Toward the Formalization of Sequence Stratigraphy

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Abstract

Sequence stratigraphy is a modern and hugely popular approach of integrated stratigraphic analysis, and yet it is the only type of stratigraphy that is not standardized in international stratigraphic codes. This paradox is explained by the existence of several competing models, and by the dissemination of confusing or even conflicting terminology. The key to the formal inclusion of sequence stratigraphy within the array of stratigraphic disciplines is the recognition of what are core aspects versus those of lesser significance, and an appreciation that the approach to standardization has to be entirely unbiased. With at least five different sequence stratigraphic models currently in use, the main task is to find what they have in common, and formalize those core aspects that everybody can accept, recognizing what is trivial and may be left to the discretion of the practicing geologist.

It is well-established that all sequence stratigraphic models have merits and pitfalls, and that success in their application may vary with the case study; otherwise, a single universal model would have emerged by now. The approach to standardization proposed here is to promote those concepts that can be accepted by all, and thus retain flexibility in the application of the sequence stratigraphic method. This approach is in line with the way allostratigraphy is standardized in the North American Stratigraphic Code and in the International Stratigraphic Guide. After including the discontinuity/unconformity-bounded units of allostratigraphy in the Code and Guide, formalizing the concept of ‘sequence’ as a unit bounded by unconformities *or their correlative conformities* is the next logical step, long overdue. Once the ‘sequence’ is formalized as a generic concept, one can take a step further and list the various types of sequences, by defining what surfaces are selected as sequence boundaries in each case. Because no one model may provide the optimum approach for all circumstances, trying to define what specific surfaces of sequence stratigraphy should receive the formal status of ‘sequence boundary’ is not practical, and will never provide an acceptable solution for all groups. Furthermore, depending on location within the basin, each sequence stratigraphic surface may be ‘practical’ (i.e., easy to map) in some depositional systems and ‘impractical’ (i.e., difficult to map) in others. Similarly, the mappability of various sequence stratigraphic surfaces also depends on the type of data (e.g., outcrop vs. well-log vs. seismic) available for analysis. This paper strives to identify the common ground between the various sequence stratigraphic ‘schools’, and assesses what is reasonable to standardize at this point in international stratigraphic codes or guides.

Introduction: background and rationale

Sequence stratigraphy is the most recent addition to the range of stratigraphic disciplines, and it is considered by many as the latest revolution in the broad field of sedimentary geology (Miall, 1995). Fundamentally, sequence stratigraphy deals with the sedimentary response to changes in base level, and the depositional trends that emerge from the interplay of sedimentation and accommodation (space available for sediments to fill). Sequence stratigraphy has revolutionized the thinking and the method of stratigraphic analysis, and, in contrast to most other types of stratigraphy, it places a strong emphasis on processes of facies formation and preservation, and on the nature and timing of the contacts that separate various stratigraphic units.

The applications of sequence stratigraphy are tremendous, from deciphering the Earth's geological record of local to global changes, to improving the success of petroleum exploration and production. Multiple data sets are integrated for this purpose, and insights from several disciplines are required (Fig. 1). The predictive aspect of sequence stratigraphy is the key to its appeal and success, as models of facies relationships and development can be constructed from local to regional scales. The predictable association of depositional systems into sequences and component systems tracts is made possible by the fact that processes in all depositional environments respond to a common control: base level. In turn, changes in base level depend on the interplay of allogenic controls such as eustasy, tectonism and climate. Base level is therefore the link that 'synchronizes' depositional processes in all environments across a sedimentary basin, bringing coherence to the sequence stratigraphic model. This in turn means that sequence stratigraphy is an effective tool for correlation on a regional basis.

The complex interplay of allogenic controls, and the variability added to the sequence stratigraphic model by the contribution of independent factors such as autogenic processes, rock types in the source areas, sediment supply and basin physiography, have been discussed in a number of syntheses including Payton (1977), Wilgus et al. (1988), Emery and Myers (1996), Galloway and Hobday (1996), Miall (1997), Gradstein et al. (1998), Shanley and McCabe (1998), Posamentier and Allen (1999), Coe (2003), Schlager (2005) and Catuneanu (2006).

While there is no doubt that sequence stratigraphy is now heavily utilized as a modern approach of integrated stratigraphic analysis, which combines insights from all other types of stratigraphy and several non-stratigraphic disciplines, such as process sedimentology, geomorphology, geophysics and basin analysis, it is a paradox that it still remains the only stratigraphic method that is not formalized yet in any international stratigraphic code. Efforts have been made by both the North American Commission on Stratigraphic Nomenclature (NACSN) and the International Subcommission on Stratigraphic Classification (ISSC) with respect to formalizing the concepts of sequence stratigraphy in the North American Stratigraphic Code (herein referred to as the Code) and the International Stratigraphic Guide (herein referred to as the Guide) respectively. The ISSC Working Group on Sequence Stratigraphy submitted its final report in 1999, without reaching a consensus regarding the sequence stratigraphic nomenclature. At the same time, the long-standing NACSN committee on Allostratigraphy and Sequence Stratigraphy tabled its efforts in 2002, concluding, following the American Association of Petroleum Geologists Hedberg Conference in 2001, that it is premature to recognize formal sequence stratigraphic units in the Code. In the meantime, however, the ISSC decided to reopen the discussion on the formalization of sequence stratigraphy, by appointing A.F. Embry to form a new Task Group on Sequence Stratigraphy in 2004. As reported by the ISSC, this Task Group consists of A.F. Embry, B. Beauchamp, E.P. Johannessen, P. Gianolla and D. Owen.

Reopening the discussion on formalizing the sequence stratigraphic approach is fully warranted, and arguably, long overdue. Yet, this process is hampered because consensus needs to be reached between 'schools' that promote rather different approaches with respect to how the sequence stratigraphic method should be applied to the rock record (Figs. 2, 3). Favoring one particular model over another will never lead to the formal acceptance, by all 'schools', of any sequence stratigraphic methodology. Instead, it is necessary to understand why these models are different, why they work in some cases (or particular tectonic settings) while they are less satisfactory in others, and what is it that they have in common. After all, everybody describes the same rocks, only using different styles of packaging of strata into sequences and systems tracts.

The need for standardization is evident from the present state of nomenclatural confusion with sequence stratigraphy. In some cases, different terms are applied by different groups to the same packages of strata or sequence stratigraphic surfaces; in other cases, similar terms are applied to different packages or surfaces. Therefore, it is now time for clarification of concepts and definitions without introducing rigidity which would restrict the flexibility needed for applying sequence stratigraphy on a case-by-case basis. Finding the right balance between clarity and flexibility is at the forefront of what a revised Code or Guide should provide to the geological community.

The present-day vacuum created by the lack of standardization of sequence stratigraphy needs to be filled carefully, as the conclusions of the international commissions will be forwarded to editors and recommended to authors. On the 30th birthday of sequence stratigraphy, we are now at an important junction in the process of formalizing sequence stratigraphy, as the work of the ISSC Task Group on Sequence Stratigraphy is in progress. The vision of this Task Group, as outlined by its leader (A.F. Embry, pers. comm.), is to make a decision on the definition of a 'sequence', by selecting what sequence stratigraphic surfaces should be used to form the unconformable and conformable portions of the sequence boundaries. Implicitly, the ISSC Task Group intends to make a choice in terms of which one of the existing sequence stratigraphic models is most suitable (or 'practical') to carry the ISSC recommendation on methodology and terminology for sequence stratigraphy. The issue of what is practical or impractical in sequence stratigraphy is, however, subjective. Each sequence stratigraphic 'school' (Figs. 2, 3) feels validated by the working experience of their proponents and supporters. Furthermore, depending on location within the basin, each sequence stratigraphic surface may be 'practical' (i.e., easy to map) in some depositional systems and 'impractical' (i.e., difficult to map) in others. The mappability of sequence stratigraphic units and surfaces also depends on the data available, and on the scale of observation (see Catuneanu, 2006, for a full discussion).

This paper cautions against any biased and inflexible approach to standardization. Our aim is to review the main similarities and contrasts between the various sequence stratigraphic schemes, and provide an impartial discussion of what is of cardinal versus secondary in importance in sequence stratigraphy, and what are the basic principles that need to be accounted for in the process of standardizing sequence stratigraphy. We also strive to identify the common ground between all sequence stratigraphic 'schools' that can be agreed upon by all practitioners.

Sequence stratigraphic models

Core versus secondary aspects in sequence stratigraphy

Considering the variety of sequence stratigraphic approaches (Figs. 2, 3), the question is: can sequence stratigraphy be standardized? The separation between primary (core) and secondary aspects provides the key to the inclusion of formal 'SEQUENCE STRATIGRAPHIC UNITS' in the Code or Guide (Fig. 4). Core aspects are fundamental, and include the correct identification of all sequence stratigraphic surfaces (Fig. 5), irrespective of the status assigned to them by different models, and the correct identification of the different genetic types of deposits separated by these surfaces. A decision on how to name the sequence stratigraphic surfaces (since two or more synonymous terms are currently available for each) and the packages of strata between them is also requisite.

A fundamental theme of sequence stratigraphy emphasizes the relationship between the architecture of the stratigraphic record and cyclic changes in base level. The concept of 'base level' defines a dynamic and imaginary surface of balance between erosion and deposition, i.e. the highest level up to which a sedimentary succession can be built (Twenhofel, 1939; Sloss, 1962) A rise in base level creates accommodation (i.e., space available for sediments to fill), whereas a fall in base level destroys accommodation. The base level is commonly approximated with the sea level (e.g., Jervey, 1988; Schumm, 1993; Posamentier and Allen, 1999), and it is generally used in the context of marine environments. The equivalent concept in the alluvial realm is the fluvial graded profile. Even though the marine base level and the fluvial graded profile are often in a process-response relationship (see full discussion in Catuneanu, 2006), the two concepts may be amalgamated into one 'stratigraphic base level' that marks the surface of equilibrium between sedimentation and erosion in all depositional environments (Cross and Lessenger, 1998). A base level positioned below the topographic profile (seascape or landscape) is referred to as 'negative' accommodation, and triggers downcutting, whereas a base level above the topographic profile marks 'positive' accommodation, and it is accompanied by sediment accumulation. Base-level changes are controlled primarily by allogenic controls, including tectonism, sea-level change (eustasy) and climatic cycles driven by orbital forcing.

While the role of fluctuating base level is central in sequence stratigraphy, by providing the common thread that links processes in all depositional environments across a sedimentary basin, one should also keep in mind that autocyclic controls may leave an equally important imprint on the architecture of the stratigraphic record. At the scale of individual depositional environments, the tendency to self organization toward the most energy-efficient state of equilibrium may generate stratigraphic signatures similar to the ones produced by allogenic mechanisms. Examples include shifts from shoreline regression to transgression without changes in the rates of sediment supply or of base-level rise; the generation of stepped surfaces during transgression; and the generation of multiple terrace-pairs and multiple incisions during constant rate of base-level fall (Steel and Muto refs.). The separation of allo- and autocyclic controls on stratigraphic architecture is therefore an important step in the process of sequence modeling and analysis. The discussion below emphasizes on the allogenic component of the mechanisms controlling the development of the stratigraphic architecture, which provides the template for stratigraphic predictability at the regional scale of a sedimentary basin.

As a result of the interplay between sedimentation and available accommodation *at the shoreline*, four main events are recorded during a full cycle of base-level changes (Figs. 3, 5):

1. Onset of forced regression (onset of base-level fall at the shoreline);
2. End of forced regression (end of base-level fall at the shoreline);
3. End of regression (during base-level rise at the shoreline);
4. End of transgression (during base-level rise at the shoreline).

These four events control the timing of formation of all sequence stratigraphic surfaces and systems tracts, and are recognized by all sequence stratigraphic 'schools'. The expression of the four events in the rock record may vary across the same depositional basin, sometimes represented as a discrete and mappable surface, and sometimes by the absence of a coincident surface. The latter holds truth for *all* four events, depending on depositional setting and location within the basin. Sequence stratigraphic surfaces that form during the four events (i.e., 'event-significant' surfaces), or the ones that form during the intervening stages (i.e., 'stage-significant' surfaces), provide an order and relative age to the stratigraphic section.

Irrespective of how one may choose to name the various sequence stratigraphic surfaces and packages of strata between them, the four main events of the base-level cycle mark changes in the type of shoreline trajectory, and implicitly, changes in stratal stacking patterns in the rock record. The *onset of forced regression* event marks the change from 'highstand' normal regression to subsequent forced regression, and implicitly, a shift from aggradation to downstepping during continuous progradation. The *end of forced regression* event signifies the shift from forced regression to subsequent 'lowstand' normal regression, and implicitly, a change from downstepping to aggradation during continuous progradation. The *end of regression* event marks the turnaround from shoreline 'lowstand' normal regression to shoreline transgression, and implicitly, the change from progradation to retrogradation. Finally, the *end of transgression* event marks the turnaround from transgression to subsequent 'highstand' normal regression, and a corresponding shift in stacking patterns from retrogradational to progradational. This succession of stages and events during a full cycle of base-level changes represents the most complete scenario, but simplified versions may be encountered depending on case study, where some stages may not be represented in the rock record because of non-deposition or subsequent erosion.

What is relevant to this discussion is that sequence stratigraphic surfaces and shoreline trajectories, whose timing depends on the four main events of the base-level cycle, are core concepts *independent* of the sequence stratigraphic model of choice. These core concepts are validated by all 'schools', even though with various degrees of assigned usefulness or significance, and are more important than the nomenclature of systems tracts or even the position of sequence boundaries, which are *model-dependent* (Figs. 3, 6). Across the spectrum of existing models, the significance of sequence stratigraphic surfaces (Fig. 5) may change from sequence boundaries to systems tract boundaries or even within-systems tract facies contacts (Figs. 2, 3). It is thus clear that no consensus can be reached if one tries to pinpoint what specific sequence stratigraphic surface(s) should be assigned the status of sequence boundary. Such a rigid definition of sequences and sequence boundaries would not even make a difference to the economic success of the sequence stratigraphic approach, which rather depends on the correct identification of *all* sequence stratigraphic surfaces that are present in the stratigraphic section under analysis. Instead, a generic definition of a 'sequence' that satisfies all 'schools', while leaving the selection of sequence boundaries to the discretion of the individual, provides the flexibility that allows one to adapt to the particularities of each case study, and the "freedom to experiment with new concepts and ideas" (W. Schlager, pers. comm.).

Beyond nomenclatural preferences for surfaces and systems tracts, and conceptual differences with respect to the selection of sequence boundaries (Fig. 3), the process-based understanding of the origin of all genetic types of deposits and their bounding surfaces is fundamental to the success of the sequence stratigraphic approach. In a most complete scenario, a full cycle of base-level changes includes two stages of sediment-driven 'normal' regression (lowstand and highstand), an intervening stage of 'forced' regression driven by base-level fall, and a stage of shoreline transgression (Fig. 7). Each of these stages results in the formation of a particular genetic type of deposits, with characteristic stratal stacking patterns and sediment distribution within the basin. The terminology applied to these genetic wedges (cf. associations of depositional systems = systems tracts) may vary with the model (Fig. 3). A classic example of nomenclatural conflict is offered by the forced regressive deposits, which may be referred to as "early lowstand", "late highstand" or "falling-stage" systems tracts (Fig. 3). This aspect is trivial from a pragmatic viewpoint, as the name applied to this forced regressive wedge is less important than the recognition of this package as forced regressive. As illustrated in Figure 7, each genetic type of deposits may include different petroleum plays, so their correct identification and separation is more important than their assigned names and position within the sequence. Even within one genetic type of deposits, the evolution of sediment dispersal systems through time may require a distinction between the early and late phases of depositional system development during that particular stage of shoreline shift (e.g., forced regressive and transgressive stages in Fig. 7).

The large data-base of sequence stratigraphic work that is already available demonstrates that no model is foolproof, and that the relative success of each approach may vary with the case study. For example, the subaerial unconformity is largely regarded as corresponding to the most significant stratigraphic hiatus in the rock record, and hence it is selected by most groups as the nonmarine portion of the sequence boundary. While the stratigraphic significance that is attributed to this surface is valid in many case studies, variations in the temporal scale of stages of base-level fall and base-level rise, as well as in the relative duration of forced regressions, normal regressions and transgressions, could generate situations where more time is absorbed in condensed sections and the unconformable portions of maximum flooding surfaces than in the nearest subaerial unconformities (Galloway, 1998, 2001a, 2002). Notwithstanding such situations, subaerial unconformities are often associated with stages of significant changes in sediment supply, sediment dispersal patterns or even tectonic reorganization within the basin (i.e., shifts in landscape gradients and tilt directions: e.g., Catuneanu and Elango, 2001; Catuneanu and Eriksson, 2002). This example involving two divergent approaches to the selection of sequence boundaries, and to the definition of a 'sequence', shows that no model can be generalized to provide the best match for the entire range of case studies. The merits and pitfalls of each sequence stratigraphic model have been discussed recently by Catuneanu (2006).

The selection of stratigraphic surfaces considered by the "depositional", "genetic stratigraphic" and "transgressive-regressive" sequence models for the nonmarine and marine portions of the sequence boundary is illustrated in Figure 8. The family of "depositional" sequences (Figs. 2, 3) considers correlative conformities (the marine portion of the sequence boundary) to be either at the base (e.g., Haq et al., 1987; Posamentier et al, 1988; Posamentier and Allen, 1999) or at the top (e.g., Van Wagoner et al., 1988, 1990; Christie-Blick, 1991; Hunt and Tucker, 1992; Plint and Nummedal, 2000) of forced regressive deposits (Figs. 3, 6, 8). In both models, correlative conformities form independently of sedimentation, corresponding to the events that mark the onset and end of base-level fall at the shoreline, and hence are closer to time lines relative to surfaces that mark the end of shoreline regression or transgression (Fig. 5). Correlative conformities may be difficult to map in shallow-water systems, especially where seismic data are not available, but are more prominent in deep-water systems (Posamentier and Kolla, 2003; Catuneanu, 2006). Regardless of systems tract terminology and the choice of correlative conformities, all depositional sequence models acknowledge the importance of separating forced regressive, normal regressive and transgressive deposits as distinct genetic wedges. This distinction is more evident in the depositional sequence IV model (Fig. 3), where forced regressive deposits are assigned to a particular systems tract.

The "genetic stratigraphic" sequence model (Galloway, 1989) uses maximum flooding surfaces as sequence boundaries (Figs. 3, 6, 8). This approach has the advantage that maximum flooding surfaces are among the easiest surfaces to map in all depositional systems. Subaerial unconformities are however included within the sequence, which, depending on case study, may or may not create a problem in terms of including strata that are genetically unrelated within the same 'sequence'. In contrast to the correlative conformities of the depositional sequences, the timing of formation of maximum flooding surfaces depends on sedimentation, and hence they may be more diachronous, especially along strike-oriented sections (see Catuneanu, 2006, for detailed discussions regarding the temporal significance of all sequence stratigraphic surfaces). As in the case of the depositional sequence models, the genetic stratigraphic approach recognizes the importance of separating forced regressive, normal regressive and transgressive deposits as distinct genetic wedges.

The "transgressive-regressive" (T-R) sequence model (Embry and Johannessen, 1992) uses the subaerial unconformity of the depositional sequence as the nonmarine portion of the sequence boundary, but chooses the marine portion of the maximum regressive surface (end of shoreline regression event) as the 'correlative conformity' (Figs. 3, 6, 8). The main reason for this is that maximum regressive surfaces are commonly prominent (i.e., easy to map) in shallow-water systems, where the model works best. However, a number of pitfalls of this approach include: maximum regressive surfaces may be cryptic in deep-water systems, where they may form within an undifferentiated succession of leveed-channel low-density turbidites (Posamentier and Kolla, 2003; Catuneanu, 2006); the formation of maximum regressive surfaces depends on sedimentation, and hence they may be more diachronous, especially along strike-oriented sections (see Catuneanu, 2006, for detailed discussion of the temporal significance of all sequence stratigraphic surfaces); the fluvial and marine portions of the sequence boundary are of different ages (Fig. 8), and so they may only connect physically where the intervening lowstand normal regressive deposits are missing; and, all 'normal' and 'forced' regressive deposits are amalgamated into one "regressive systems tract", which is impractical for petroleum exploration because each of these genetic types of deposits is associated with different play opportunities (Fig. 7). The preservation of lowstand normal regressive deposits in the rock record is the key to the applicability of the T-R sequence model, or to its failure to provide a single mappable surface as a sequence boundary. Lowstand normal regressive deposits are documented from a variety of depositional settings including fluvial (e.g., Kerr et al., 1999; Leckie and Boyd, 2003), clastic coastal to shallow-water (e.g., Plint, 1988; Plint and Nummedal, 2000; Hampson and Storms, 2003; Ainsworth, 2005), clastic deep-water (e.g., Posamentier and Kolla, 2003) and carbonate platforms (e.g., Cathro et al., 2003; Schlager, 2005) (Fig. 9).

In can thus be concluded that no one model may work in all circumstances, which is the reason why so many different approaches have been proposed so far. Hence, trying to define what specific surfaces of sequence stratigraphy should receive the formal status of 'sequence boundary' is not practical, and will never provide an acceptable solution for all groups. Furthermore, depending on the location within the basin, each sequence stratigraphic surface may be 'practical' (i.e., easy to map) in some depositional systems and 'impractical' (i.e., difficult to map) in others.

Principles of standardization

This section provides a set of model-independent principles that need to be considered in the process of formalizing sequence stratigraphy:

1. Sequence stratigraphic surfaces are surfaces that can serve, at least in part, as systems tract boundaries. Seven sequence stratigraphic surfaces are defined relative to the four main events of the base-level cycle (Fig. 5). Their assigned degree of usefulness or importance varies with the model (Fig. 3).

2. As a function of subsidence patterns, the magnitude and timing of base-level changes may vary from one area to another within a sedimentary basin. The reference curve relative to which sequence stratigraphic surfaces and systems tracts are defined describes changes in base level at the shoreline.

3. The four main events of the reference base-level curve mark changes in the direction and/or type of shoreline shift (i.e., forced regressions, normal regressions, transgressions). These changes control the formation and timing of all sequence stratigraphic surfaces and systems tracts.

4. Recognition of sequence stratigraphic surfaces in the rock record is data dependant. Inherent difficulties in recognizing any of the sequence stratigraphic surfaces do not negate their existence or validity. In most cases, this is just a reflection of lack of sufficient data. Limitations of mappability may also be related to position within the basin, or a combination of basin position and data availability. For example, subaerial unconformities expressed as paleosols may be difficult to map in interfluve areas; correlative conformities may be difficult to map in shallow-water systems; maximum regressive surfaces may be difficult to map in fluvial and deep-water systems; maximum flooding surfaces may be difficult to map in deep-water systems.

5. Integration of outcrop, core, well-log and seismic data affords the most effective application of the sequence stratigraphic method.

6. Different genetic types of deposits (forced regressive, normal regressive, transgressive) need to be separated as distinct systems tracts, data permitting, as this is the key to the predictive aspect of sequence stratigraphy. Each such systems tract is characterized by different sediment dispersal patterns and petroleum plays.

7. Sequence stratigraphic surfaces that form independently of sedimentation (i.e., "correlative conformities" 1 and 2 in Fig. 8) are closer to time lines than surfaces that mark the end of regression (maximum regressive surfaces) or the end of transgression (maximum flooding surfaces).

8. The highest-frequency (lowest rank) cycles in the rock record reflect the true changes in depositional trends. All higher-rank cycles represent trends that approximate the true facies shifts at different scales of observation.

9. Lower-rank surfaces superimposed on higher-rank ones do not change the stratigraphic significance of the latter within the bigger-picture framework. A sequence stratigraphic framework constructed at a particular hierarchical level should consistently include stratigraphic surfaces of equal rank.

10. Where two or more sequence stratigraphic surfaces are superimposed, always use the name of the youngest surface. Examples may include a maximum flooding surface superimposed on the older maximum regressive surface due to the absence of transgressive deposits, a transgressive ravinement surface reworking the underlying subaerial unconformity during shoreline transgression, a regressive surface of marine erosion reworking the underlying basal surface of forced regression during base-level fall, etc. Amalgamation of sequence stratigraphic surfaces occurs where systems tracts, or portions thereof, are not preserved in the rock record.

Recommendations

The section on 'ALLOSTRATIGRAPHIC UNITS' in the 2005 Code (NACSN, 2005) can serve as an example of how standardization of sequence stratigraphy can be achieved. The key is to leave the definition of a 'sequence' generic, with no association to any specific sequence stratigraphic model. Implicitly, just as in the case of allostratigraphic units, boundaries are left to the discretion of the practicing geologist; such flexibility allows one to adapt more easily to the particularities of each case study. Without this balanced approach, leaning toward one particular model or another will never lead to the formal acceptance, by all 'schools', of any sequence stratigraphic concept – a point proven unequivocally at the 2001 AAPG Hedberg meeting in Dallas.

Leaving the concept of 'sequence' generic, with no direct affiliation to any existing model, eliminates the problem of having to decide what surface(s) should serve as sequence boundaries (Figs. 3, 4, 8, 9). This bypasses the main obstacle in the way of formalizing sequence stratigraphy. In fact, once all sequence stratigraphic surfaces that can be mapped in the context of a case study are recognized (Fig. 9), the choice of sequence boundary makes little difference to the (economic) success of the sequence stratigraphic analysis. Another trivial aspect, from a practical viewpoint, is the nomenclature that should be applied to particular genetic types of deposits (Figs. 3, 4). A classic example includes the definition of forced regressive deposits as ‘early lowstand’, ‘late highstand’ or ‘falling stage’ (Fig. 3). This is again an issue of secondary importance, which can be looked at after a generic definition for a ‘systems tract’ is formalized.

Sequence stratigraphy, definition

Several definitions of sequence stratigraphy are available in the literature (Fig. 10). Fundamentally, sequence stratigraphy studies the *sedimentary response to changes in base level, and the depositional trends that emerge from the interplay of accommodation (space available for sediments to fill) and sedimentation*. All available definitions of sequence stratigraphy stress on the concepts of cyclicity (i.e., a sequence is a cyclothem that represents the product in the rock record of a stratigraphic cycle), time framework (i.e., age-equivalent depositional systems are correlated across a basin, which provides the foundation for the definition of systems tracts), genetically related strata (i.e., no major hiatuses are assumed within a sequence), and the quantified interplay of sedimentation and base-level changes.

Definition of a ‘sequence’

<u>Sequence</u>: a relatively conformable succession of genetically related strata bounded by unconformities or their correlative conformities (Mitchum, 1977). A sequence corresponds to a full cycle of base-level changes. The definition of a sequence is independent of temporal and spatial scales. The relative importance of sequences is resolved via the concept of hierarchy. Higher-rank sequences may consist of two or more lower-rank sequences.

The addendum to the original definition of Mitchum (1977) that a sequence corresponds to a full cycle of base-level changes is required to separate a sequence from component systems tracts. As more than one sequence stratigraphic surface may have unconformable portions, the package of strata between two consecutive unconformities in the rock record is likely to correspond to only one stage of a full cycle of base-level changes, i.e. to a systems tract. The bounding unconformities and correlative conformities referred to in the definition of a sequence have to be consistently represented by the same type(s) of sequence stratigraphic surfaces, albeit not specified in the definition.

Beyond the definition of a ‘sequence’ as a generic concept, specific types of sequences (i.e., ‘depositional’, ‘genetic stratigraphic’ or ‘transgressive-regressive’) may be recognized depending on the model of choice (Figs. 2, 3). Each such sequence is defined by specific unconformable and conformable portions of the sequence boundary (Fig. 8).

Parasequences

Parasequences are stratigraphic units bounded by ‘flooding surfaces’ (Van Wagoner et al., 1988, 1990), which, depending on circumstances, may be represented by transgressive ravinement surfaces, maximum flooding surfaces, maximum regressive surfaces, or facies contacts within the transgressive systems tract (see Catuneanu, 2006, for a recent discussion and examples).

Consequently, parasequences are not just smaller-scale sequences, as parasequence boundaries may be represented by surfaces other than sequence boundaries.

<u>Parasequence</u>: a relatively conformable succession of genetically related beds or bedsets bounded by flooding surfaces or their correlative surfaces (Van Wagoner et al., 1988, 1990).

<u>Flooding surface</u>: a surface separating younger from older strata across which there is evidence of an abrupt increase in water depth (Van Wagoner et al., 1988, 1990).

Parasequences are commonly used to describe individual prograding lobes in coastal to shallow-water systems, where evidence of abrupt water deepening (i.e., documentation of flooding surfaces) is easiest to demonstrate. Confusions regarding the meaning of parasequences arouse with the application of the term to all shoaling upward stratal units, whether or not bounded by flooding surfaces, which is beyond the original intent of Van Wagoner et al. (1988, 1990). The applicability and the usefulness of the 'parasequence' concept in fully fluvial and deep-water systems have been questioned by Posamentier and Allen (1999). This is also our position, that the term should only apply to the units similar to those originally defined by Van Wagoner et al. (1988, 1990). The restriction of parasequences to coastal and shallow-water systems marks another difference between the concepts of sequence and parasequence.

Systems tracts

A sequence may be subdivided into component systems tracts, which consist of packages of strata that are genetically distinct (e.g., forced regressive, normal regressive, transgressive). The original definition by Brown and Fisher (1977) is generic and devoid of nomenclatural ambiguity, and thus remains acceptable by all 'schools':

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

The timing of systems tract boundaries is set by the four main events of the base-level cycle (Fig. 3). As such, a systems tract includes all strata (cf. association of depositional systems) that accumulate across the basin during a particular stage of shoreline shifts (forced regressive, normal regressive, transgressive). Systems tracts are interpreted based on stratal stacking patterns, position within the sequence, and types of bounding surfaces.

Types of shoreline shifts

Each type of shoreline shift (forced regression, normal regression, transgression) is associated with the formation of a particular genetic type of deposits (cf. systems tract; Fig. 9). The separation of forced regressive, normal regressive and transgressive deposits is central to sequence stratigraphy and petroleum exploration, because each such genetic wedge (systems tract) is characterized by distinct sediment dispersal patterns and includes different petroleum plays (Fig. 7).

Forced regression: regression of the shoreline driven by base-level fall. Forced regressive deposits display diagnostic progradational and downstepping stacking patterns (Fig. 9).

Normal regression: regression of the shoreline driven by sediment supply, during a time of base-level rise at the shoreline. The necessary condition for normal regressions to occur is that sedimentation rates must outpace the rates of base-level rise at the shoreline. In a most complete scenario, two normal regressions are expected during a full cycle of base-level changes: a lowstand normal regression following the onset of base-level rise (early stage of base-level rise), and a highstand normal regression during the late stage of base-level rise (Fig. 7). Normal regressive deposits display a combination of progradational and aggradational depositional trends (Fig. 9).

Transgression: landward shift of the shoreline, commonly triggered by a rise in base-level at rates higher than the sedimentation rates at the shoreline. Transgressive deposits display diagnostic retrogradational stacking patterns (Fig. 9).

Sequence stratigraphic surfaces

Standardizing sequence stratigraphic surfaces is more important than standardizing sequence boundaries. The latter is a model-dependent choice (Fig. 9) and makes little difference to the (economic) success of the sequence stratigraphic approach. The following seven sequence stratigraphic surfaces can be defined relative to a reference curve of base-level changes (Fig. 5):

Subaerial unconformity:

- Synonymous terms: lowstand unconformity (Schlager, 1992); regressive surface of fluvial erosion (Plint and Nummedal, 2000); fluvial entrenchment/incision surface (Galloway, 2004).
- Origin: fluvial erosion or bypass, pedogenesis, wind degradation.
- Timing: stages of base-level fall (standard sequence stratigraphic models; Fig. 3); stages of transgression (e.g., Leckie, 1994); climate-driven stages of increased fluvial discharge (e.g., Blum, 1994).
- Temporal significance: stage-significant (Fig. 5).

Correlative conformity (*sensu* Posamentier et al., 1988; Posamentier and Allen, 1999):

- Synonymous terms: basal surface of forced regression (Hunt and Tucker, 1992).
- Origin: oldest clinoform (paleoseafloor) associated with offlap.
- Timing: onset of base-level fall at the shoreline (i.e., onset of forced regression).
- Temporal significance: event-significant (Fig. 5).

Correlative conformity (*sensu* Hunt and Tucker, 1992):

- Synonymous terms: N/A.
- Origin: youngest clinoform (paleoseafloor) associated with offlap.
- Timing: end of base-level fall at the shoreline (i.e., end of forced regression).
- Temporal significance: event-significant (Fig. 5).

Regressive surface of marine erosion:

• Synonymous terms: regressive ravinement surface (Galloway, 2001b); regressive wave ravinement (Galloway, 2004).
• Origin: wave scouring in the lower shoreface.
• Timing: during forced regression.
• Temporal significance: stage-significant (Fig. 5).

Maximum regressive surface:
• Synonymous terms: transgressive surface (Posamentier and Vail, 1988); top of lowstand surface (Vail et al., 1991); initial transgressive surface (Nummedal et al., 1993); conformable transgressive surface (Embry, 1995); surface of maximum regression (Mellere and Steel, 1995); maximum progradation surface (Emery and Myers, 1996).
• Origin: youngest clinoform (paleoseafloor) of regression, onlapped by transgressive strata.
• Timing: end of shoreline regression (i.e., end of lowstand normal regression).
• Temporal significance: event-significant (Fig. 5).

Maximum flooding surface:
• Synonymous terms: final transgressive surface (Nummedal et al., 1993); maximum transgressive surface (Helland-Hansen and Gjelberg, 1994; Helland-Hansen and Martinsen, 1996).
• Origin: top of retrogradational strata, downlapped by highstand normal regressive strata.
• Timing: end of shoreline transgression.
• Temporal significance: event-significant (Fig. 5).

Transgressive ravinement surfaces (wave and tidal):
• Synonymous or more specific terms: wave-ravinement surface (Swift, 1975); transgressive surface of erosion (Posamentier and Vail, 1988); tidal ravinement surface (Allen and Posamentier, 1993); shoreface ravinement (Embry, 1995).
• Origin: wave or tidal scouring in the coastal to upper shoreface environments. The tidal ravinement surface always forms before the wave ravinement surface, and it is often reworked by the latter.
• Timing: during shoreline transgression.
• Temporal significance: stage-significant (Fig. 5).

The full set of criteria that can be used to identify each sequence stratigraphic surface has been reviewed recently by Catuneanu (2006). These criteria include the nature of the contact (conformable or unconformable); the nature of facies underlying the contact; the nature of facies overlying the contact; the depositional trends recorded by the strata below the contact; the depositional trends recorded by the strata above the contact; the types of substrate-controlled ichnofacies that may be associated with the contact; and stratal terminations associated with the contact.

Non-standardized concepts

Concepts that are model-dependent include the nomenclature of systems tracts and the definition of sequence boundaries in terms of the choice of surface(s) that should receive this status (Fig.

3). Arguably, these are trivial aspects in terms of the (economic) success of the sequence stratigraphic approach, and therefore they can be left to the discretion of the individual. All sequence stratigraphic surfaces that are present in a succession are important to recognize, and the selection of which one(s) should serve as sequence boundary may depend on case study, data availability, and personal preference. This choice regarding the style of conceptual packaging of strata into sequences, as well as the terminology applied to the various genetic wedges (systems tracts) is less important than the correct identification of sequence stratigraphic surfaces present in the succession and of the genetic nature (forced regressive, normal regressive, transgressive) of the deposits separated by these surfaces (Fig. 9).

Discussion

The value of sequence stratigraphy lies in its practical use for the subdivision, classification and interpretation of stratigraphic successions. Therefore, any definitions and terms must have practical application. Some of the types of surface defined above may be difficult to recognize and classify in particular field cases, and care should be taken to ensure that all available field evidence regarding facies, facies successions and architecture, and facies relationships, is taken into account when erecting a field terminology. In some cases, considerable interpretation may be required for the appropriate classification of systems tracts and surfaces, especially where only limited data are available for analysis, or where the lack of preservation may obliterate diagnostic criteria that are used to identify particular stratigraphic surfaces. For example, the mapping of both 'correlative conformities' of the depositional sequence model (Fig. 8) relies on the preservation of offlapping stratal terminations in the rock record, and on the ability to map the subaerial unconformity towards the basin margin. Such interpretive steps are important to remember during sequence analysis, because they add a possible layer of error to the outcome. Nonetheless, inherent difficulties in recognizing any of the sequence stratigraphic surfaces do not reflect lesser value for modeling or exploration, but rather only a lack of sufficient data.

There are at least two environments in which difficulties may be encountered in the application and interpretation of sequence data:

Nonmarine sequences: Sequence concepts are applicable, with modifications, to successions that are entirely nonmarine in origin, even where there are no marine surfaces with which to correlate. In the nonmarine environment, accommodation is created and destroyed by differential tectonic movement between basin and source area(s), or by cycles of climate change. In such settings, there is no transgressive ravinement or forced regression, but subaerial unconformities are, of course, widespread, and may be used to define sequence boundaries. Tectonic- or climate driven cyclothems may also be recognized by vertical changes in facies, such as grain size, and by the mapping of facies shifts recording progradation or retrogradation of marginal facies across a basin floor. Concepts such as transgression and regression do not apply, but equivalent concepts may be useful. For example, upward coarsening within a succession may mean source-area uplift and basinward progradation. The formation of subaerial unconformities may be attributed to stages of increased fluvial energy, which may be triggered by differential isostatic rebound or deglaciation. In such cases, the timing of fluvial erosion and sedimentation may be completely out of phase with cycles driven by marine base-level changes. The responses of fluvial systems to allogenic forcing are complex, and have been reviewed by numerous researchers (e.g., Miall, 1991; Schumm, 1993; Ethridge at al., 1998; Blum and Törnqvist, 2000; Catuneanu, 2006).

Deep-marine sequences: A number of surfaces which are directly correlatable to marine base-level changes and shoreline shifts do not form in the deep-water setting, including the transgressive ravinement, the regressive surface of marine erosion, and the subaerial unconformity. This hampers the applicability of the sequence stratigraphic approach to deep-water settings, although a sequence framework may still be constructed by mapping the four event-surfaces that do develop in the deep-water realm (i.e., the two correlative conformities of the depositional sequence model, the maximum flooding surface and the maximum regressive surface; Fig. 8). Recent process-response insights into the shifts in the type of gravity flows that are expected to occur across the four main events of the base-level cycle (Fig. 3) show that predictable facies changes may accompany the formation of correlative conformities and maximum flooding surfaces, while the maximum regressive surface is likely to be cryptic, within a conformable and undifferentiated succession of leveed-channel turbidites (Catuneanu, 2006). However, the sequence interpretation of deep-water deposits is complicated by the fact that facies shifts respond only in part to regional changes in accommodation (e.g., Hiscott et al., 1997), and that additional controls may include changes in sediment supply and dispersal patterns, or autocyclic processes of fan switching (Underhill, 1991; Galloway, 2001b, 2004; Posamentier and Kolla, 2003).

Conclusions

First and foremost, personal preferences of applying one model over another (Figs. 2, 3) need to be separated from what is fair and reasonable to formalize in stratigraphic codes. Only the common ground that is acceptable by all can provide the unbiased solution to formalizing sequence stratigraphy to the satisfaction of all ‘schools’. This implies a separation between core and trivial aspects in sequence stratigraphy. Core aspects include the generic definition of a ‘sequence’ (cf. Mitchum, 1977); the generic definition of a ‘systems tract’ (cf. Brown and Fisher, 1977); the definition of sequence stratigraphic surfaces (their identification and mapping is more important than choosing which one(s) should be assigned the status of sequence boundary); and the definition of different genetic types of deposits (forced regressive, normal regressive, transgressive). This set of core concepts is validated and accepted by all ‘schools’.

Given the careful mapping and definition of the surfaces within a succession of sequences, the selection of what sequence stratigraphic surface(s) should be used to form the unconformable and conformable portions of the sequence boundaries (Figs. 8, 9) and the nomenclature of systems tracts (Fig. 3), is of lesser importance, so long as the choices are clearly defined by the user. These aspects are model-dependent, and do not make a difference to the success resulting from application of the sequence stratigraphic method. Therefore, at this point, there is no need, nor it is advisable, to standardize any particular model in Figures 2 and 3 as the recommended approach that should be applied in all case studies. The feasibility of each particular model may vary with the case study, tectonic setting, and/or data availability.

A successful sequence stratigraphic interpreter must have a sound understanding of process sedimentology and the ability to adapt to the particularities of each case study, data set, or tectonic setting. These qualities allow one to be flexible and to rationalize ‘exceptions’ to the basic sequence stratigraphic templates that may be encountered, on a case-by-case basis. Significant departures from the standard sequence stratigraphic model that predicts particular responses to changes in base level are well documented. For example, on the east coast of South Island, New Zeeland, subaerial unconformities, which are generally assumed to form during forced regressions, may also form during transgression (Leckie, 1994); at the same time, fluvial aggradation, generally associated with stages of base-level rise (normal regressions and transgressions) may also proceed during forced regression, depending on the contrast in slope gradients between the landscape and seascape profiles (Summerfield, 1985; Pitman and Golovchenko, 1988; Butcher, 1990; Schumm, 1993; Blum and Tornqvist, 2000). Admittedly, such departures from the expected models may be rare.

Another caveat is that sequence stratigraphic models that emphasize the role of allocyclic controls on sedimentation may not capture the autocyclic component of depositional system development, which may need to be assessed on a case-by-case basis. This is one more reason to promote flexibility in the application of sequence stratigraphy, and a process-based approach to the construction of sequence stratigraphic models.

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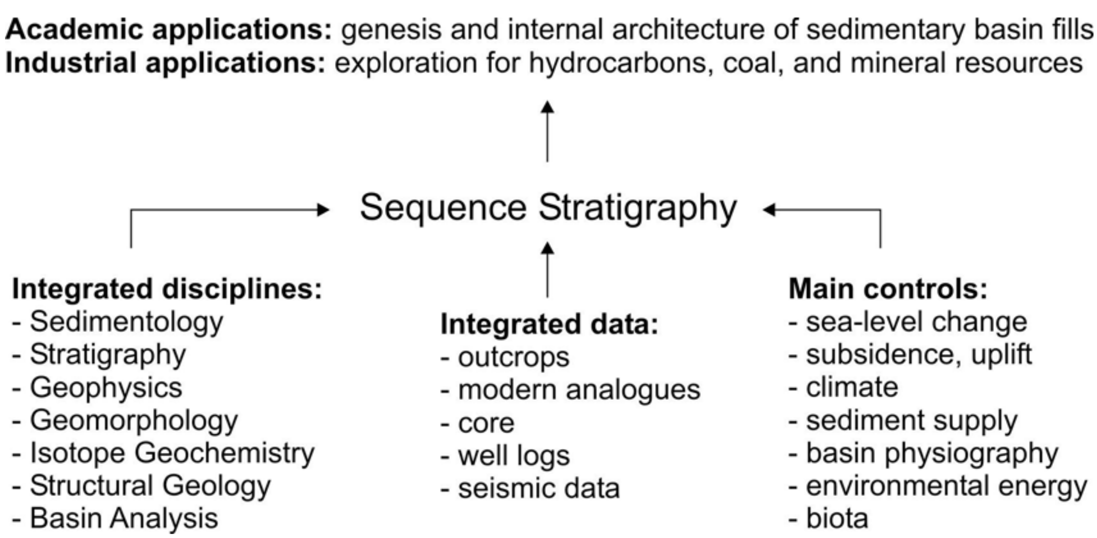

Figure 1. Sequence stratigraphy in the context of interdisciplinary research (from Catuneanu, 2006).

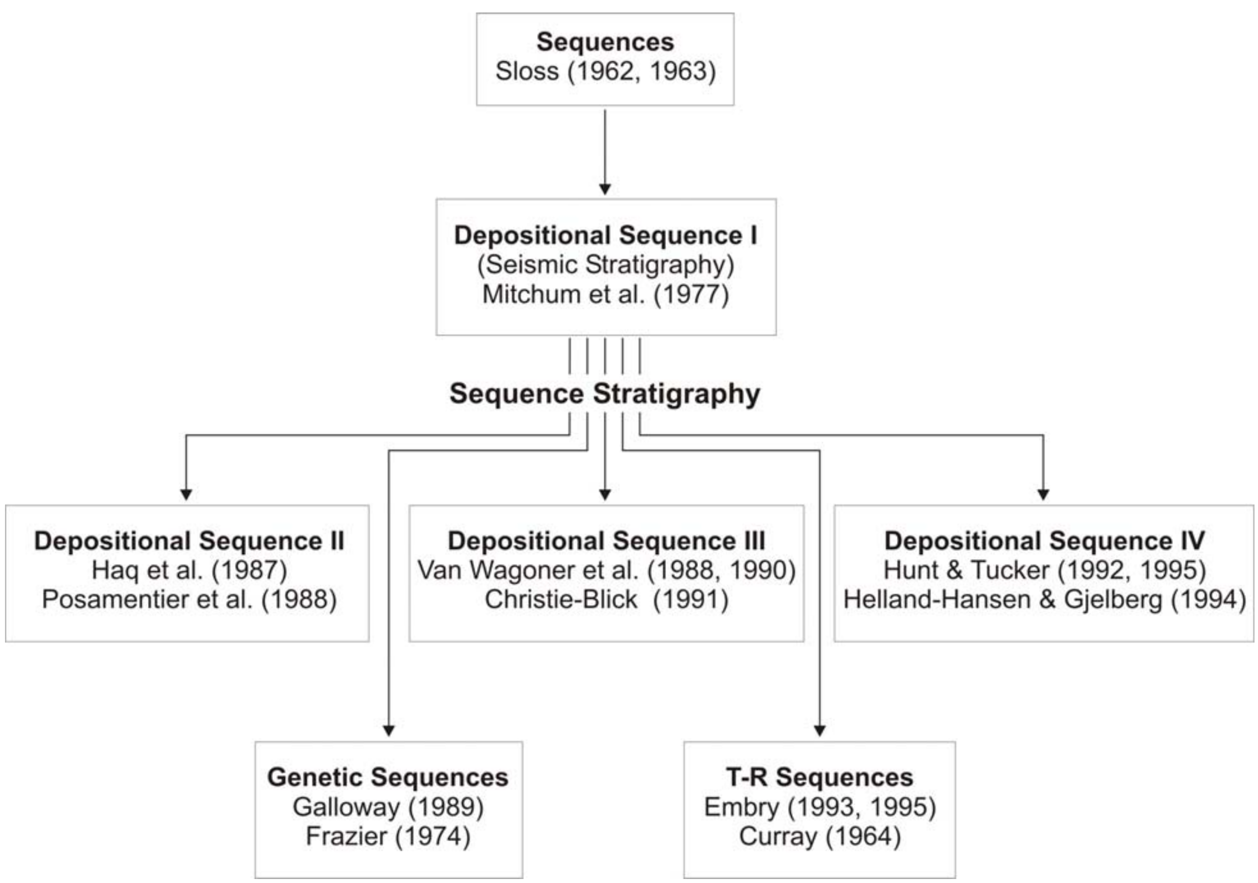
Sequences
Sloss (1962, 1963)
Depositional Sequence I
(Seismic Stratigraphy)
Mitchum et al. (1977)
Sequence Stratigraphy
Depositional Sequence II
Haq et al. (1987)
Posamentier et al. (1988)
Depositional Sequence III
Van Wagoner et al. (1988, 1990)
Christie-Blick (1991)
Depositional Sequence IV
Hunt & Tucker (1992, 1995)
Helland-Hansen & Gjelberg (1994)
Genetic Sequences
Galloway (1989)
Frazier (1974)
T-R Sequences
Embry (1993, 1995)
Curray (1964)

Figure 2. Evolution of sequence stratigraphic models (from Catuneanu, 2006; modified after Donovan, 2001).

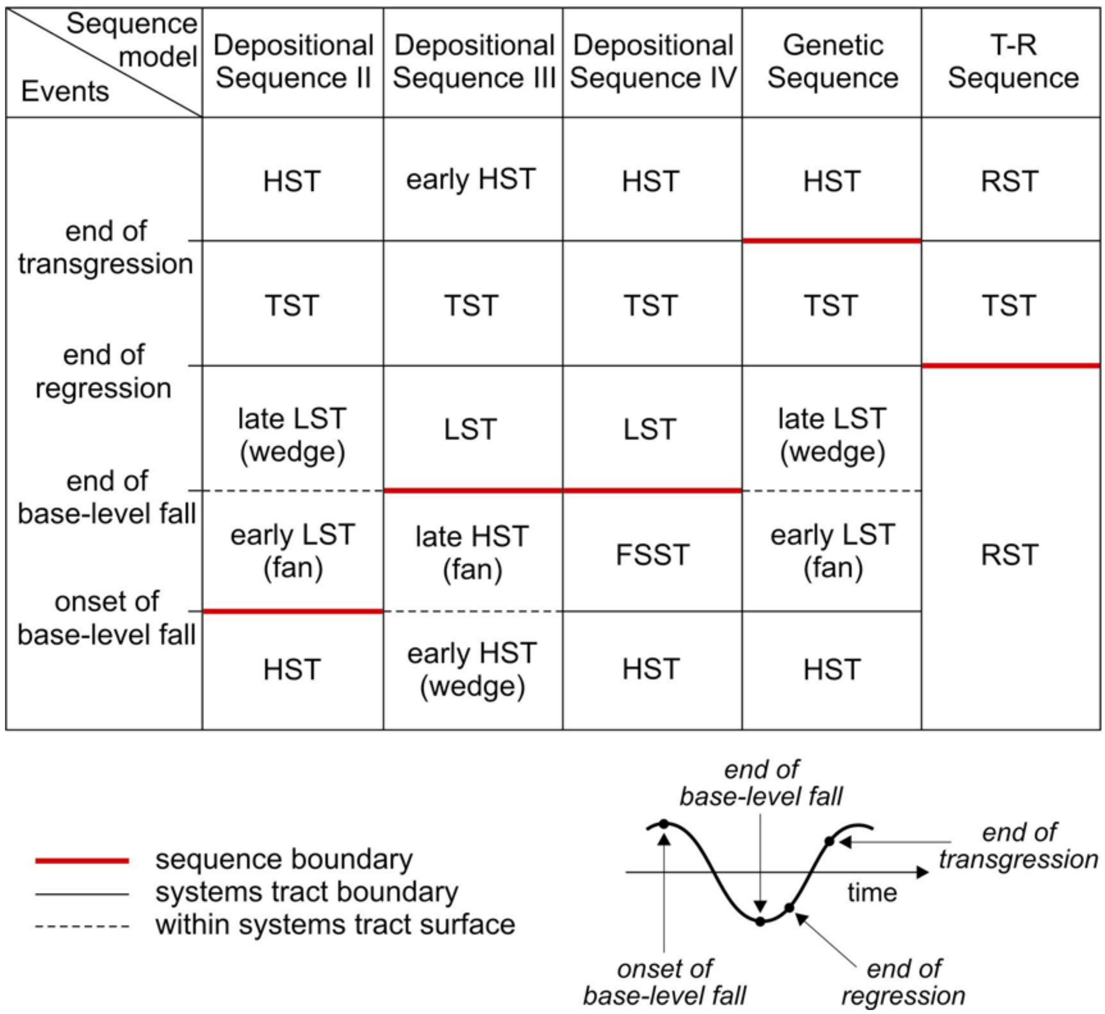

Figure 3. Timing of systems tracts and sequence boundaries for the existing sequence stratigraphic models (from Catuneanu, 2006). Abbreviations: LST – lowstand systems tract; TST – transgressive systems tract; HST – highstand systems tract; FSST – falling-stage systems tract; RST – regressive systems tract; T-R – transgressive-regressive.

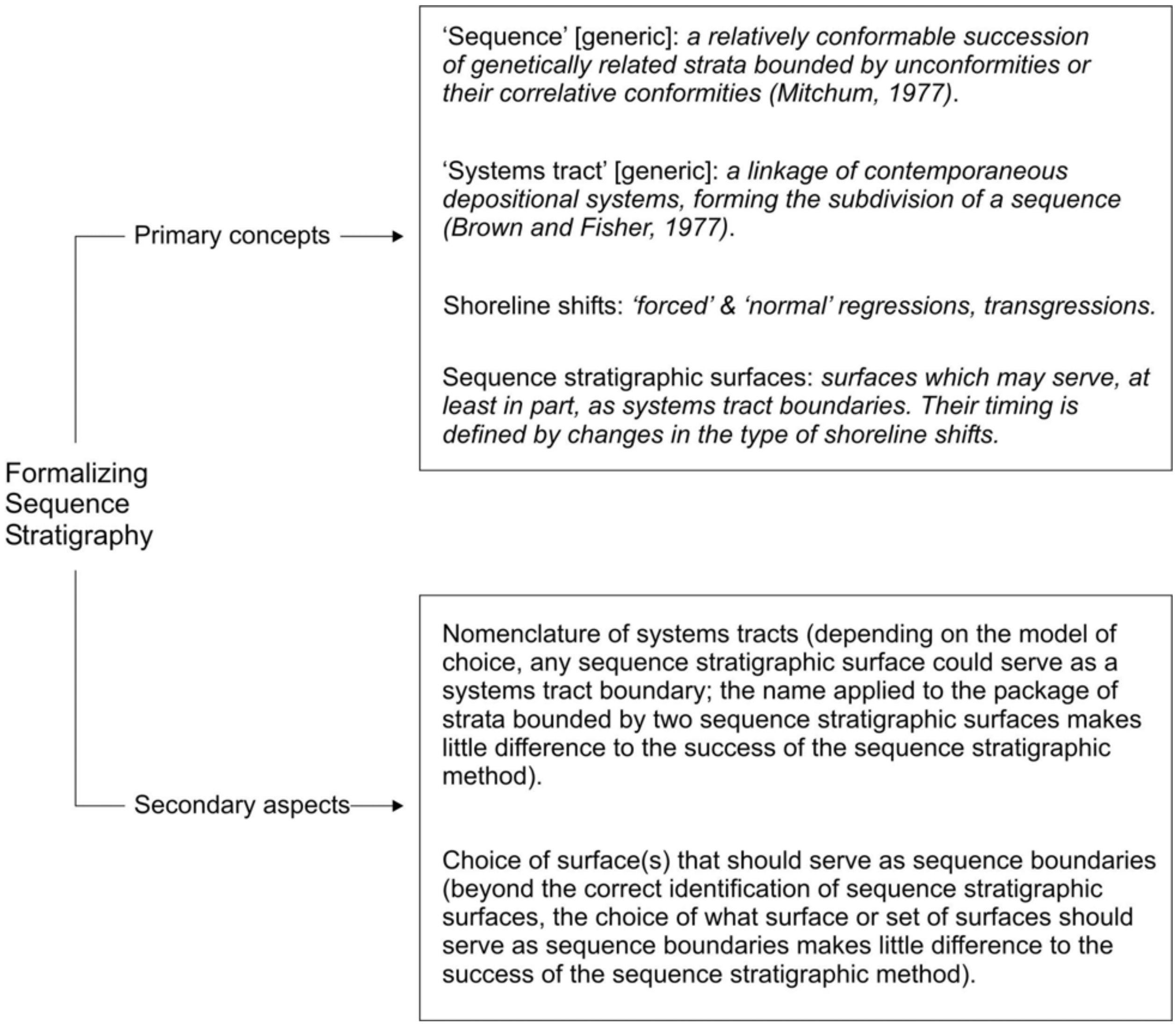

Figure 4. Primary (core) vs. secondary aspects in sequence stratigraphy. Core aspects are validated and accepted by all 'schools'. Secondary aspects are model-dependent. Once the 'sequence' is formalized as a generic concept, one can take a step further and list the various types of sequences, by defining what surfaces are selected as sequence boundaries in each case (Fig. 3).

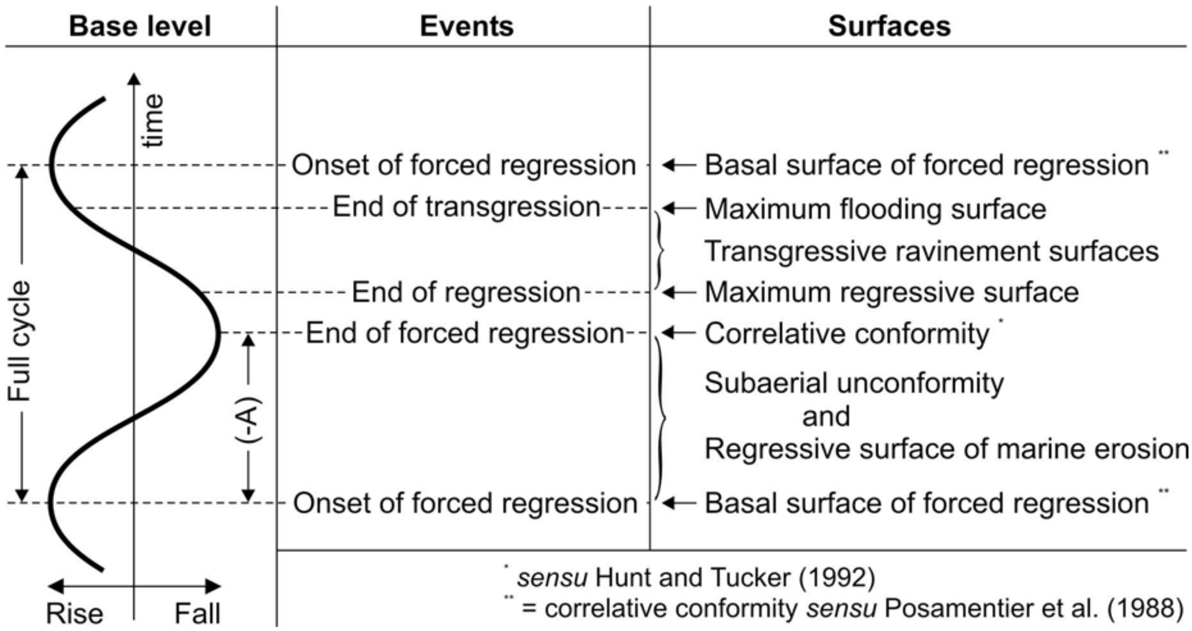

Figure 5. Timing of the seven sequence stratigraphic surfaces relative to the four main events of the base-level cycle (from Catuneanu, 2006). The erosion that generates transgressive ravinement surfaces may be triggered by waves or tides (hence the usage of plural). Abbreviation: (-A) – negative accommodation.

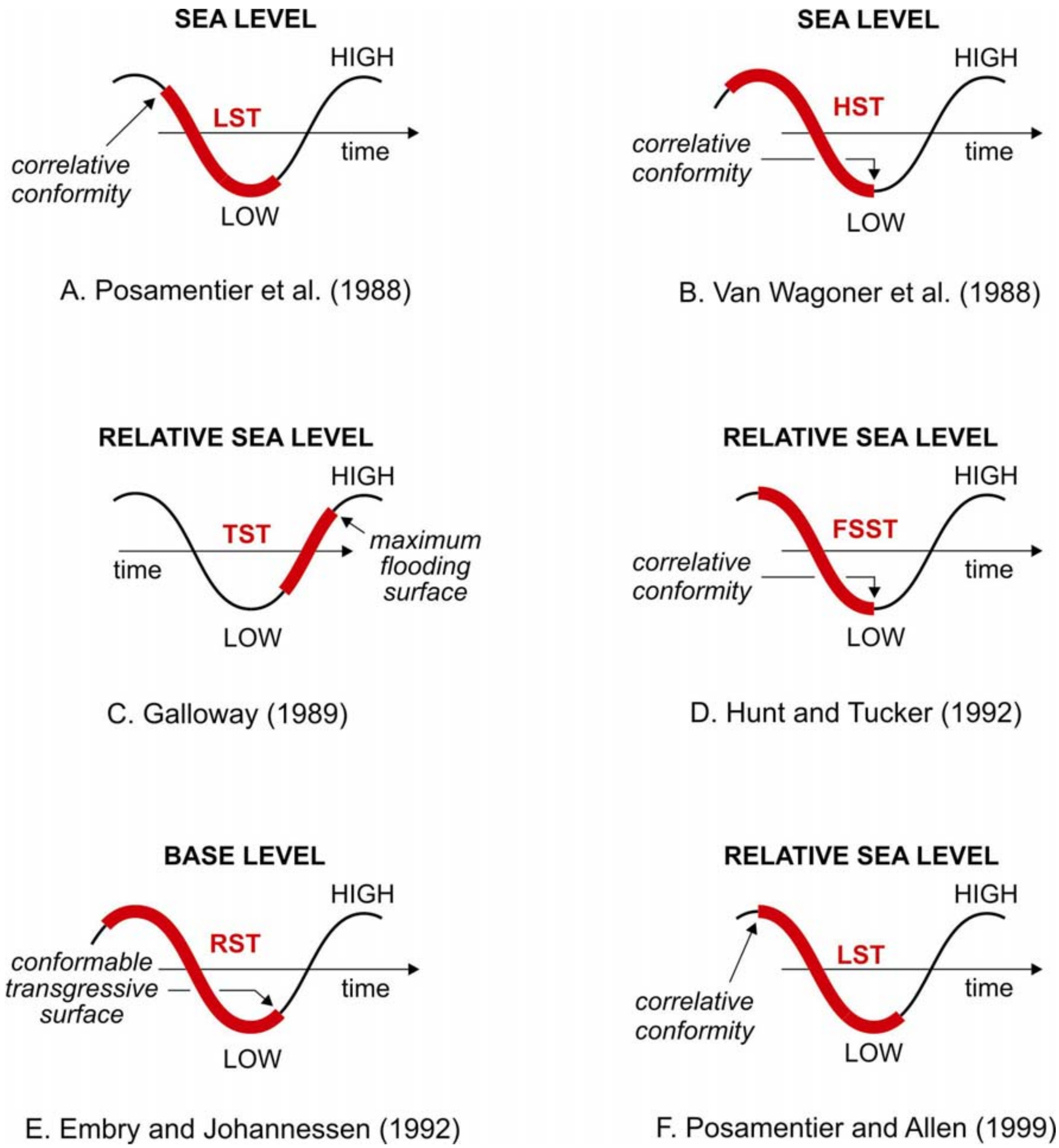

Figure 6. Correlative conformities as defined in various sequence stratigraphic models (from Catuneanu, 2006). The timing of formation of correlative conformities may be independent of sedimentation (models A, B, D and F), or dependent of sedimentation (models C and E). Each correlative conformity shown in this diagram corresponds to a particular type of stratigraphic surface shown in Figure 5: the "basal surface of forced regression" (correlative conformity *sensu* Posamentier et al., 1988; models A and F), the correlative conformity *sensu* Hunt and Tucker (1992) (models B and D), the "maximum flooding surface" (model C) and the "maximum regressive surface" (model E). The thicker portion of the reference sine curve in each diagram represents the timing of formation of particular systems tracts (see abbreviations). Abbreviations: LST – lowstand systems tract; HST – highstand systems tract; TST – transgressive systems tract; FSST – falling-stage systems tract; RST – regressive systems tract.

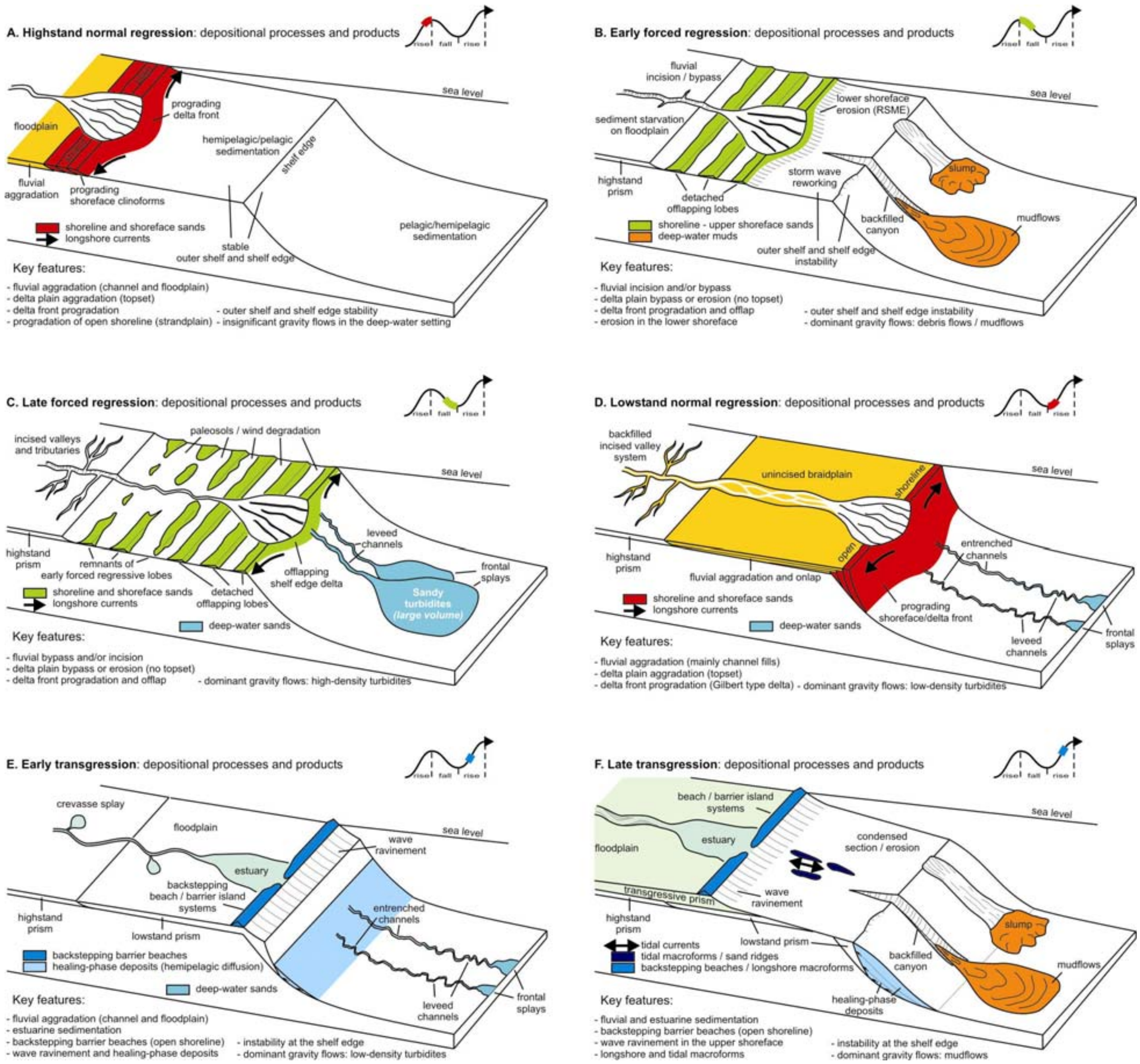

Figure 7. Genetic types of deposits: processes and products (from Catuneanu, 2006). Not to scale. Each genetic wedge (cf. systems tract; forced regressive, normal regressive, transgressive) is associated with different exploration opportunities and petroleum plays. The name associated with each genetic type of deposit (Fig. 3) is less important than their correct identification (Fig. 4). Abbreviation: RSME – regressive surface of marine erosion.

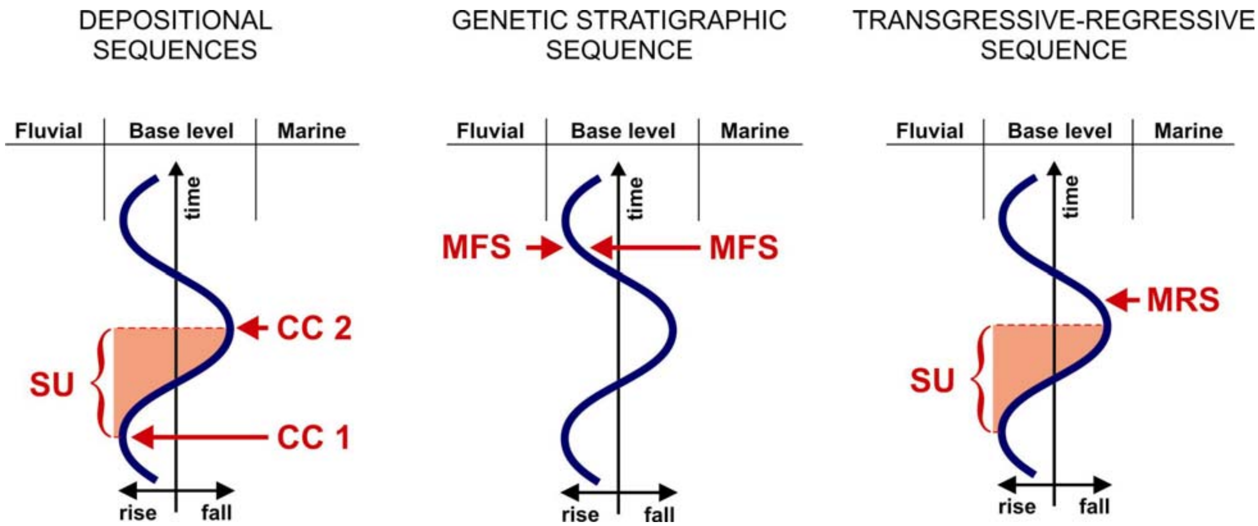

Figure 8. Selection of sequence boundaries according to the “depositional”, “genetic stratigraphic” and “transgressive-regressive” sequence models. The choice of sequence boundary is less important than the correct identification of all sequence stratigraphic surfaces that are present in a succession (Fig. 4). Abbreviations: SU – subaerial unconformity; CC 1 – correlative conformity *sensu* Posamentier et al., 1988; CC 2 – correlative conformity *sensu* Hunt and Tucker, 1992; MFS – maximum flooding surface; MRS – maximum regressive surface. The subaerial unconformity is a stage-significant surface, whereas all other surfaces shown in this diagram are event-significant.

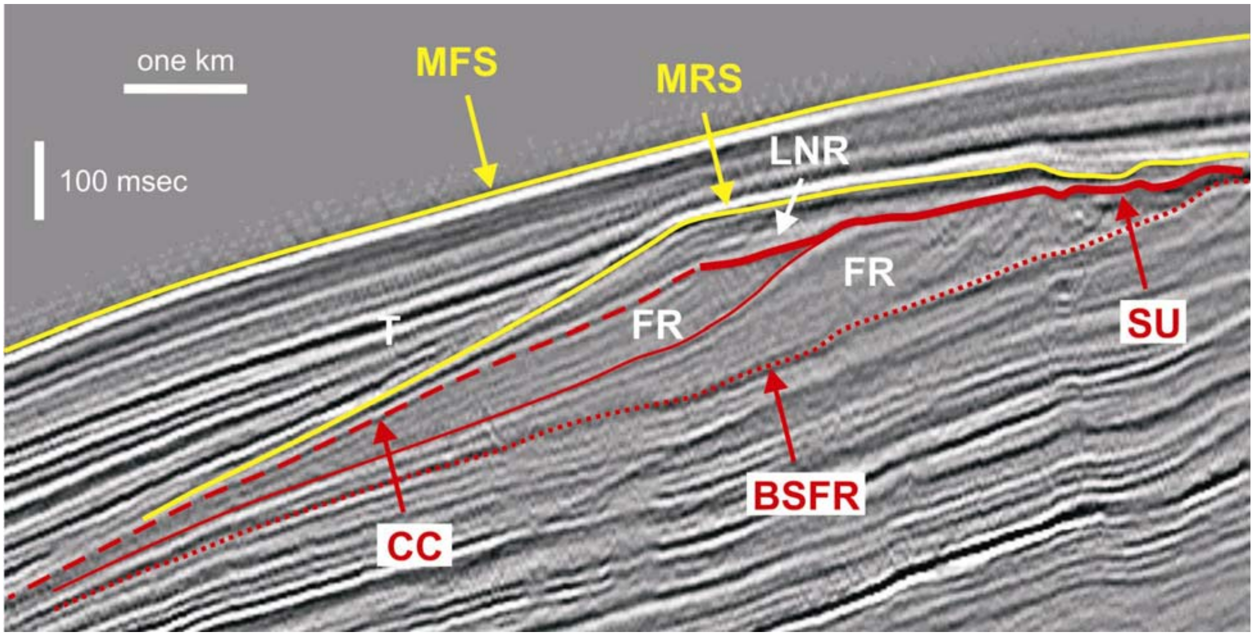

Figure 9. Seismic line in the Gulf of Mexico showing different genetic types of deposits (forced regressive, normal regressive, transgressive) and stratigraphic surfaces that may serve as sequence boundaries according to different sequence stratigraphic models (modified from Posamentier and Kolla, 2003). Abbreviations: FR – forced regressive; LNR – lowstand normal regressive; T – transgressive; SU – subaerial unconformity; BSFR – basal surface of forced regression (correlative conformity 1 in Figure 8); CC – correlative conformity *sensu* Hunt and Tucker, 1992 (correlative conformity 2 in Figure 8); MRS – maximum regressive surface; MFS – maximum flooding surface. The maximum flooding surface is yet to form, as the shoreline is still transgressing today. Clearly evident are the progradational depositional trend associated with forced and normal regressive deposits, and the retrogradational depositional trend that characterizes the transgressive deposits. The line displays the typical stratal terminations associated with forced regressive (offlap and downlap), normal regressive (downlap, in parallel with the formation of a topset), and transgressive (onlap of the youngest clinoform of regression) deposits.

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, 2001): 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.

Figure 10. Definitions of sequence stratigraphy. In the simplest sense, sequence stratigraphy studies *the sedimentary response to changes in base level, and the depositional trends that emerge from the interplay of accommodation (space available for sediments to fill) and sedimentation*. Such sedimentary responses and depositional trends can be analyzed from the scale of individual depositional systems to the scale of entire sedimentary basins.