a "rapid eustatic fall, greater than the rate of subsidence at shelf edge" (resulting in a "type 1" subaerial unconformity: Vail et al. (1984)), whereas the shelf-margin systems tract was associated with a "slow eustatic fall, less than the rate of subsidence at shelf break" (resulting in a "type 2" subaerial unconformity: Vail et al. (1984)). The "type 2" sequences, dealing with type 2 unconformities and the shelf-margin systems tract, have not received much acceptance, which is why the Exxon model is generally regarded as a tripartite scheme (i.e., lowstand, transgressive, and highstand systems tracts) of subdividing a sequence.

The lowstand systems tract, as defined by the Exxon school, includes a "lowstand fan" (falling sea level: Posamentier et al. (1988)) and a "lowstand wedge" (sea level at a lowstand: Posamentier et al. (1988)). The lowstand fan systems tract consists of autochthonous (shelf-perched deposits, offlapping slope wedges), and allochthonous gravity flow (slope and basin-floor fans) facies, whereas the lowstand wedge systems tract includes the aggradational fill of incised valleys, and a progradational wedge which may downlap onto the basin-floor fan (Posamentier and Vail, 1988). A major source of controversy in the early 1990s was where to place the sequence boundary in relation to the lowstand fan deposits. While everybody in the Exxon team agreed to place the boundary at the base of the allochthonous facies (onset of base level fall), the boundary was traced either at the top (Van Wagoner et al., 1990: end of base level fall) or at the base (Posamentier et al., 1992: onset of base level fall) of the autochthonous facies. This problem was resolved by Hunt and Tucker (1992) who redefined the lowstand fan deposits as the "forced regressive wedge systems tract", placing the sequence boundary at the top of the new systems tract (i.e., at the end of base level fall). In doing so, the base of all falling stage deposits became the "basal surface of forced regression" (Fig. 18). The advantage of this approach is that the correlative conformity now meets the seaward termination of the subaerial unconformity (Figs. 24 and 25). Hunt and Tucker (1992) also modified the timing of the various systems tracts relative to the curve of base level changes, using the highstand and lowstand points as the temporal boundaries of the new forced regressive wedge systems tract (see discussion in Miall (1997, p. 332–333)). The forced regressive wedge systems tract is also known as the "falling stage systems tract" (Plint and Nummedal, 2000).

Five systems tracts are currently in use, as defined by the interplay of base level changes and sedimentation (Figs. 18, 24 and 25).

4.2. Lowstand systems tract

The lowstand systems tract is bounded by the subaerial unconformity and its marine correlative conformity at the base, and by the maximum regressive surface at the top (Figs. 18, 24 and 25). It forms during the early stage of base level rise when the rate of rise is outpaced by the sedimentation rate (case of normal regression; Fig. 13). The lowstand systems tract includes the coarsest sediment fraction of both marine and nonmarine sections, i.e. the upper part of an upward-coarsening profile in a marine succession, and the lower part of a fining-upward profile in nonmarine strata (Fig. 18). Coastal aggradation decreases the slope gradient in the downstream portion of the fluvial systems (Fig. 26), which induces a lowering in fluvial energy, fluvial aggradation, and an overall upwards-decrease in grain size. The increase with time in the rate of base level rise also contributes to the overall fining-upward fluvial profile, as it creates more accommodation for floodplain deposition and increases the ratio between floodplain and channel sedimentation.

Typical examples of lowstand deposits include incised valley fills and amalgamated fluvial channels in nonmarine successions, as well as low-rate aggradational and progradational (normal regressive) coastal and marine deposits (Posamentier and Allen, 1999). As following the stage of base level fall, when most of the shelf becomes subaerially exposed, the lowstand systems tract may include shelf-edge deltas with diagnostic topset geometries (Fig. 24). The aggradation of lowstand fluvial strata starts from the delta plain area and gradually extends upstream by onlapping the subaerial unconformity (Figs. 24 and 25). The distance along dip that is subject to fluvial onlap is a function of several controls, including the duration of the lowstand stage, the rates of coastal aggradation, and the topographic gradients of the land surface. A flat topography (e.g., in a shelf-type setting) triggers fluvial aggradation over a large area, whereas a steep topography (e.g., in ramp settings) restricts the size of the area that is subject to fluvial aggradation. In the latter case, the subaerial unconformity may be directly overlain by transgressive fluvial strata over much of its extent (Embry, 1995; Dalrymple, 1999).

The preservation potential of the coastal and adjacent lowstand fluvial strata may be low due to the subsequent ravinement erosion (Fig. 26). Where overlying estuarine facies are preserved, fluvial lowstand strata are likely to develop between the subaerial unconformity and the estuarine strata. The contact between lowstand fluvial and the overlying estuarine facies is the maximum regressive surface (Fig. 26). This stratigraphic surface tends to be sharp, because of the rapid development of the estuarine system as soon as the shoreline starts its landward shift. This contact should not be confused

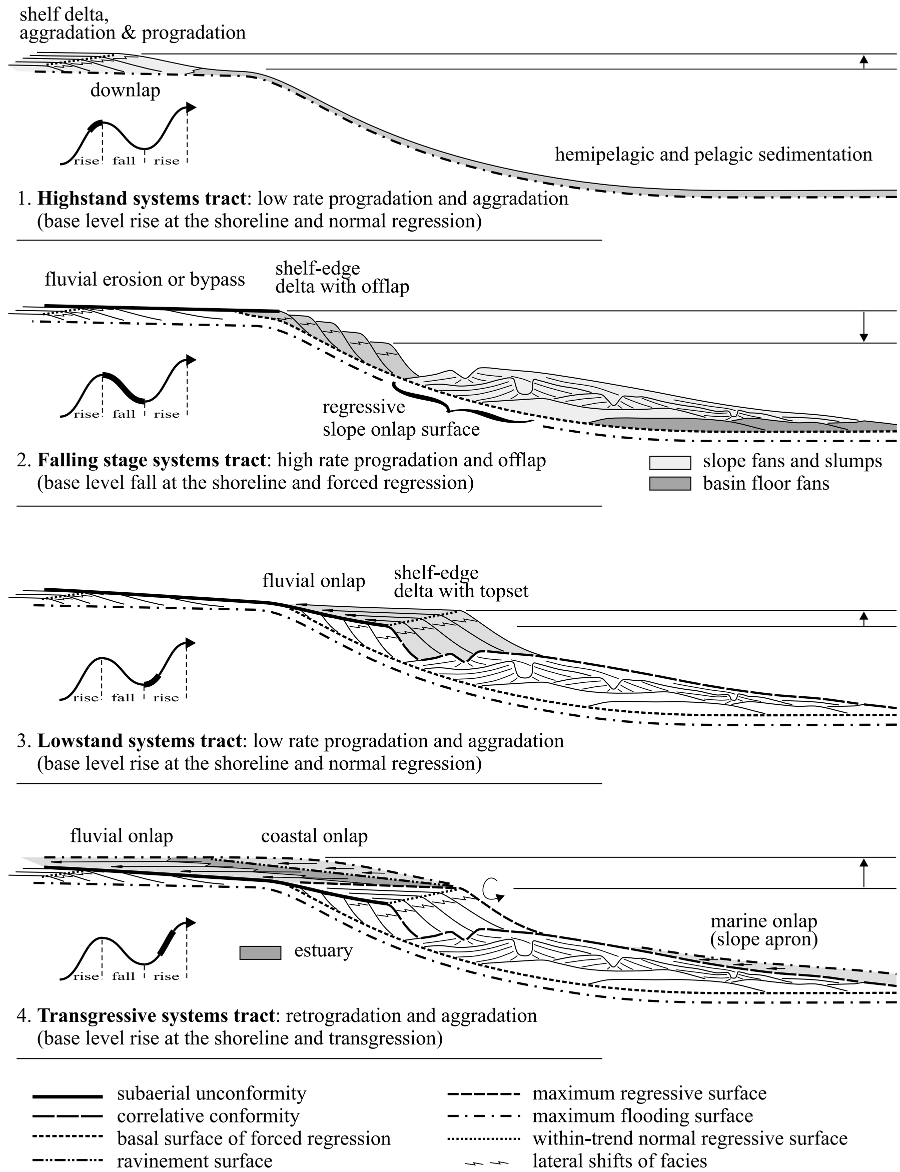

Fig. 24. Regional architecture of depositional systems, systems tracts, and stratigraphic surfaces. Note that systems tracts are defined by stratal stacking patterns and bounding surfaces, with an inferred timing relative to the base level curve at the shoreline. The formation of these systems tracts in a time–distance framework is illustrated in Fig. 25.

with the transition between transgressive fluvial facies and the overlying estuarine strata (Fig. 26). The latter facies shift is gradational, with significant interfingering between fluvial and estuarine facies. Excepting for the earliest lowstand shoreface strata, which are sharp-based as overlying the regressive surface of marine erosion, the shoreface deposits of the lowstand systems tract are gradationally based (Fig. 26).

4.3. Transgressive systems tract

The transgressive systems tract is bounded by the maximum regressive surface at the base, and by the maximum flooding surface at the top. This systems tract forms during the portion of base level rise when the rates of rise outpace the sedimentation rates. It can be recognized from the diagnostic retrogradational stacking patterns, which result in overall fining-upward profiles within both marine and nonmarine successions (Fig. 18). The marine portion of the transgressive systems tract develops primarily in shallow areas adjacent to the shoreline, with correlative condensed sections, unconformities and onlapping gravity flow and pelagic deposits offshore (Galloway, 1989; Fig. 24). The shallow marine facies are represented by onlapping healing-phase deposits that accumulate in the lower shoreface (Dominguez and Wanless, 1991; Posamentier and Chamberlain, 1993), plus a transgressive lag that

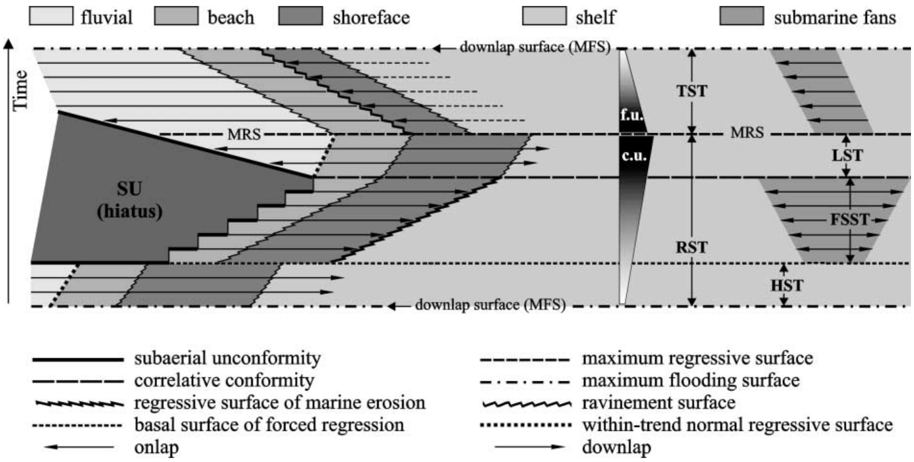

Fig. 25. Wheeler diagram illustrating the depositional patterns during a full regressive–transgressive cycle (a "genetic stratigraphic sequence", *sensu* Galloway (1989)). For the stratal stacking patterns of the four systems tracts, as well as their inferred timing relative to the base level curve, see Fig. 24. The subaerial unconformity extends basinward during the forced regression of the shoreline. The correlative conformity (*sensu* Hunt and Tucker (1992)) meets the basinward termination of the subaerial unconformity. The basal surface of forced regression (correlative conformity of Posamentier et al. (1988)) partly overlaps with the subaerial unconformity, the two surfaces being separated by forced regressive nearshore deposits. The diagram shows fluvial onlap onto the subaerial unconformity during subsequent base level rise. The rate of onlap depends on the topographic gradients, ranging from pronounced onlap (steep topography) to no onlap at all (flat topography). Abbreviations: SU—subaerial unconformity; MRS—maximum regressive surface; MFS—maximum flooding surface; HST—highstand systems tract; FSST—falling stage systems tract; LST—lowstand systems tract; TST—transgressive systems tract; RST—regressive systems tract; f.u.—fining-upward; c.u.—coarsening-upward.

blankets the ravinement surface in the upper shoreface (Fig. 26).

In coastal settings, the transgressive systems tract includes backstepping foreshore (beach) deposits, diagnostic estuarine facies, and the associated barrier island systems. The formation and preservation of estuarine facies depends on the rates of base level rise, the depth of falling stage fluvial incision, the wind regime and the amount of associated wave ravinement erosion, and the topographic gradients at the shoreline. Coastal aggradation is favored by high rates of base level rise, weak ravinement erosion, and shallow topographic gradients (e.g., in shelf-type settings; Fig. 26). Steeper topographic gradients (e.g., in ramp settings) tend to induce coastal erosion in relation to a combination of factors including higher fluvial energy, wave ravinement, and slope instability (Fig. 27). This may explain the general lack of estuarine facies in fault-bounded basins.

The fluvial portion of the transgressive systems tract displays tidal influences and an overall fining-upward profile due to the gradual decrease in topographic gradients and fluvial energy in response to coastal aggradation. The preservation potential of the transgressive deposits is high due to the fact that the subsequent normal regression leads to sediment aggradation across the entire basin (Fig. 26).

4.4. Highstand systems tract

The highstand systems tract is bounded by the maximum flooding surface at the base, and by a composite surface at the top that includes the subaerial unconformity, the regressive surface of marine erosion, and the basal surface of forced regression (Figs. 18, 24–26). It corresponds to the late stage of base level rise during which the rates of rise drop below the sedimentation rates, generating a normal regression of the shoreline. As a result of differential fluvial aggradation (with higher rates in the proximity of the shoreline) and a corresponding decrease in topographic slope, the nonmarine portion of the highstand systems tract may record a lowering with time in fluvial energy (Shanley et al., 1992). This trend, superimposed on continued denudation of the sediment source areas, tends to generate an upward-fining fluvial profile that continues the overall upwards decrease in grain size recorded by the underlying lowstand and transgressive systems tracts. However, the late highstand may be characterized by laterally interconnected, amalgamated channel and meander belt systems with poorly preserved floodplain deposits, due to the lack of floodplain accommodation once the rate of base level rise decreases, approaching the stillstand (Shanley and McCabe, 1993). During subsequent base level fall, the top of the nonmarine highstand systems tract may be affected by erosion or pedogenic processes (Wright and Marriott, 1993).

The marine portion of the highstand systems tract displays a coarsening-upward profile related to the basinward facies shift, and includes low-rate prograding and aggrading normal regressive strata. Within the overall regressive marine succession, this systems tract occupies the lower part of the coarsening-upward profile

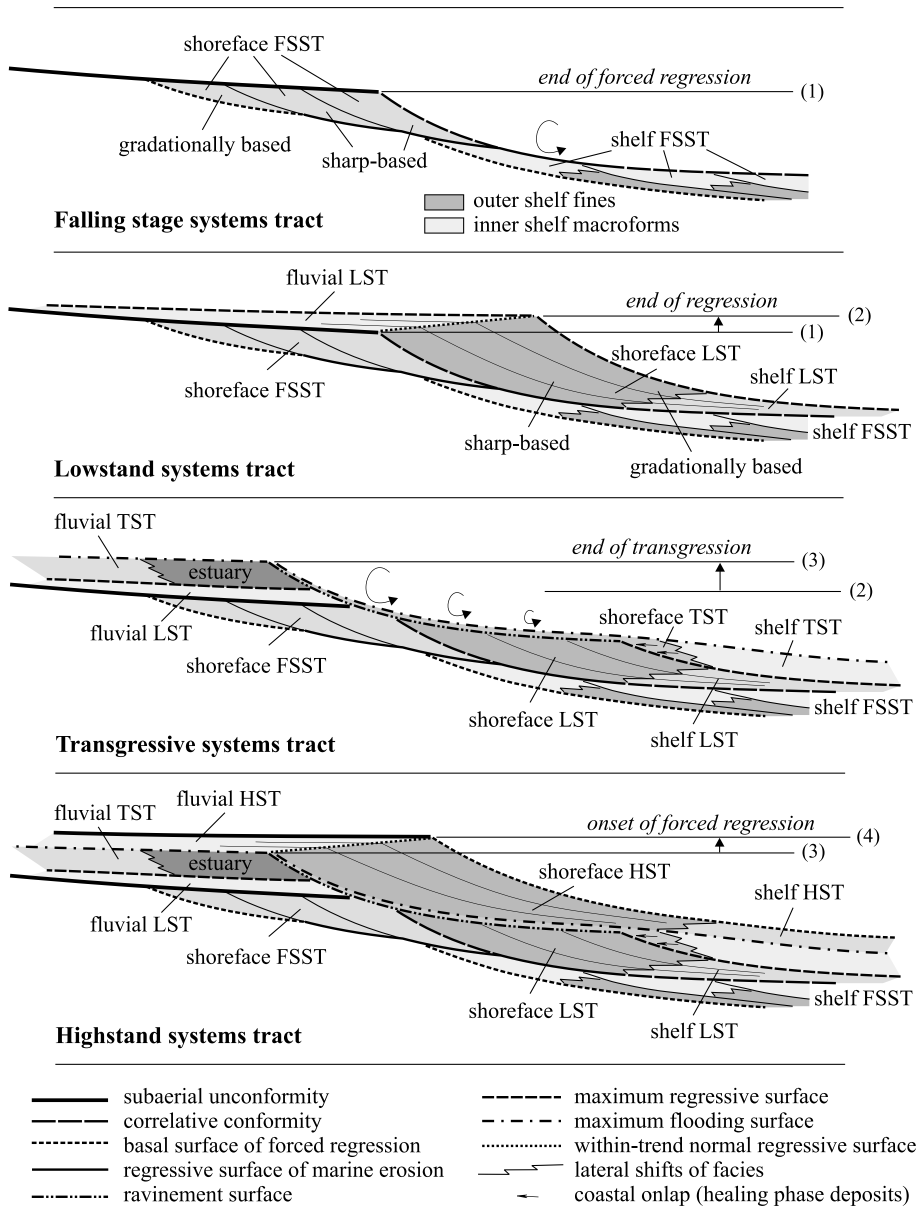

Fig. 26. Detailed architecture of facies and stratigraphic surfaces in the transition zone between fluvial and shallow marine environments, in a shelf-type setting. The falling stage shelf deposits have a low preservation potential where the shoreline falls below the shelf-break (Fig. 24). Note that the earliest lowstand shoreface deposits are sharp-based. The ravinement surface is commonly overlain by a transgressive lag.

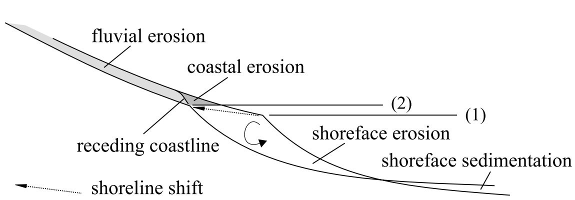

Fig. 27. Transgression with coastal erosion, where the wave scouring in the upper shoreface dominates the shoreline processes. Coastal erosion is likely to trigger fluvial incision as the river mouth shifts below the previous graded profile. These processes are likely to occur in ramp settings where the steeper topographic gradients at the shoreline are unfavorable for estuary development.

(Figs. 18 and 25). The highstand systems tract typically includes deltas with topset geometries, in clastic-dominated settings, or carbonate platforms, when the submerged shelf hosts favorable conditions for a "carbonate factory".

The preservation potential of the upper fluvial to shallow marine highstand deposits is low due to the subaerial and marine erosional processes that are associated with the subsequent fall in base level.

4.5. Falling stage systems tract

The falling stage systems tract includes all strata that accumulate during base level fall in the marine portion of the basin, at the same time with the formation of the subaerial unconformity landwards relative to the shoreline. Diagnostic for this systems tract are the shallow marine deposits with rapidly prograding and offlapping stacking patterns, which are age-equivalent with the deep marine submarine fans (e.g., Hunt and Tucker, 1992; Plint and Nummedal, 2000). This systems tract was independently described by Hunt and Tucker (1992) who specifically referred to slope and basin floor settings, and by Plint and Nummedal (2000) who studied the processes and products of forced regressions in a shelf-type setting.

In a most complete scenario, falling stage deposits include offlapping shoreface lobes, shelf macroforms, slope and basin floor fans, and offlapping slope deltaic wedges (Figs. 24–26). These deposits do not necessarily coexist. The type of falling stage facies that accumulate at any given time largely depends on the position of the base level relative to the shelf break.

If the base level is above the shelf break (Figs. 21 and 26), the falling stage deposits include offlapping shoreface lobes, shelf macroforms, and deep sea (slope and basin floor) submarine fans. The systems tract boundaries are composite surfaces which include the subaerial unconformity, the correlative conformity and the youngest portion of the regressive surface of marine erosion at the top, and the basal surface of forced regression and the older portion of the regressive surface of marine erosion at the base (Figs. 21 and 26). The shoreface deposits that accumulate in a shelf setting during the forced regression are sharp-based, excepting for the earliest falling stage shoreface strata which are gradationally based (Figs. 21 and 26). The preservation potential of the falling stage strata that accumulate on the shelf is low where the base level falls below the shelf-break.

If the base level falls below the shelf-break (Fig. 24), a shelf-edge delta with offlapping geometries will prograde over the continental slope, and downlap onto the partly coeval submarine fans. These falling stage deposits are bounded at the top by the subaerial unconformity and its correlative conformity, and at the base by the basal surface of forced regression (Fig. 24).

4.6. Regressive systems tract

The undifferentiated regressive package includes all strata accumulated during shoreline regression, i.e. the entire succession of highstand, falling stage, and lowstand deposits. It is bounded by the maximum flooding surface at the base, and by the maximum regressive surface at the top, and it is defined by progradational stacking patterns in both marine and nonmarine strata.

Within the nonmarine portion of the basin, the regressive package may include the time gap corresponding to the subaerial unconformity, if lowstand fluvial deposits are present (Figs. 18 and 25). The effects of ravinement erosion coupled with fluvial onlap may result in the subaerial unconformity to be directly overlain by transgressive strata (Embry, 1995; Dalrymple, 1999; Figs. 25 and 26), in which case, the subaerial unconformity becomes a boundary between the regressive and the overlying transgressive deposits.

Within the marine portion of the basin, the regressive package displays a coarsening-upward profile which relates to the basinward shoreline shift. The coarsening-upward profile should strictly be regarded as a *progradational* trend, which is not the same with a *shallowing-upward* trend (Catuneanu et al., 1998). It is documented that the earliest, as well as the latest deposits of a marine coarsening-upward succession are likely to accumulate in a deepening water (Galloway, 1989; Naish and Kamp, 1997; Catuneanu et al., 1998).

The regressive systems tract, as defined by Embry (1995), is bounded at the base by the maximum flooding surface within both the marine and nonmarine portions of the basin. At the top, the regressive systems tract is bounded by the maximum regressive surface in a marine succession, and by the subaerial unconformity in nonmarine strata. The latter portion of the systems tract boundary is taken by definition (Embry, 1995), even though there is a possibility that lowstand fluvial strata (still regressive) may be present above the subaerial unconformity. In this practice, all fluvial strata directly overlying the subaerial unconformity are assigned to the transgressive systems tract by definition (Embry, 1995).

In many instances the use of the regressive systems tract over the use of individual lowstand, falling stage, and highstand systems tracts is preferable, due to the difficulty in field recognition of some of the surfaces that separate the lowstand, falling stage, and highstand facies (notably the correlative conformity and the conformable portions of the basal surface of forced regression; Embry (1995)).

5. Sequence models

5.1. Methods of sequence delineation

Five sequence stratigraphic models are currently in use, all stemming from the original depositional sequence of seismic stratigraphy (Fig. 28). These models may be grouped into two main categories: one group defines the sequence boundaries relative to the base level curve (depositional sequences II, III, and IV in Fig. 28), whereas the other group defines the sequence boundaries relative to the T–R curve (genetic and T–R sequences in Fig. 28). The timing of sequence boundary formation for each of these models is presented in Fig. 29.

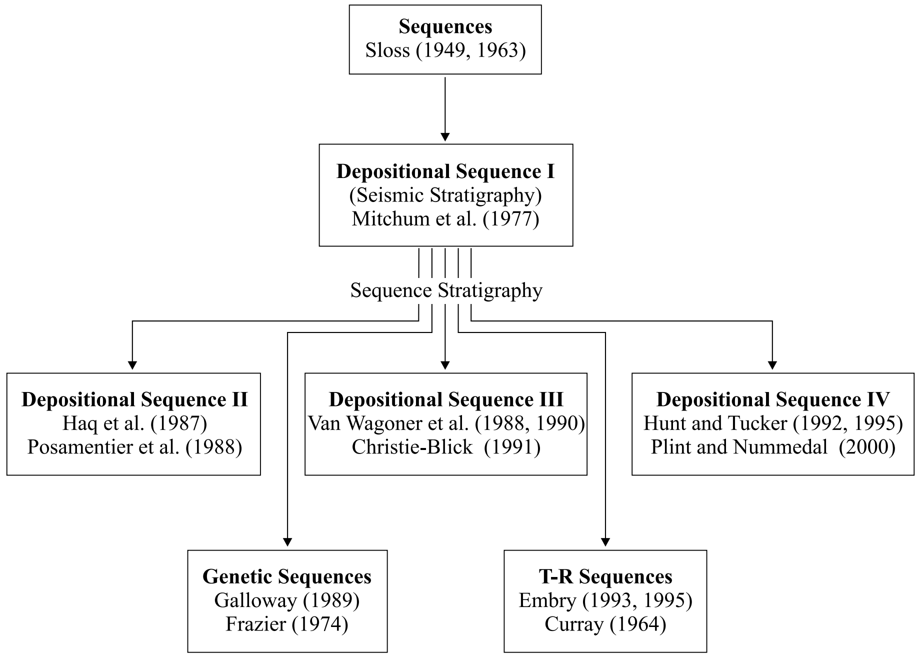

Fig. 28. Family tree of sequence stratigraphy (modified from Donovan (2001)). The various sequence stratigraphic models mainly differ in the style of conceptual packaging of strata into sequences, i.e. with respect to where the sequence boundaries are picked.

5.2. Depositional sequence

The depositional sequence uses the subaerial unconformity and its marine correlative conformity as a composite sequence boundary. The timing of the subaerial unconformity is equated with the stage of base level fall at the shoreline (Fig. 18). The correlative conformity is either picked as the sea floor at the onset of forced regression (depositional sequence II in Figs. 28 and 29), or as the sea floor at the end of forced regression (depositional sequences III and IV in Figs. 28 and 29). Depositional sequences III and IV are similar, with the exception that a fourth, falling stage systems tract, is recognized in the latter. The depositional sequence illustrated in Fig. 18 is the depositional sequence IV.

The conceptual merit of the depositional sequence models is that the correlative conformity is independent of sedimentation (as it is defined relative to the base level curve), hence it can be equated with a chronostratigraphic marker. The pitfall of these models is that the shallow marine portion of the correlative conformity is typically invisible in small to average size outcrops, in cores, or on wireline logs, although its position may be inferred on larger scale seismic data within 10^0–10^1 m intervals. In deep marine settings, the correlative conformity is easier to pinpoint in relation to the falling stage submarine fan systems.

5.3. Genetic stratigraphic sequence

The genetic stratigraphic sequence (Galloway, 1989; Fig. 28) uses maximum flooding surfaces as sequence boundaries, and it is subdivided into highstand, lowstand (fall and early rise), and transgressive systems tracts similar to the depositional sequence II (Figs. 18 and 29). This model overcomes the recognition problems related to the correlative conformity, and has the merit that maximum flooding surfaces are relatively easy to map across a basin. The criticism that this model received is two-fold. Firstly, the genetic stratigraphic sequence includes the subaerial unconformity within the sequence, which allows for the possibility that strata genetically unrelated are put together into the same "genetic" package. Secondly, the timing of the maximum flooding surfaces depends on the interplay of base level and sedimentation, and hence these surfaces may be diachronous (Posamentier and Allen, 1999). The rate of diachroneity of maximum flooding surfaces defined on stratal stacking patterns is, however, considered to be very low (Catuneanu et al., 1998).

5.4. Transgressive–regressive sequence

The T–R sequence (Embry and Johannessen, 1992) is bounded by composite surfaces that include subaerial unconformities and/or ravinement surfaces and their correlative maximum regressive surfaces. This model offers an alternative way of packaging the strata into sequences, by addressing the main pitfalls of the depositional sequence and the genetic stratigraphic sequence. The correlative conformity is replaced with the marine portion of the maximum regressive surface. The latter surface has the advantage of being recognizable in shallow marine settings on virtually any type of outcrop

Sequence model / Events	Depositional Sequence II	Depositional Sequence III	Depositional Sequence IV	Genetic Sequence	T-R Sequence
	HST	early HST	HST	HST	RST
end of transgression	TST	TST	TST	TST	TST
end of regression	late LST (wedge)	LST	LST	late LST (wedge)	RST
end of base level fall	early LST (fan)	late HST (fan)	FSST	early LST (fan)	
onset of base level fall	HST	early HST (wedge)	HST	HST	

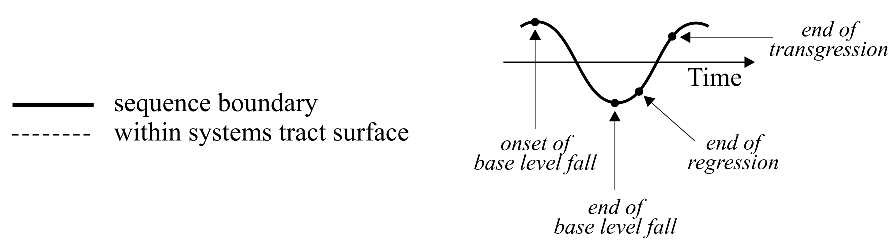

Fig. 29. Position of sequence boundaries, as well as the subdivision into systems tracts, for the sequence models currently in use.

or subsurface data, but it may pose the same problem of recognition in deep marine settings. For the nonmarine portion of the basin, the subaerial unconformity is used as the sequence boundary because this is the most important break in sedimentation, and therefore it should not be included within the sequence. The maximum flooding surfaces are used to subdivide the T–R sequence into transgressive and regressive systems tracts (Figs. 18 and 29).

The pitfall of the T–R sequence is that its nonmarine and marine portions of the sequence boundary (the subaerial unconformity and the maximum regressive surface respectively) are temporally offset with the duration of the lowstand normal regression (Fig. 18). The physical connection between these two surfaces is made by the ravinement surface, based on the assumption that the wave erosion in the upper shoreface during transgression removes the lowstand fluvial strata that accumulated in the vicinity of the shoreline. This may only happen where the thickness of the nearshore lowstand fluvial strata is <20 m, which is the maximum amount of scouring that can be attributed to the wave ravinement processes (Demarest and Kraft, 1987). The potential pitfall of the ravinement surface not removing all the lowstand nonmarine strata was discussed by Embry (1995).

5.5. Parasequences

The parasequence is defined as "a relatively conformable succession of genetically related beds or bedsets bounded by flooding surfaces" (Van Wagoner, 1995). Parasequences are commonly identified with the coarsening-upward prograding lobes in shallow marine, regressive settings. The problem with the concept of parasequence rests with its bounding surfaces, i.e. the flooding surfaces. As explained earlier in the paper, the flooding surface is a poorly defined term that allows for multiple meanings, such as ravinement surface, maximum regressive surface, maximum flooding surface, or within-trend facies contact (Fig. 23). Depending on what the flooding surface actually is, parasequences may be anything from T–R sequences (where only thin transgressive facies are present), to genetic stratigraphic sequences (where the transgressive facies are absent), or allostratigraphic units (where the flooding surface is a facies contact within a transgressive package). The usefulness of such equivocal terminology is thus questionable, especially since each of the parasequence types is already covered by clearly defined terms.

6. Time attributes of stratigraphic surfaces

6.1. Subaerial unconformity

The subaerial unconformity (Fig. 30) is generally perceived as a “time barrier” (Winter and Brink, 1991; Embry, 2001a) based on the assumption that time lines do not cross this surface, i.e. all the strata below the unconformity are older than the strata above it. Whether this is a general truth or an artifact of the lack of rigorous testing remains to be seen. The possibility of formation of diachronous unconformities which are crossed by time lines is emphasized in the literature, generally in relation to the migration of uplifted areas (e.g., Cohen, 1982; Johnson, 1991). Other mechanisms may contribute as well to the formation of time transgressive subaerial unconformities, such as the process of forced regression itself.

It is now well established that base level changes at the shoreline may only control fluvial processes within a limited distance upstream (Shanley and McCabe, 1994). This distance varies with the size of the river and the magnitude of base level changes, but generally ranges from tens of kilometers (e.g., 90 km in the case of the Colorado River in Texas) to more than 200 km in the case of larger rivers (e.g., 220 km for the Mississippi

Synonymous term: *regressive surface of fluvial erosion* (Plint and Nummedal, 2000).

Defining features:
- Nature of contact: scoured or top of paleosol;
- Strata below: variable (where marine, coarsening-upward);
- Strata above: nonmarine.

Timing: during base level fall, low diachroneity.

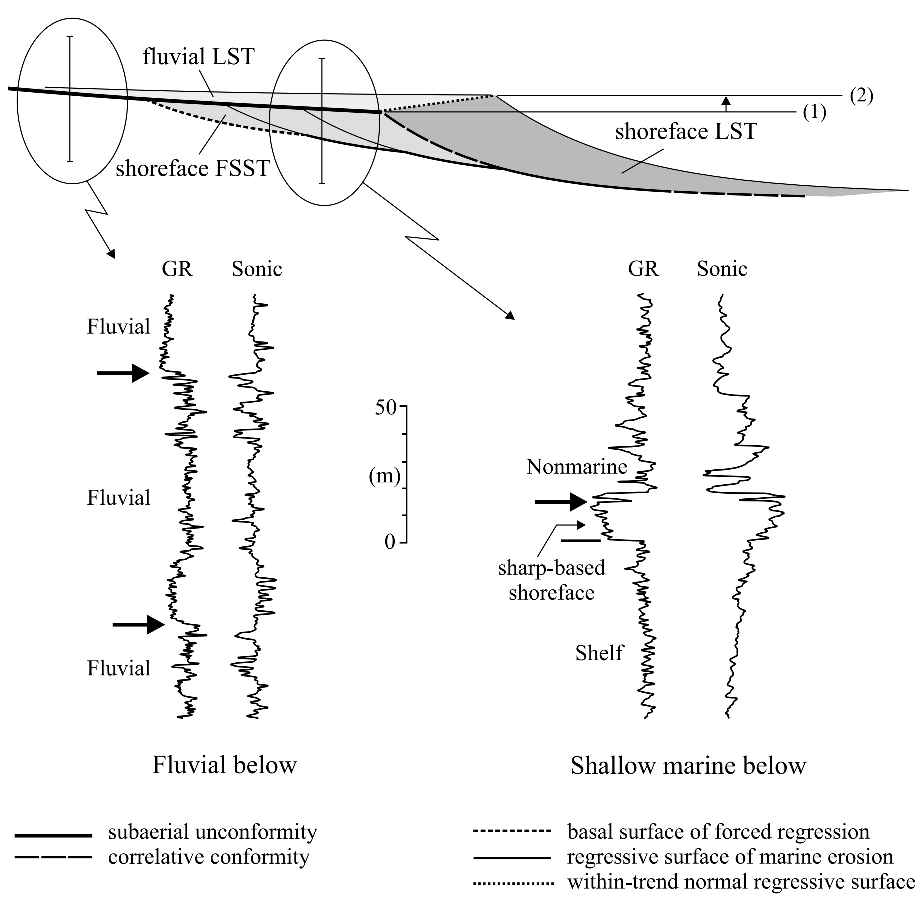

Fig. 30. Subaerial unconformity—features, timing, and log signatures. Horizontal arrows indicate the position of the subaerial unconformities on wireline logs. Log examples from the Scollard and Paskapoo Formations (left), and Cardium Formation (right), Western Canada Basin. Abbreviations: GR—gamma ray log; LST—lowstand systems tract; FSST—falling stage systems tract.

River; Shanley and McCabe, 1994). Beyond the landward limit of the base level control, the river responds primarily to a combination of climatic and tectonic mechanisms (Shanley and McCabe, 1994; Blum, 1994). In such inland areas, cycles of fluvial aggradation and degradation may be driven by changes in discharge and sediment load. These cycles may be completely out of phase with those driven purely by base level changes (Miall, 1996).

The formation of a subaerial unconformity in response to a base level fall at the shoreline is illustrated in Fig. 31. As the shoreline shifts towards the basin during forced regression, the landward limit of the area of influence of base level fall shifts accordingly, which may allow for fluvial aggradation above the older portion of the subaerial unconformity (Sylvia and Galloway, 2001; Fig. 32). In this way, the early fluvial strata that prograde the subaerial unconformity during the forced regression may be older than the late falling stage shoreface deposits that are truncated by the same subaerial unconformity (Fig. 32).

6.2. Correlative conformity

The correlative conformity (*sensu* Hunt and Tucker, 1992; Fig. 33) marks the top of the marine deposits accumulated during the forced regression of the shoreline, including the deep marine submarine fans. It is defined on stratal stacking patterns (Haq, 1991: "a change from rapidly prograding parasequences to aggradational parasequences"), with a timing that connects to the end of base level fall at the shoreline. The correlative conformity is usually taken as a time line (sea floor at the end of forced regression: Embry (1995)), although technically it is diachronous, younger basinward, with the rate of offshore sediment transport (Catuneanu et al., 1998). This diachroneity rate is very low, ranging from 10^{-1}–10^{0} m/s in shelf-type settings to 10^{1}–10^{2} m/s in ramp settings, which is below the resolution of the current dating techniques.

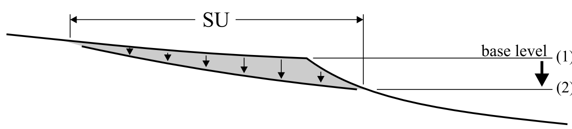

Fig. 31. Formation of a subaerial unconformity in response to the base level fall at the shoreline (modified from Shanley and McCabe (1994)). Note that the effect of base level fall fades away in a landward direction. The arrows indicate the amounts of differential fluvial incision, which decrease upstream. The position of the upstream limit of the area controlled by base level changes at the shoreline depends on the interplay between the magnitudes of base level changes, climatic shifts and source area tectonism, as well as on the size of the river.

It is important to note that the timing of the correlative conformity only depends on the base level changes *at the shoreline*, and it is independent of the base level changes that take place *within* the marine portion of the basin. A surface mapped at the temporal boundary between relative fall and subsequent relative rise in the marine part of the basin (type B correlative conformity in Fig. 34) is highly diachronous and independent of stratal stacking patterns (i.e., not a systems tract boundary). Relative to the slope fan systems, the correlative conformity is taken at the top of the coarsening-upward trend (Fig. 33), because the sand:mud ratio increases during the forced regression and decreases during the subsequent lowstand (early rise) as the sand starts to be trapped in aggrading fluvial and deltaic systems (H. Posamentier, pers. comm.).

6.3. Basal surface of forced regression

The basal surface of forced regression (correlative conformity of Posamentier et al. (1988); Fig. 35) marks the base of the marine deposits accumulated during the forced regression of the shoreline, including the slope and basin floor submarine fans. It is defined on stratal stacking patterns, with a timing that connects to the onset of base level fall at the shoreline. Similar to the correlative conformity, the basal surface of forced

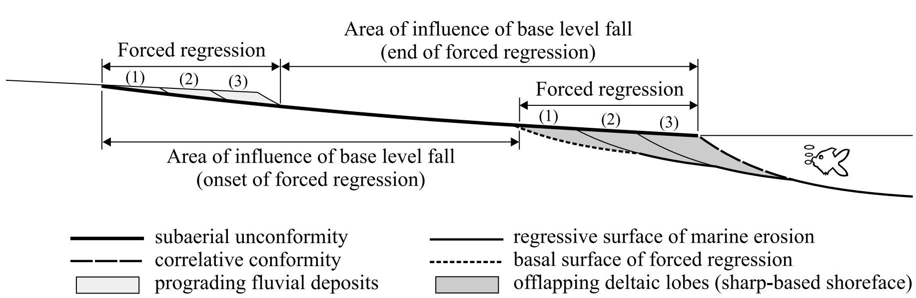

Fig. 32. Fluvial and shoreface forced regressive deposits in relation to the subaerial unconformity (modified from Sylvia and Galloway (2001)). The area of influence of base level fall is kept constant, but it shifts towards the basin with the rate of forced regression. The time sequence (1), (2), and (3) suggests timesteps in the process of forced regression. The early fluvial strata that prograde the subaerial unconformity during the forced regression are older than the late forced regressive shoreface deposits. The latter are topped by the subaerial unconformity, which extends basinward during the forced regression.

Defining features:
- Nature of contact: conformable;
- Strata below: marine, coarsening upward;
- Strata above: marine (where shallow marine, coarsening-upward).

Timing: end of forced regression (onset of base level rise at the shoreline), low diachroneity.

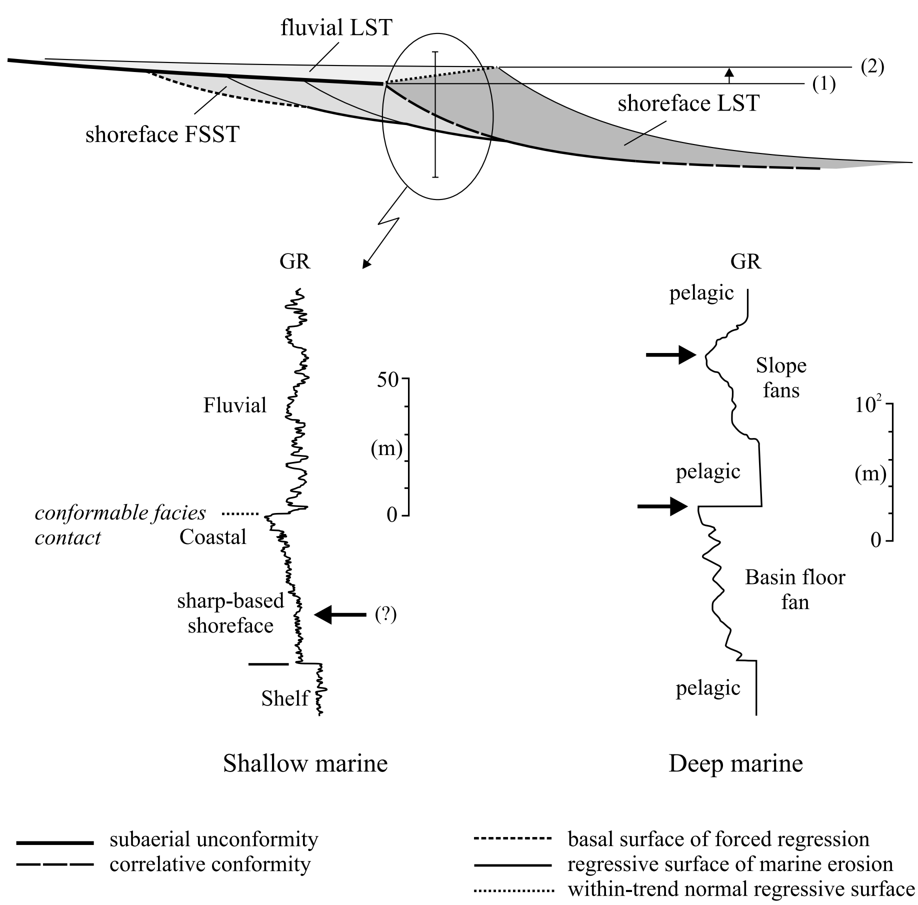

Fig. 33. Correlative conformity (*sensu* Hunt and Tucker, 1992)—features, timing, and log signatures. Horizontal arrows indicate the position of the correlative conformity on wireline logs. In a shoreface succession, the correlative conformity is the clinoform surface that correlates with the basinward termination of the subaerial unconformity, but this surface is difficult to pinpoint on individual 1D logs (see question mark). Log examples from the Lea Park Formation, Western Canada Basin (left), and modified from Vail and Wornardt (1990) and Kolla (1993) (right). Abbreviations: GR—gamma ray log; LST—lowstand systems tract; FSST—falling stage systems tract.

regression is often approximated with a time line (sea floor at the onset of forced regression), but in fact it is diachronous, younger basinward, with the rate of offshore sediment transport (Catuneanu et al., 1998).

As in the case of the correlative conformity, the timing of the basal surface of forced regression is controlled by the base level changes *at the shoreline*, and is independent of the basinward fluctuations in base level which are affected by the differential rates of vertical tectonics (Fig. 34). A surface mapped at the temporal boundary between relative rise and subsequent relative fall in the marine side of the basin (type B basal surface of forced regression in Fig. 34) is highly diachronous and independent of stratal stacking patterns (i.e., not a systems tract boundary).

6.4. Regressive surface of marine erosion

The regressive surface of marine erosion (Fig. 36) is a highly diachronous surface, with the rate of shoreline forced regression (Fig. 34). This surface may become a systems tract boundary where it reworks the basal surface of forced regression (Figs. 20 and 21). The regressive surface of marine erosion should not, however, be indiscriminately used as a systems tract boundary, because its basinward portion may be separated from the basal surface of forced regression (the true systems tract boundary) by falling stage shelf deposits (Fig. 21). In this case, the regressive surface of marine erosion develops *within* the falling stage systems tract.

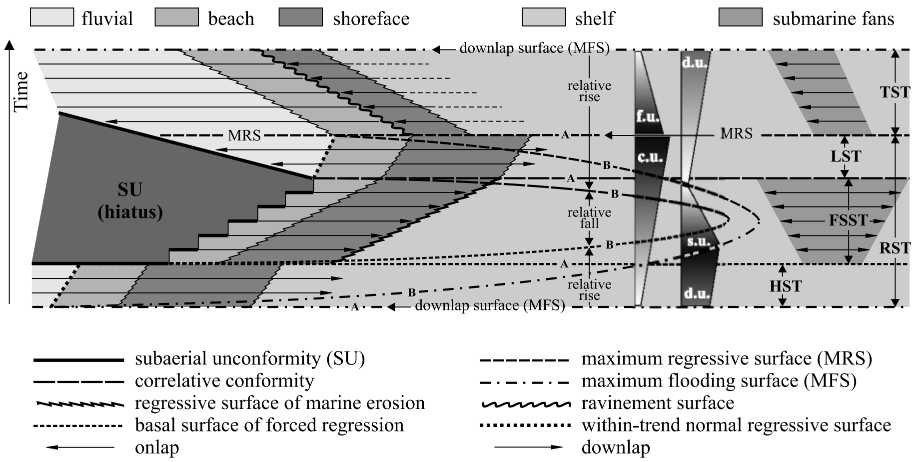

Fig. 34. Temporal significance of types A and B surfaces (modified from Catuneanu et al. (1998)). Type A surfaces are defined by stratal stacking patterns, and are systems tract boundaries. The timing of type A surfaces depends on base level changes, or on the interplay between base level changes and sedimentation, *at the shoreline*. The timing of type A surfaces is independent of the offshore variations in subsidence and sedimentation rates. The timing of type B surfaces depends on the *offshore variations* in subsidence and sedimentation rates, which confers those surfaces high diachroneity rates (a quarter of the period of the highest frequency variable: Catuneanu et al. (1998)). Types A and B surfaces join at the shoreline, but diverge in an offshore direction. Abbreviations: HST—highstand systems tract; FSST—falling stage systems tract; LST—lowstand systems tract; TST—transgressive systems tract; RST—regressive systems tract; c.u.—coarsening-upward; f.u.—fining-upward; d.u.—deepening-upward; s.u.—shallowing-upward. Note that grading and water depth changes are not interchangeable concepts.

6.5. Maximum regressive surface

The maximum regressive surface (Fig. 37) is often interchangeably defined on either *observed stratal stacking patterns* (the limit between progradational and overlying retrogradational strata) or *inferred bathymetric changes* (the surface that forms when the water depth reaches the shallowest peak) (Embry, 1993). These definitions are not equivalent, as demonstrated by the modeling of a typical shelf setting (Catuneanu et al., 1998).

Maximum regressive surfaces defined on stratal stacking patterns (type A in Fig. 34) are mapped at the top of coarsening-upward (progradational) marine successions. The coarsening-upward trend is controlled by the *shoreline shift*, i.e. the seaward migration of the sediment entry points, and is independent of the offshore variations in water depth. Regression is associated with water shallowing in the vicinity of the shoreline, as more accommodation is consumed than it is created in the shoreline area, but coeval water deepening may occur offshore (Fig. 38). Maximum regressive surfaces defined on stratal stacking patterns are systems tract or sequence boundaries. Their timing depends on the interplay between the rates of sedimentation and base level rise *at the shoreline*, and it is not affected by the offshore variations in the sedimentation and subsidence rates (Catuneanu et al., 1998). These surfaces are close to time lines in a depositional-dip section, as there is only one point in time when the shoreline changes from regressive to transgressive. A low diachroneity rate may, however, be recorded in relation to the rates of sediment transport. A similar low diachroneity characterizes the nonmarine portion of the maximum regressive surface, as the formation of the estuary and the associated changes in fluvial styles are also controlled by shoreline shifts.

Maximum regressive surfaces defined on bathymetric changes (type B in Fig. 34) are much more diachronous, with a timing that depends on the offshore variations in the sedimentation and subsidence rates. As indicated by modeling, surfaces marking the shallowest peak form *within* regressive successions, crossing the systems tract boundaries (Fig. 34). Consequently, the marine strata overlying a type B maximum regressive surface (peak of shallowest water) are commonly coarser than the underlying strata, although the former accumulate in a deepening water (Galloway, 1989; Fig. 34).

6.6. Maximum flooding surface

Maximum flooding surfaces (Fig. 39) are also often interchangeably defined on the basis of either *stratal stacking patterns* (top of retrogradational strata) or *bathymetric changes* (peak of deepest water). These two approaches allow for different temporal attributes, i.e. they define different surfaces that are temporally offset (Fig. 34).

Maximum flooding surfaces defined on stratal stacking patterns (type A in Fig. 34) are systems tract or sequence boundaries. Their timing depends on the interplay between the rates of sedimentation and base level rise *at the shoreline*, and is not affected by the variations in the sedimentation and subsidence rates away from the shoreline (Catuneanu et al., 1998). These

Defining features:
- Nature of contact: conformable or scoured;
- Strata below: marine, variable (where shallow marine, coarsening-upward);
- Strata above: marine, coarsening-upward.

Timing: onset of forced regression (onset of base level fall at the shoreline), low diachroneity.

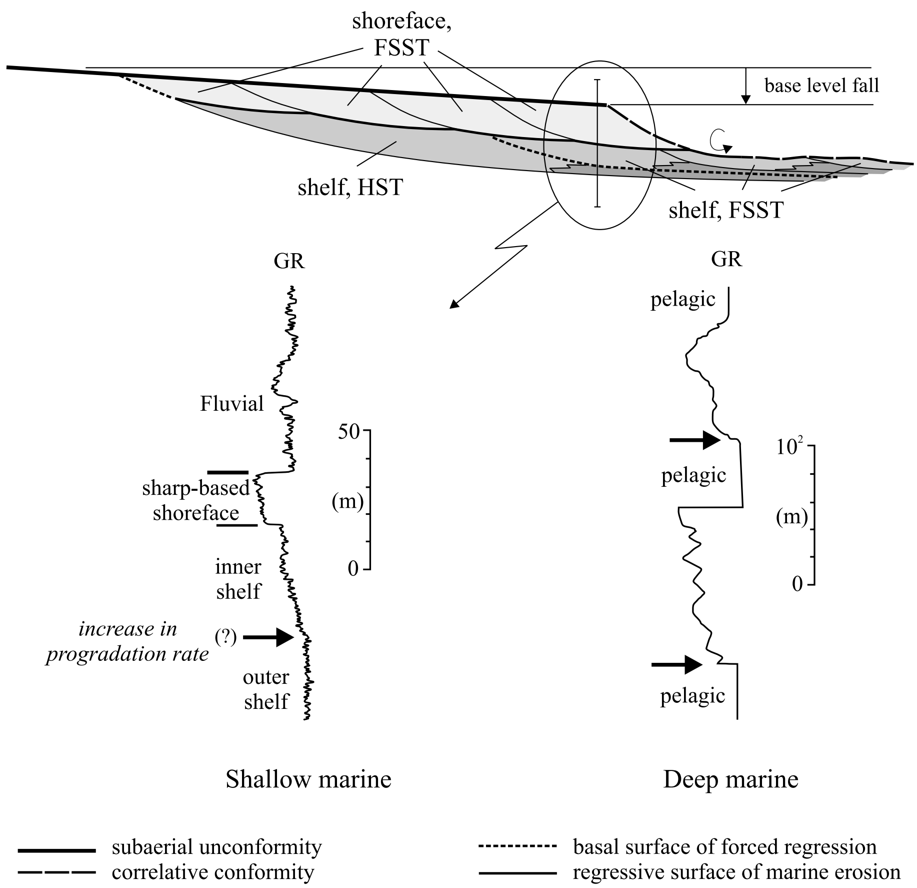

Fig. 35. Basal surface of forced regression (correlative conformity of Posamentier et al. (1988))—features, timing, and log signatures. Horizontal arrows indicate the position of the basal surface of forced regression on wireline logs. In shallow marine successions (shoreface and shelf), the conformable portions of the basal surface of forced regression are difficult to recognize on individual 1D logs (see question mark). The increase in the progradation rate across this surface may however provide a hint on its position. Log examples from the Lea Park Formation, Western Canada Basin (left), and modified from Vail and Wornardt (1990) and Kolla (1993) (right). Abbreviations: GR—gamma ray log; HST—highstand systems tract; FSST—falling stage systems tract.

surfaces are close to time lines in a depositional-dip section, as there is only one point in time when the shoreline changes from transgressive to regressive. A low diachroneity rate may however be recorded in relation to the rates of sediment transport.

Maximum flooding surfaces defined on bathymetric changes (type B in Fig. 34) are much more diachronous, with a timing that depends on the offshore variations in the sedimentation and subsidence rates. These surfaces, which mark the peak of deepest water, form *within* regressive (coarsening-upward) successions, and may cross the systems tract boundaries (Fig. 34). As noted by Naish and Kamp (1997), and also by Tim Naish (pers. comm.), the surface indicating the maximum water depth (type B maximum flooding surface, identified on the basis of fossil assemblages) often occurs *within* the highstand systems tract. This surface is lithologically undeterminable, and can only be identified using foram or trace fossil paleobathymetry.

6.7. Ravinement surface

The ravinement surface (Fig. 40) is a highly diachronous surface, with the rate of shoreline transgression (Fig. 34). This surface may become a systems tract boundary where it reworks the nonmarine portion of

Synonymous term: *regressive ravinement surface* (Galloway, 2001).

Defining features:
- Nature of contact: scoured (waves in the lower shoreface);
- Strata below: shelf, coarsening-upward;
- Strata above: shoreface, coarsening-upward.

Timing: during forced regression (base level fall in the shoreline area), high diachroneity.

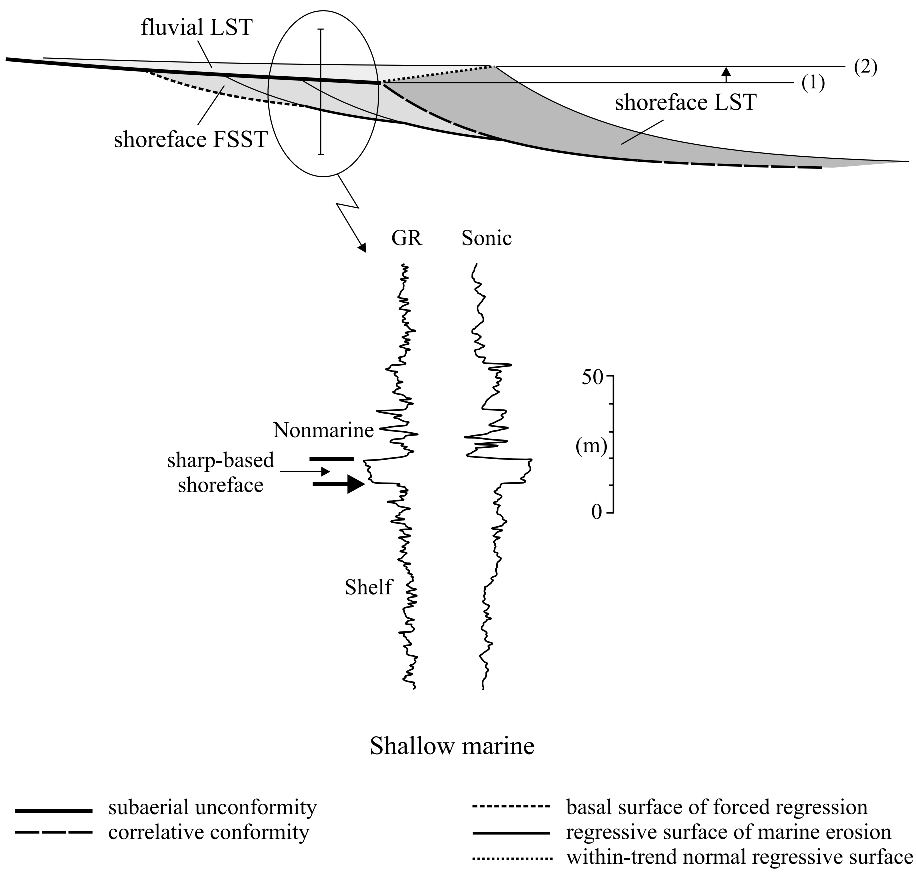

Fig. 36. Regressive surface of marine erosion—features, timing, and log signatures. Horizontal arrow indicates the position of the regressive surface of marine erosion on the wireline log. Log example from Plint (1988) (Cardium Formation, Western Canada Basin). Abbreviations: GR—gamma ray log; LST—lowstand systems tract; FSST—falling stage systems tract.

the maximum regressive surface, or even a sequence boundary where it reworks the subaerial unconformity (Embry, 1995; Helland-Hansen and Martinsen, 1996). Where estuarine facies are preserved, the ravinement surface can be traced *within* the transgressive systems tract, at the limit between estuarine facies and the overlying shoreface deposits (Fig. 26).

6.8. Within-trend normal regressive surface

The within-trend normal regressive surface (Fig. 41) is highly diachronous, with the rate of normal regression (Fig. 34). Given its conformable nature, this facies contact does not rework the underlying deposits or systems tract boundaries. It develops *within* lowstand or highstand systems tracts.

6.9. Within-trend flooding surface

The within-trend flooding surfaces (Fig. 42) are highly diachronous, with the rate of shoreline transgression. They represent facies contacts between shoreface sands and overlying shelf shales, and develop *within* transgressive systems tracts.

7. Hierarchy of sequences and bounding surfaces

A sequence hierarchy involves the separation of different orders of stratigraphic sequences and surfaces

Synonymous terms: *transgressive surface* (Posamentier and Vail, 1988), *conformable transgressive surface* (Embry, 1995).

Defining features:
- Nature of contact: conformable or scoured;
- Strata below: variable (where marine, coarsening-upward);
- Strata above: variable (where marine, fining-upward).

Timing: end of shoreline regression, low diachroneity.

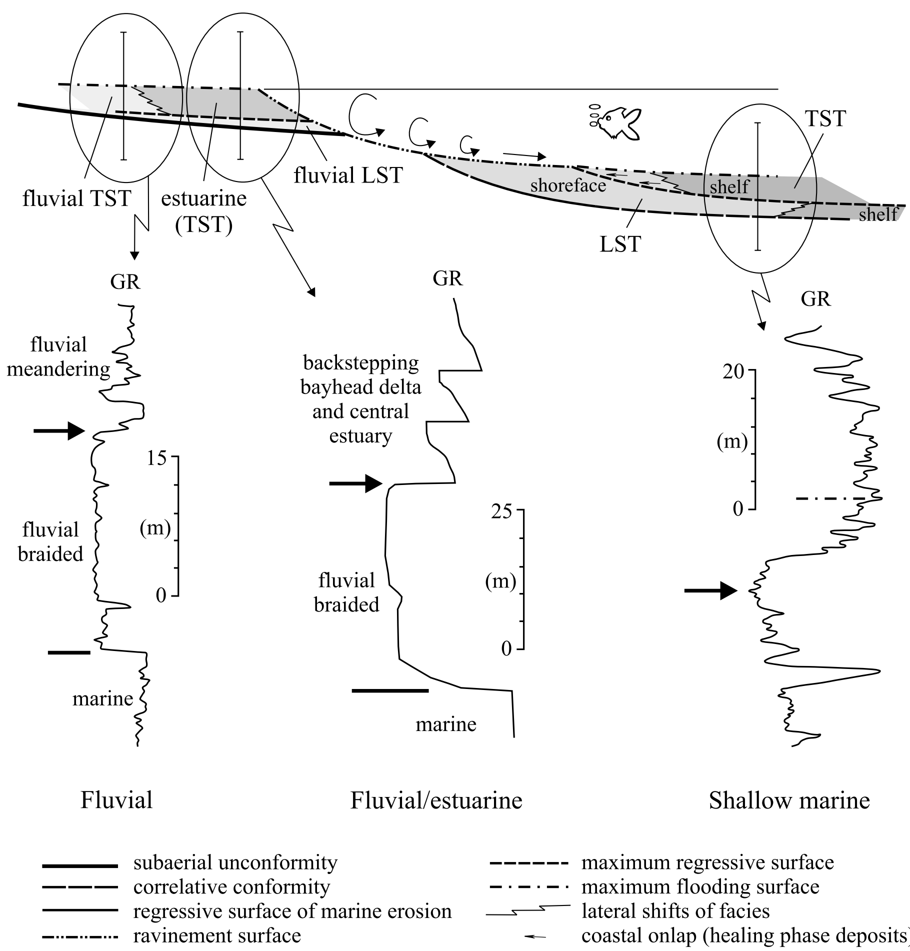

Fig. 37. Maximum regressive surface—features, timing, and log signatures. Horizontal arrows indicate the position of the maximum regressive surfaces on wireline logs. Log examples from Kerr et al. (1999) (left and centre) and Embry and Catuneanu (2001) (right). Abbreviations: GR—gamma ray; LST—lowstand systems tract; TST—transgressive systems tract.

based on their relative importance. Within a hierarchical system, the most important sequence is recognized as of "first-order" and may be subdivided into two or more "second-order" sequences. In turn, a second-order sequence may be subdivided into two or more "third-order" sequences, and so on (Fig. 43). The more important sequences are designated as "high-order", and usually occur with a low frequency in the stratigraphic record. The less important sequences are of lower-order, and occur more frequently in the rock record (Fig. 44). The critical element in developing a system of sequence hierarchy is the *criterion* that should be used to differentiate the relative importance of sequences and bounding surfaces. Two different approaches are currently in use: (i) a system based on boundary frequency (sequence duration), and (ii) a system based on the magnitude of base level changes which resulted in boundary formation.

The system based on boundary frequency (Vail et al., 1977; Mitchum and Van Wagoner, 1991; Vail et al., 1991) considers eustasy as the main drive behind the boundary generation at any order of cyclicity. Each order of cyclicity is assigned a certain dominant mechanism that controls eustatic changes over well defined time scales (see discussion in Miall (1997)). A pitfall of this hierarchy system based on cycle duration is that the

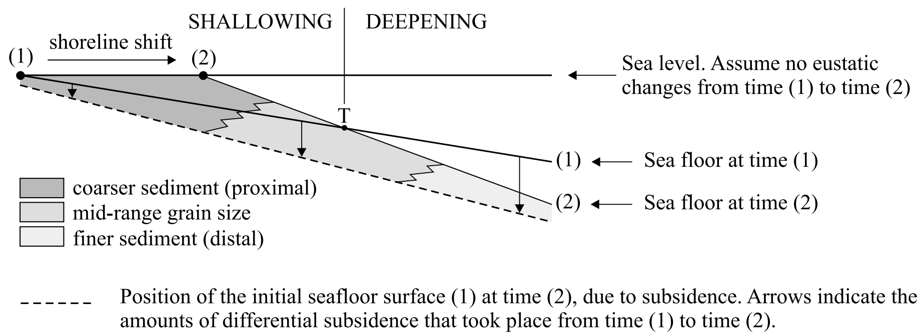

Fig. 38. Progradation of a coarsening-upward succession onto a sea floor that is subject to varying bathymetric conditions. The threshold T separates areas of water shallowing and deepening. This threshold is placed where sedimentation and subsidence are in a perfect balance. Landwards from T, sedimentation outpaces subsidence. Seawards from T, accommodation is created more rapidly that it is consumed by sedimentation. The succession that accumulates in the deepening water is still coarsening-upward, as the sediment entry points shift towards the sea (regression). This is the case of the Mahakam delta in Indonesia.

span of time of similar tectonic processes-driven cycles changed through time, from the Precambrian to the Phanerozoic, in response to changes in the dynamics of plate tectonic processes (Catuneanu and Eriksson, 1999). Other practical pitfalls of the hierarchy system based on boundary frequency relate to the potential for subjectivity in picking surfaces of different orders in outcrop or subsurface sections, as pointed out by Embry (1995).

The system based on the magnitude of base level changes uses physical attributes to establish a boundary hierarchy, irrespective of the time span between bounding surfaces (Embry, 1995). Six attributes have been chosen to establish the boundary classification: the areal extent over which the sequence boundary can be recognized; the areal extent of the unconformable portion of the boundary; the degree of deformation that strata underlying the unconformable portion of the boundary underwent during the boundary generation; the magnitude of the deepening of the sea and the flooding of the basin margin as represented by the nature and extent of the transgressive strata overlying the boundary; the degree of change of the sedimentary regime across the boundary; and the degree of change of the tectonic setting of the basin and surrounding areas across the boundary. Five different orders of sequence boundaries have been defined on the basis of these characteristics (Embry, 1995). Two potential pitfalls with this classification scheme have been discussed by Miall (1997, p. 330–331). One is that it implies tectonic control in sequence generation. Sequences generated by glacio-eustasy, such as the Upper Paleozoic cyclothems and those of Late Cenozoic age on modern continental margins would be first-order sequences in this classification on the basis of their areal distribution, but lower-order on the basis of the nature of their bounding surfaces. The second problem is that this classification requires good preservation of the basin margin in order to properly assess the areal extent of the unconformable portion of the boundary, or the degree of deformation across the boundary.

As both hierarchy systems that are currently in use present conceptual and/or practical problems, the practitioner of sequence stratigraphy still faces the dilemma of how to deal with the variety of sequences which are more or less important relative to each other. No universally applicable hierarchy system, that could work for the entire variety of case studies, has been devised yet. The easiest solution to this problem is to deal with the issue of hierarchy on a case by case basis, assigning hierarchical orders to sequences and bounding surfaces based on their relative importance within each individual basin. This method may prove to be more realistic given the fact that each basin is unique in terms of formation, evolution, and history of base level changes.

8. Discussion and conclusions

8.1. Sequence stratigraphy: theory versus reality

Sequence stratigraphic models idealize reality in the sense that they provide simplified, theoretical two- or three-dimensional representations of how the architecture of facies and stratigraphic surfaces is expected to be in the field. The central assumption of all models is that the predictable stacking pattern of systems tracts and stratigraphic surfaces is mainly controlled by the interplay of base level changes and sedimentation *at the shoreline*. This interplay controls the direction of shoreline shifts, as well as the timing of all systems tract and sequence boundaries. Under this assumption, the subaerial unconformity is the time equivalent of the falling stage systems tract, the maximum flooding surface has a predictable position above the subaerial unconformity, and so on (Figs. 18, 24–26). Although these expected relationships are valid in most of the cases, Synonymous term: *maximum transgressive surface* (Helland-Hansen and Martinsen, 1996).

Defining features:
- Nature of contact: conformable or scoured;
- Strata below: variable (where marine, fining-upward);
- Strata above: variable (where marine, coarsening-upward).

Timing: end of shoreline transgression, low diachroneity.

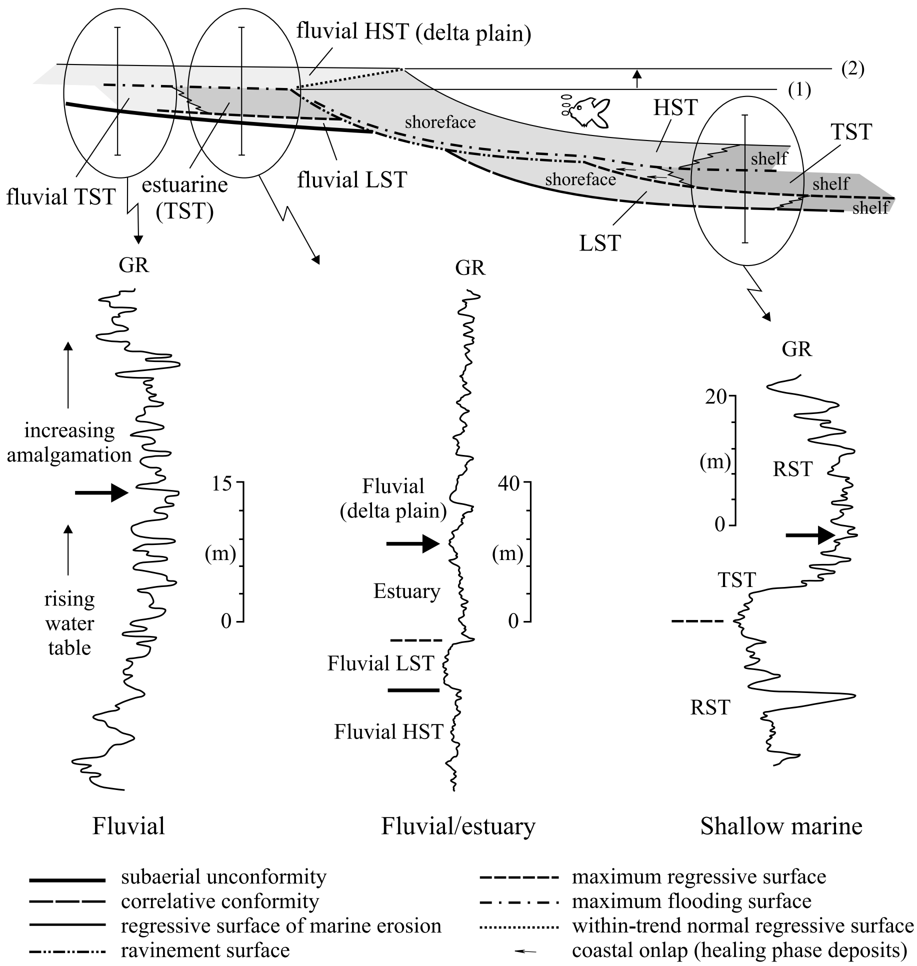

Fig. 39. Maximum flooding surface—features, timing, and log signatures. Horizontal arrows indicate the position of maximum flooding surfaces on wireline logs. Log examples from the Wapiti Formation, Western Canada Basin (left and center), and Embry and Catuneanu (2001) (right). Abbreviations: GR—gamma ray; LST—lowstand systems tract; TST—transgressive systems tract; HST—highstand systems tract; RST—regressive systems tract.

especially in coastal regions, possible deviations from the model predictions should be carefully evaluated. For example, the influence of base level changes at the shoreline on fluvial processes only extends for a limited distance upstream (Fig. 31). The extent of the base level control depends on the balance between the magnitudes of base level changes, climatic influences, and source area tectonism. There are instances when the role of climate is so dominant that processes of fluvial aggradation and incision are mainly controlled by changes in the balance between river discharge and sediment load, with a timing that is offset relative to the base level fluctuations at the shoreline (Blum, 1994). The resulting subaerial unconformity will therefore not fit the position predicted by standard sequence models. There are also cases where a subaerial unconformity forms during transgression, in relation to processes of coastal erosion (Leckie, 1994; Fig. 27).

One other common problem in the real world is the possible lack of preservation of systems tracts, or of portions of systems tracts. In this case, stratigraphic surfaces that are normally expected to be separated by strata may be superimposed. Examples include a ravinement surface that reworks the subaerial unconformity, a regressive surface of marine erosion that reworks the basal surface of forced regression, a maximum

Synonymous terms: *transgressive ravinement surface* (Galloway, 2001), *wave-ravinement surface* (Swift, 1975), *shoreface ravinement* (Embry, 1995), *transgressive surface of erosion* (Posamentier and Vail, 1988).

Defining features:
- Nature of contact: scoured (waves in the upper shoreface);
- Strata below: variable (where marine, coarsening-upward);
- Strata above: marine, fining-upward.

Timing: during the shoreline transgression, high diachroneity.

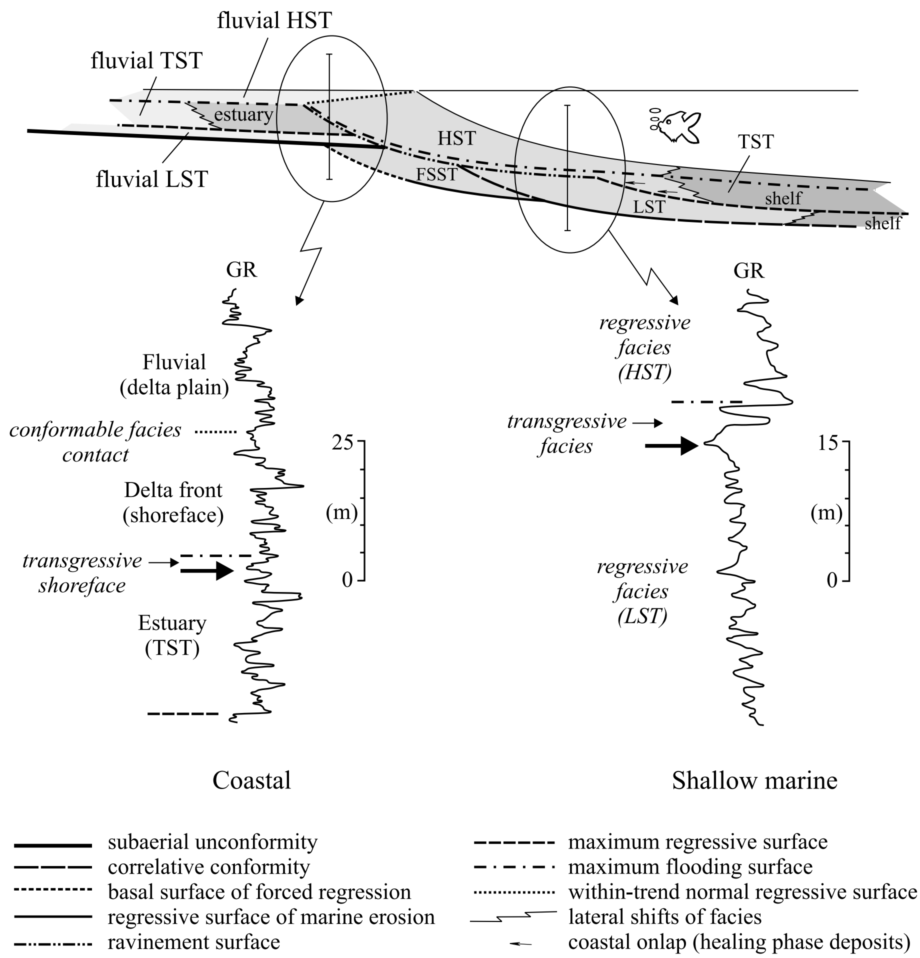

Fig. 40. Ravinement surface—features, timing, and log signatures. Horizontal arrows indicate the position of the ravinement surfaces on wireline logs. Log examples from the Bearpaw Formation (left) and Embry and Catuneanu (2001) (right). Abbreviations: GR—gamma ray; LST—lowstand systems tract; TST—transgressive systems tract; FSST—falling stage systems tract; HST—highstand systems tract.

flooding surface that reworks the maximum regressive surface, or a subaerial unconformity that reworks the underlying maximum flooding surface. In these situations, the observed surface should be labeled using the name of the younger surface, as the latter overprints the attributes of the original contact.

8.2. Sequence models: the importance of the tectonic setting

The diversity of sequence models that are currently in use (Fig. 28) may in part be attributed to the fact that their proponents draw their own research experience from different types of basins. Hence, each model is designed to fit the field observations from a particular tectonic setting. For example, the models of Posamentier et al. (1988) and Galloway (1989) describe a divergent continental margin, Van Wagoner and Bertram (1995) as well as Plint and Nummedal (2000) refer to foreland basin deposits, whereas Embry (1995) proposed a T–R sequence model based on the study of the Sverdrup rift basin. Each of these tectonic settings is unique in terms of morphology, subsidence history, and topographic gradients, and as a result differences in stratal architecture

Defining features:
- Nature of contact: conformable allostratigraphic facies contact;
- Strata below: beach (open shoreline) or delta front (river mouth);
- Strata above: fluvial (open shoreline) or delta plain (river mouth).

Timing: during the shoreline normal regression, high diachroneity.

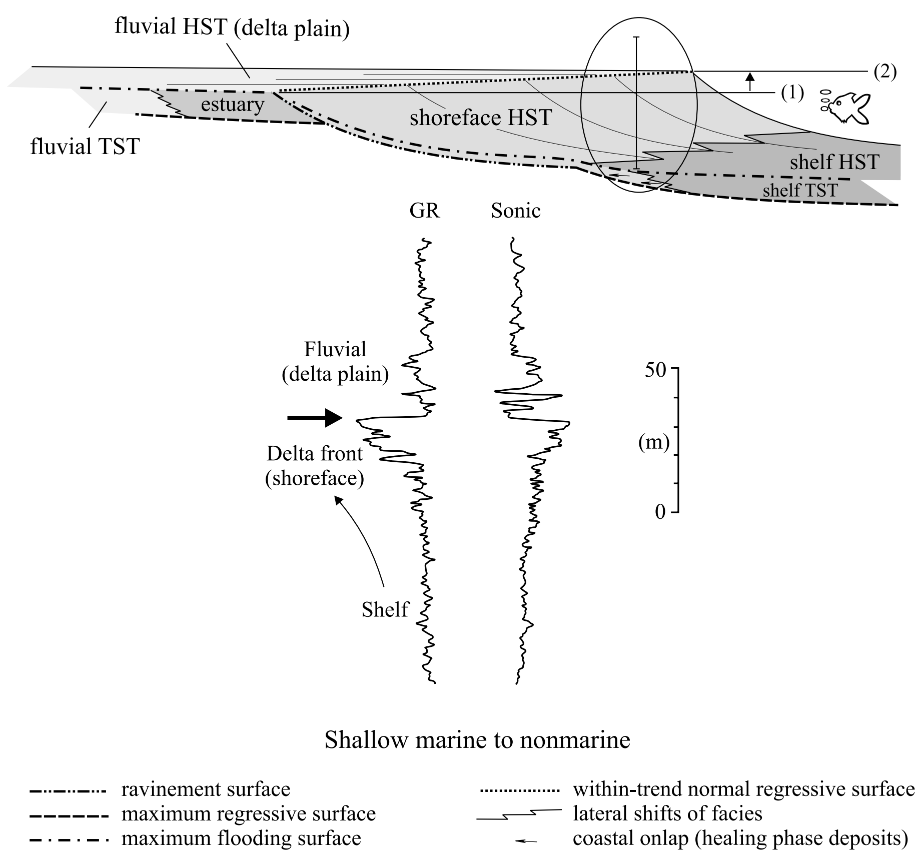

Fig. 41. Within-trend normal regressive surface—features, timing, and log signatures. Horizontal arrow indicates the position of the within-trend normal regressive surface on wireline logs. Log example from the Cardium Formation, Western Canada Basin. Abbreviations: GR—gamma ray; TST—transgressive systems tract; HST—highstand systems tract.

and the development and preservation of particular depositional systems are expected as well.

A summary of the topographic controls on sequence architecture is presented in Fig. 45. Notably, shelf-type settings (flat topography at the shoreline) have a much better potential of accumulating fluvial lowstand deposits over much of the extent of the subaerial unconformity, and also a much better potential of forming and preserving estuarine facies. In contrast, ramp settings (steep topography at the shoreline) are unlikely to preserve either fluvial lowstand or estuarine deposits. Topography is not, of course, the only control on the accumulation and preservation of lowstand fluvial and transgressive estuarine deposits, as favorable accommodation conditions must be met as well. A common theme emerges, however, which is that the accumulation and preservation of lowstand fluvial and transgressive estuarine deposits are favored by similar sets of conditions, which means that the presence of estuarine facies in the rock record is likely to indicate the presence of underlying fluvial lowstand deposits as well. The lack of estuarine and underlying fluvial lowstand deposits in ramp settings may explain why the T–R sequence model works so well in rift and other ramp-type basins, where the ravinement surface commonly reworks the subaerial unconformity. This may not necessarily be the case in shelf-type settings such as filled foredeeps, where thick fluvial lowstand and estuarine deposits are often preserved.

8.3. Concluding remarks

All sequence models have merits and limitations, and work best in the tectonic setting for which there were

Defining features:
- Nature of contact: conformable or scoured allostratigraphic facies contact;
- Strata below: transgressive marine sands;
- Strata above: transgressive marine shales.

Timing: during the shoreline transgression, high diachroneity.

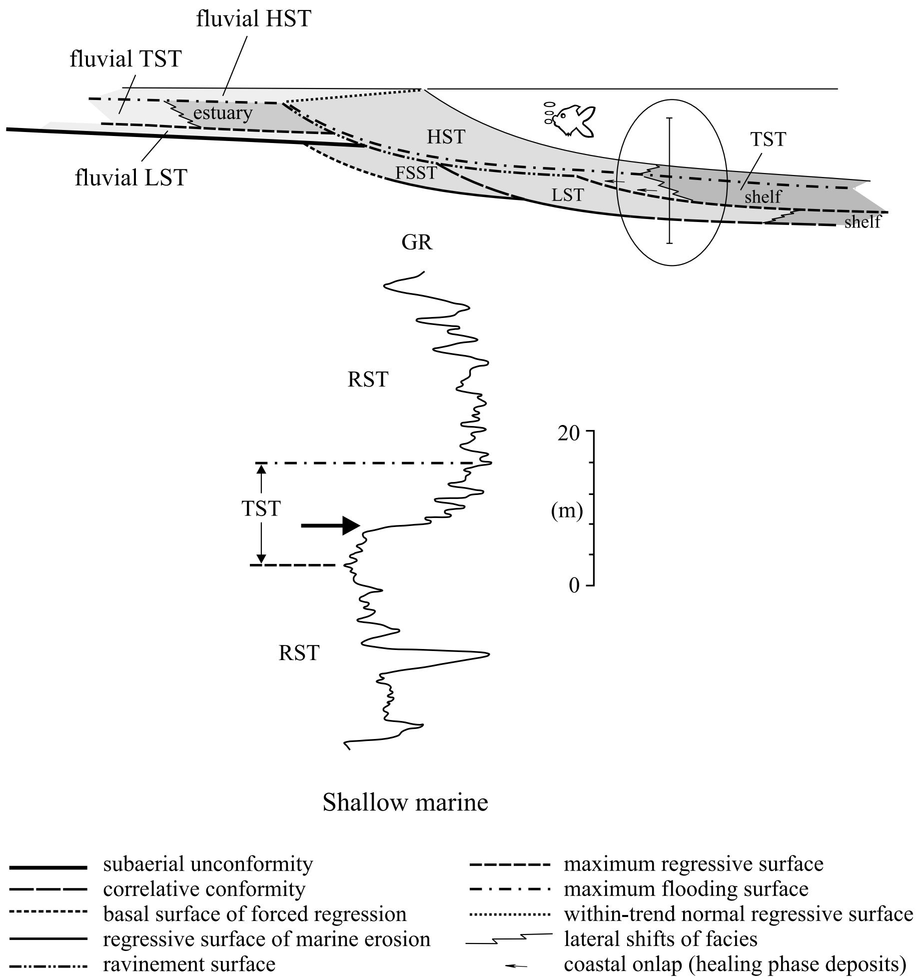

Fig. 42. Within-trend flooding surface—features, timing, and log signatures. Horizontal arrow indicates the position of the within-trend flooding surface on a gamma ray log. Log example from Embry and Catuneanu (2001). Abbreviations: GR—gamma ray; LST—lowstand systems tract; TST—transgressive systems tract; HST—highstand systems tract; FSST—falling stage systems tract; RST—regressive systems tract.

designed. Careful analysis and a thorough understanding of all controls on sedimentation are thus required when doing sequence stratigraphic interpretations, as opposed to a dogmatic application of rigid theoretical models. Trying to force specific case studies into the framework predicted by one particular model may be more damaging and misleading than no sequence stratigraphic interpretation at all. There are instances where the stratigraphic cyclicity is controlled by changes in the balance between sedimentation and subsidence rates, during a prolonged stage of base level rise (e.g., Catuneanu et al., 1999). In this case the depositional sequence model does not work, since no subaerial unconformities form, but the sequence stratigraphic framework of regressive and transgressive systems tracts may be resolved by using the genetic stratigraphic or the T–R sequence model. In contrast, the stratigraphic architecture of overfilled foredeeps is defined by stacked fluvial depositional sequences bounded by subaerial unconformities. In this case, the depositional sequence model is the best choice, since no coeval shoreline existed to interfere with the fluvial processes (e.g., Catuneanu and Elango, 2001). Flexibility is thus recommended when choosing the sequence model that is most appropriate for a specific case study.

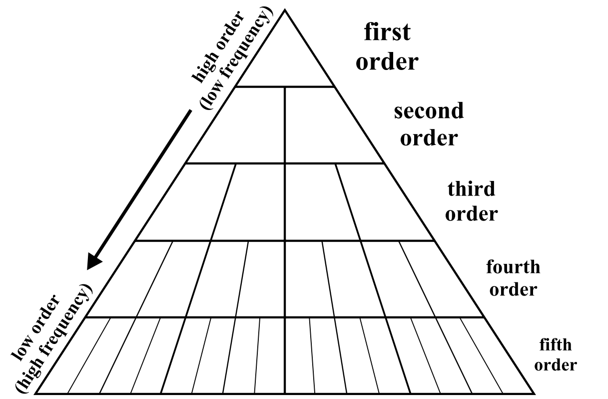

Fig. 43. Diagrammatic representation of the concept of hierarchy. This pyramid approach assumes that the events leading to the formation of the most important sequences and bounding surfaces (first-order) occurred less often through the geological time relative to the events leading to the formation of lower order sequence boundaries.

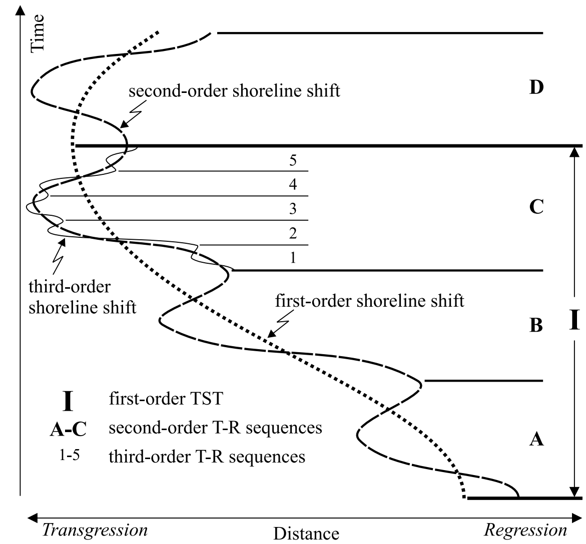

Fig. 44. Superimposed patterns of shoreline shifts at different orders of cyclicity. The lowest order of cyclicity reflects the true shift of the shoreline. The higher orders of cyclicity reflect overall trends, at increasingly larger scales.

<table>
<tr><th>Basin types / Shoreline shifts</th><th>Shelf-type settings
(continental shelves, filled foreland basins, intracratonic basins)</th><th>Ramp settings
(continental slopes, underfilled forelands, rift and strike-slip basins)</th></tr>
<tr><td>Transgressions</td><td>Estuaries are likely to form. The preservation of estuarine facies is a function of the rates of base level rise and wind/wave energy.</td><td>Estuaries are unlikely to form, due to the steep topography, higher fluvial energy, wave erosion, and slope instability (Fig. 27).</td></tr>
<tr><td rowspan="2">Normal regressions</td><td colspan="2">Deltas have diagnostic topsets, as a result of aggradation in the delta plains.</td></tr>
<tr><td>Fluvial aggradation extends over a relatively large distance upstream (little or no onlap onto the subaerial unconformity at lowstand; Fig. 25).</td><td>Fluvial aggradation is restricted to a relatively small area adjacent to the shoreline (pronounced onlap). Fluvial strata have low preservation potential.</td></tr>
<tr><td rowspan="2">Forced regressions</td><td colspan="2">Deltas have diagnostic offlapping geometries (delta plain erosion or bypass).</td></tr>
<tr><td>The regressive surface of marine erosion forms in the lower shoreface.</td><td>No erosion in the lower shoreface, as the sea floor is steeper then the equilibrium shoreface profile.</td></tr>
</table>

Fig. 45. Summary of distinctive features between shelf-type and ramp settings, during transgressions, normal regressions, and forced regressions. Much of these differences are due to the contrast in syn-depositional topographic gradients, irrespective of the subsidence patterns (e.g., opposite from extensional to foreland basins) and the resulting large-scale sequence geometry.

Acknowledgements

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