Sequence Stratigraphy as a "Concrete" Stratigraphic Discipline

Report of the ISSC Task Group on Sequence Stratigraphy

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Abstract

Sequence stratigraphy is a stratigraphic discipline in which stratigraphic surfaces that represent changes in depositional trend are used for correlation and for defining specific types of sequence stratigraphic units. On the basis of both empirical observations and theoretical models, numerous different types of surfaces have been proposed as unit boundaries in sequence stratigraphy. Our systematic evaluation of these proposals has revealed that only four surfaces are appropriate for bounding units in sequence stratigraphy. These are a subaerial unconformity, an unconformable shoreline ravinement, a maximum regressive surface and a maximum flooding surface. Proposed surfaces that are not suitable to act as a sequence stratigraphic unit boundary include hypothetical time surfaces at the start and end base level fall (the basal surface of forced regression and the correlative conformity), highly diachronous sequence stratigraphic surfaces (normal shoreline ravinement, regressive surface of marine erosion) and highly diachronous within-trend facies boundaries (base of turbidites or shallow water strata, marine flooding surfaces).

A sequence is the main unit of sequence stratigraphy and it is defined in a generic fashion as a unit bounded by a specific type of unconformity and its correlative surfaces. Two distinct types of sequences have been recognized. A depositional sequence has a subaerial unconformity as its primary unconformity and an unconformable shoreline ravinement and a maximum regressive surface as the correlative surfaces. An R-T sequence has maximum flooding surfaces as its boundaries. Both of these sequence types can be divided into two systems tracts, a transgressive systems tract and a regressive systems tract. Proposed systems tracts, which require unrecognizable time surfaces or highly diachronous surfaces as part of their boundaries, are not scientifically valid and should be avoided. These include entities such as lowstand, highstand and forced regressive systems tracts. Highly interpretive terms such as lowstand, highstand and forced regressive can be used as descriptive adjectives for specific facies interpreted to be deposited during a specific interval of a base level cycle (e.g. a forced regressive sandstone,).

Twenty specific recommendations are put forward to guide sequence stratigraphic methods and terminology. These include recommendations on the appropriate surfaces to use for the boundaries of various sequence stratigraphic units, on how best to create a sequence hierarchy and on the question of whether or not to formalize sequence stratigraphic units. The application of empirically-based methods and terms and the avoidance of theoretically-based concepts with no empirical support allow sequence stratigraphy to become a concrete stratigraphic discipline on a par with lithostratigraphy, biostratigraphy, magnetostratigraphy and chemostratigraphy.

Introduction

During the last 30 years sequence stratigraphy has been discussed in dozens of books and thousands of scientific papers. It also has become the most commonly used stratigraphic discipline for developing a correlation framework within a sedimentary basin because of the low costs associated with such an analysis as well as its applicability in many cases to a well log and seismic data base in addition to cores and outcrop (Embry, 2002). Despite such popularity, considerable confusion and various misconceptions are associated with the methods and terminology (e.g. unit definition) for sequence stratigraphy. Furthermore, sequence stratigraphy has never been addressed by either the International Subcommission on Stratigraphic Classification (ISSC) in their International Stratigraphic Guide or the North American Commission on Stratigraphic Nomenclature (NACSN) in their Stratigraphic Code, and this has contributed to the lack of any standardization in methodology and terminology.

To improve this situation, ISSC, under the direction of Dr Maria Cita, appointed a task group to review the sequence stratigraphic literature and to make recommendations regarding practical and scientifically valid methods and terminology for sequence stratigraphy. These recommendations, following vetting by ISSC members and the stratigraphic community at large, would then form the basis for describing sequence stratigraphy as a specific, “concrete” stratigraphic discipline in the forthcoming, revised edition of the International Stratigraphic Guide (ISG). A “concrete” stratigraphic discipline is one in which the recognized surfaces in that discipline, which are used for correlation and bounding specific unit types, can be defined and delineated on the basis of observable physical features. The established concrete stratigraphies, which were described in the second and last edition of the ISG, include lithostratigraphy, biostratigraphy, magnetostratigraphy and chemostratigraphy. These “concrete” stratigraphies contrast with chronostratigraphy which is a “highly interpretive” stratigraphic discipline. In chronostratigraphy, the unit boundaries, which are time surfaces, are extremely interpretative, bordering on speculative, because they are not based on observable physical features.

This document is the initial report of the ISSC Task Group on Sequence Stratigraphy and it provides numerous recommendations for the methods and terminology of sequence stratigraphy. These recommendations will bring sequence stratigraphy on a par with the aforementioned, concrete stratigraphic disciplines. These recommendations rest on a foundation of a few basic principles which govern the well-established, stratigraphic disciplines. As will be demonstrated, past attempts to develop methods and terminology for sequence stratigraphy have not honored these principles (e.g. Posamentier et al, 1988; Van Wagoner et al, 1990; Emery and Meyers, 1996; Posamentier and Allen, 1999; Coe et al, 2003; Catuneanu, 2006) because they were formulated primarily on the foundation of a deductive model rather than on empirical observations. This approach has led to a number of problems which continue to negatively affect the understanding and application of sequence stratigraphy and to prevent it from taking its place along side the other concrete, stratigraphic disciplines.

Stratigraphy primarily deals with the study of layered rocks (strata) that obey Steno’s Law of Superposition. It includes recognizing and interpreting the physical, biological and chemical properties of strata and, on the basis of these properties, defining a variety of stratigraphic surfaces and units for correlation, mapping and communication purposes.

As Hedberg (1959, p.674) put it “ Stratigraphic classification involves firstly the analysis of strata with respect to the distribution of any selected property or attribute and secondly, the grouping of strata into unit bodies, …each bounded by variations in the presence or development of this property or attribute”. Each specific stratigraphic discipline focuses on a specific property of the strata for the definition, description and interpretation of various units and surfaces in that discipline. For example lithostratigraphy focuses on the lithology of the strata and each lithologic unit is characterized by a specific lithology or combination of lithologies. Boundaries of lithologic units are drawn at recognizable changes in lithology just as biostratigraphic boundaries are drawn at changes in fossil content. Sequence stratigraphy differs somewhat from the other widely accepted stratigraphic disciplines in that the units are defined mainly by specific sequence stratigraphic surfaces and individual sequence stratigraphic units often do not have any specific and characteristic properties *per se*. The recognizable property change of strata that allows sequence stratigraphic surfaces to be defined and delineated and provides the rationale for sequence stratigraphy being a distinct stratigraphic discipline is a change in depositional trend (Embry, 2002). Examples of changes in depositional trend include the change from sedimentation to erosion and/or starvation and vice-versa, as well as the change from a regressive trend to a transgressive one and vice-versa.

It is also worth noting that changes in stratal properties are due to various phenomena which occur on our planet. For example, surfaces in biostratigraphy represent changes in fossil content that are due mainly to a combination of evolution and shifting environments of deposition. In this context, sequence stratigraphic surfaces represent changes in depositional trend that are generated by the interaction of sedimentation with changes in base level (Embry, 2002). Given this, sequence stratigraphy can be defined as “The recognition and correlation of stratigraphic surfaces which represent changes in depositional trends in the rock record. Such changes, which are the product of the interplay of sedimentation, erosion and shifting base level, are now recognized by sedimentological criteria and geometric relationships”. The various sequence stratigraphic surfaces that are recognized can be used in two main ways:

1) For constructing an approximate chronostratigraphic, correlation framework to facilitate facies analysis and related endeavours.
2) For defining individual sequence stratigraphic units such as sequences and systems tracts for mapping and communication purposes.

We will be concentrating on the second use of sequence stratigraphy, that is, the definition of stratigraphic surfaces and units within the discipline. Embry (in press) provides a review of the use of sequence stratigraphic surfaces in correlation. In this article we will first draw attention to the two, very different scientific approaches that have been used in sequence stratigraphy over its entire development. We then review the history of the development of sequence stratigraphy as a specific stratigraphic discipline. Following this, we will describe various sequence stratigraphic surfaces which have been defined and evaluate each one for its usefulness for correlation and unit definition. This naturally leads to a discussion of the different types of sequence stratigraphic units which have been recognized. Each of these will be evaluated for its scientific validity and its practical value. We also discuss how a hierarchy of units can be established and briefly review the pros and cons of formalizing sequence stratigraphic units. Following this we present some real world examples of our preferred methods and terminology for sequence stratigraphic analysis of strata in different depositional settings. The article concludes with a list of 20 specific recommendations that will allow sequence stratigraphy to become a concrete stratigraphic discipline, free from a dominance of abstract concepts and invisible surfaces.

Two Approaches to Sequence Stratigraphy

Before discussing the historical development of sequence stratigraphy, it is important to briefly look at the two very different approaches that have been used to define surfaces and units in sequence stratigraphy from the time of its inception to the present day. This will allow the various proposals for sequence nomenclature to be better understood and to be placed in context. Miall (2004, p.4) drew attention to the two approaches which he called inductive and deductive. He commented that, in regards to sequence stratigraphy, “two distinct intellectual approaches resulted in the development of two conflicting and competing paradigms which are currently vying for the attention of practicing earth scientists”. Miall and Miall (2004, p. 28) in a companion paper point out that the two approaches “affect the collection and interpretation of observations in that field”. As will be demonstrated, these two approaches have led to two different sets of stratigraphic surfaces and consequent units for sequence stratigraphy and have even resulted in two different hierarchical schemes. Most of the current confusion, misconceptions and miscommunication in sequence stratigraphy can be traced back to these two different approaches and their different methods and terminology for sequence stratigraphy. The other stratigraphic disciplines have not had these problems mainly because the units in each were established, for the most part, using only a rigorous, data-driven, inductive approach and were not burdened by a model-driven, deductive approach. It is worthwhile to remember that biostratigraphy was already a well developed stratigraphic discipline long before the concept of evolution was put forward.

The inductive or data-driven approach emphasizes empirical scientific observations and, for sequence stratigraphy, such observations concern the recognition of distinct stratigraphic surfaces that represent a change in deposition trend. Notably, such surfaces were recognized in the stratigraphic record long before sequence stratigraphy was proposed and the current deductive models of sequence stratigraphy were generated (Donovan, in press). These empirical surfaces include a subaerial unconformity, a shoreline ravinement, a maximum flooding surface and a maximum regressive surface. The names for these empirically recognized surfaces have changed during the years but the characteristic properties, which allow their recognition and interpretation of their origin, have not. An overriding principle followed in this article is that only surfaces which can be empirically delineated and correlated with relatively objective, scientific data are useful for defining sequence stratigraphic units. This follows one of the dictums of the NACSN Code which states “Emphasis is placed on the relative objectivity and reproducibility of data in defining units in each category” (NACSN, 2005). If sequence stratigraphy is to join the other well-established, stratigraphic disciplines in the ISSC

Guide and NACSN Code, it must adhere to this principle and avoid the use of theoretically-generated, but empirically unrecognizable, surfaces.

The deductive or model-driven approach involves the generation of a sequence stratigraphic model based on various *a priori* input parameters such as rates of sediment supply and base level change. The model then yields a result which predicts the occurrence of various sequence stratigraphic surfaces and units. As noted by Miall (2004), those who follow such a model-driven approach tend to ignore data which doesn’t fit the model or, at best, to “shoehorn” collected data into the model. The model remains inviolate regardless of subsequent empirical observations.

When it comes to models, our approach is to formulate an inductive model based on empirical observations and to be constantly refining such a model as more data are collected. In this regard, it is most important that the input parameters such as the nature of base level changes be as actualistic as possible. Deductions from such an inductive model can be very useful for guiding observations, for making reasonable interpretations of observed entities and for maximizing the predictive power of sequence stratigraphy.

Throughout the historical summary, we will refer each major contribution to sequence stratigraphy to one of the two approaches. When we discuss the various surfaces and units of sequence stratigraphy, we will assign the origin of each to either a data-driven approach or a model-driven approach. In this way, it will become clear how such a unit or surface was defined and what support there is for its use in sequence stratigraphy. We must record that all of us have enjoyed many field seasons and have measured countless stratigraphic sections. Thus we are strong empiricists. Our approach to sequence stratigraphy is one that is driven by our personal observations and those of others as well as by our attempts to observe and correlate various surfaces which have been defined through both the data-driven and the model-driven approaches.

The Historical Development of Sequence Stratigraphy

The Early Years

Sequence stratigraphy began almost 60 years ago when Sloss et al (1949) coined the term sequence for a stratigraphic unit bounded by large-magnitude, regional unconformities which spanned most of North America. Krumbein and Sloss (1951, p. 380-381) elaborated on the concept of a sequence which they characterized as a "major tectonic cycle". It was not until the early 1960s that Sloss (1963) fully developed the concept and named six sequences which occurred throughout North America. Sloss recognized the major unconformities that bounded the sequences through empirical science and he inductively interpreted that they were generated by repeated episodes of continent-wide, tectonic uplift.

Thus, from the start, unconformities were the critical stratigraphic surfaces in the discipline. An unconformity is defined as a stratigraphic surface across which there is a significant gap in the stratigraphic record (Salvador, 1994) and, as mentioned above, it represents a change in depositional trend from deposition to non-deposition and back again to deposition. The unconformities which Sloss (1963) employed as unit boundaries would now be classified as either subaerial unconformities or unconformable shoreline ravinements and were created almost entirely by subaerial erosion. Thus the significant gap in the stratigraphic record represented by each of Sloss' unconformities is due to a combination of removal of previously deposited strata and the lack of any deposition during the time of erosion.

Unconformities can also be created by submarine erosion and by non-deposition alone. An unconformity as a specific stratigraphic surface was first described by James Hutton in the late 1700s during the birth of modern geological practice. Barrell (1917) was perhaps the first person to clearly describe how subaerial unconformities are generated by base level fall and he proposed a deductive model of cycles of base level rise and fall to produce repeated unconformities in the stratigraphic record. Notably, he also defined a diastem which, in contrast to an unconformity, is a stratigraphic surface which represents an insignificant gap in the stratigraphic record.

After Sloss et al (1949) gave us the concept of a sequence, Harry Wheeler published a series of papers (Wheeler and Murray, 1957; Wheeler 1958, 1959, 1964a, b) which used deduction and model building to provide a theoretical foundation for the development of unconformities and consequent sequences. The main parameters in Wheeler's model, like that of Barrell (1917) were sediment supply on a background of rising and falling base level (base level transit cycles). Wheeler (1958, 1959) provided real-world examples of unconformity-bounded sequences to support his model. In most cases, the recognized unconformities were of smaller magnitude than the continent-wide unconformities of Sloss (1963) and many of the unconformities of Wheeler (1958, 1959) disappeared in a basinward direction. As illustrated by Wheeler (1958, Fig. 3), where one of the bounding unconformities disappeared, that specific sequence was no longer recognizable. Thus to Wheeler (1958), a sequence was an "unconformity-only" bounded unit.

In summary, by the mid 1960s, sequence stratigraphy was characterized by two separate approaches, one of data-driven empiricism as exemplified by the work of Sloss (1963) and the other of model-driven deduction as used by Wheeler (1958). Notably, both approaches came to a similar place, that of a sequence being a unit bounded by subaerial unconformities generated by base level fall (tectonic uplift or eustatic fall). Such harmony between the two approaches, unfortunately, did not last.

"Unconformity Only"-Bounded Units

As discussed above, all the elements of a new stratigraphic discipline were established by Sloss (1963 and Wheeler (1958), but sequence stratigraphy stalled in the mid 1960s. It lay in limbo for most of the 1960s and 1970s as process sedimentology and facies analysis dominated sedimentary geology. The main reasons for this seem to be: 1) The restriction of the definition of a sequence to a unit which was bound by unconformities meant that most sequences occurred only on the flanks of a basin and 2) Sequence stratigraphy was subject to nomenclatural chaos as unconformities appeared and disappeared along depositional strike and basinward and new sequences had to be recognized at every place this happened (Fig. 1).

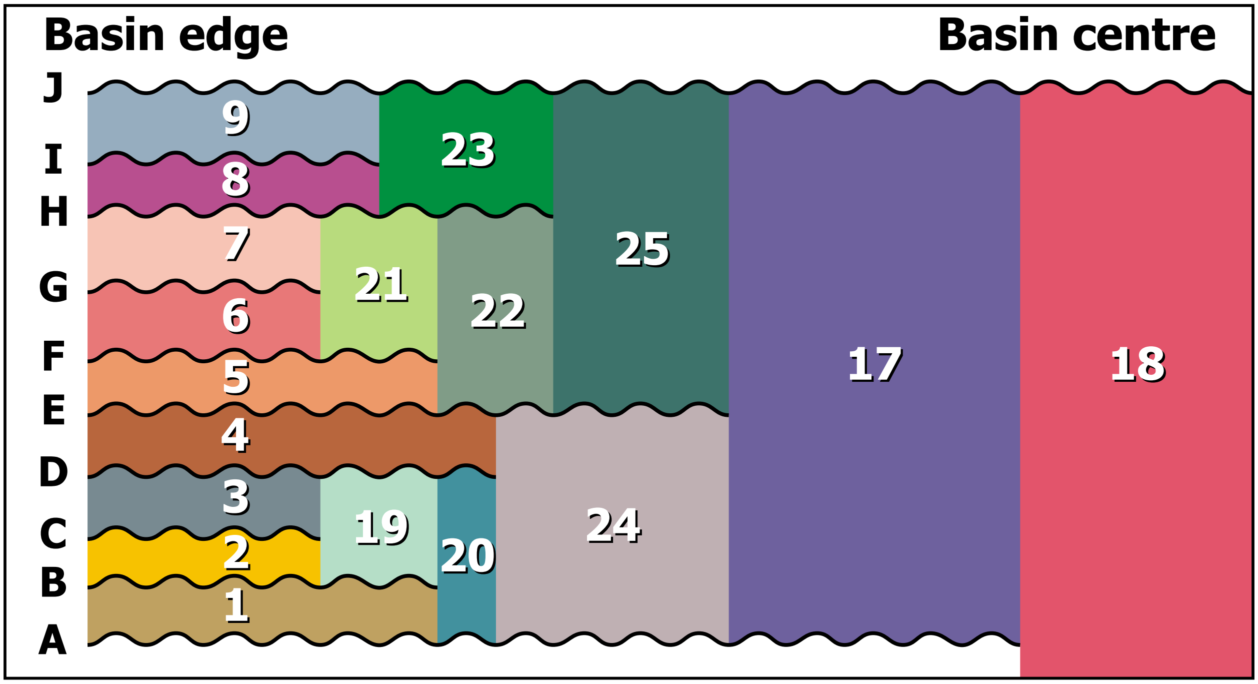


Fig. 1 The occurrence of 10 unconformities on the basin margin allows 10 "unconformity-only" sequences to be defined. Because each unconformity extends a different distance into the basin, a new series of "unconformity-only" sequences has to be defined each time an unconformity disappears. Such a chaotic nomenclatural system ensured that "unconformity-only" sequences were not widely adopted.

Both ISSC and NACSN have included a category of stratigraphic units bounded by unconformities in their respective Guide and Code. A chapter on unconformity-bounded units was included in the 1994 edition of the International Stratigraphic Guide (Salvador, 1994). Based on Chang's (1975) work, the name "synthem" was recommended for such a unit despite the fact that such units were exactly the same as the sequence of Sloss (1963) and Wheeler (1958) (i.e. an unconformity-only bounded unit of regional extent). The 1983 and 2005 editions of the North American Stratigraphic Code (NACSN, 1983, 2005) discussed nearly identical units under a category termed "allostratigraphy" and the main unit was called the alloformation.

The use of unconformity-only bounded units in stratigraphic analysis has been minimal during the past 50 years and the nomenclatural recommendations of ISSC and NACSN for such units have been almost completely ignored by the stratigraphic community. The reasons for this lack of utilization of "unconformity-only" bounded units are, once again, the restricted occurrence of such units and the nomenclatural problems that accompany them. Fortunately, as will be described, sequence stratigraphy can readily accommodate such units within its methods and terminology and can avoid the problems that have previously discouraged the adoption of "unconformity-only"- bounded units.

Revitalization with Seismic Data

Sequence stratigraphy entered the mainstream of stratigraphic practice in 1977 with the publication of AAPG Memoir 26 on Seismic Stratigraphy (Payton, 1977). Seismic stratigraphy is in actuality sequence stratigraphy with seismic data and perhaps is better referred to as seismic sequence stratigraphy (Embry et al, in press). In the 1977 watershed publication, Peter Vail and his colleagues from Exxon demonstrated, through the use of seismic sections, that the sedimentary record consists of a series of units that are partially bound by unconformities (Vail et al, 1977). Such units were termed "depositional sequences" following Sloss' work. Of critical importance, the Exxon researchers modified the definition of a sequence from a unit bounded by unconformities to one "bounded by unconformities or their correlative conformities" (Mitchum et al, 1977). This change was precipitated by the fact that on the seismic sections the reflectors that encompassed unconformities on the basin flanks could be continued into the conformable succession in more central areas of the basin. Thus, on a seismic section, a sequence bounding reflector could be correlated over most of a basin and this led to the concept that a sequence boundary could also be correlated over all or most of a basin. The new definition allowed the stratigraphic succession of a given basin to be subdivided into a series of sequences, each of which could be recognized over most or all of a basin. The problems that had prevented the acceptance of the unconformity-only bounded sequences of Sloss (1963) and Wheeler (1958) were thus resolved (Fig. 2) and new life was breathed into sequence stratigraphy. Overall, the Exxon seismic data clearly demonstrated that sequence boundaries are key correlation horizons and that sequences are the most practical units to use for stratigraphic subdivision if one wants to describe and interpret the depositional history of a stratigraphic succession.

Because of the poor vertical resolution of the seismic data of the time (20-30 metres for a single reflector), the seismic data were not adequate in many cases to resolve the necessary details to confidently identify the specific types of stratigraphic surfaces which were generating the reflectors that were designated as sequence boundaries on seismic sections. There was little doubt that one or more types of unconformity formed sequence boundaries on the basin flanks but it was not clear what type of stratigraphic surfaces formed the “correlative conformity” portion of the boundaries farther basinward. The correlative conformities were portrayed as a time surface equivalent to the start of base level rise on their sequence stratigraphic model which was inductively derived from the seismic data (Mitchum et al, 1977, Fig 1b). Furthermore it is worth noting that a seismically recognized, submarine unconformity, termed a downlap surface, was also included as part of the sequence boundary in their model (Fig. 3) (Mitchum et al, 1977, Fig 1a).

The use of conceptual time surfaces as part of the sequence boundary led to sequence stratigraphy being equated with chronostratigraphy (Vail et al, 1977). As will be subsequently described, this interpreted equivalence of sequence stratigraphy with chronostratigraphy has led to a number of misconceptions and problems associated with

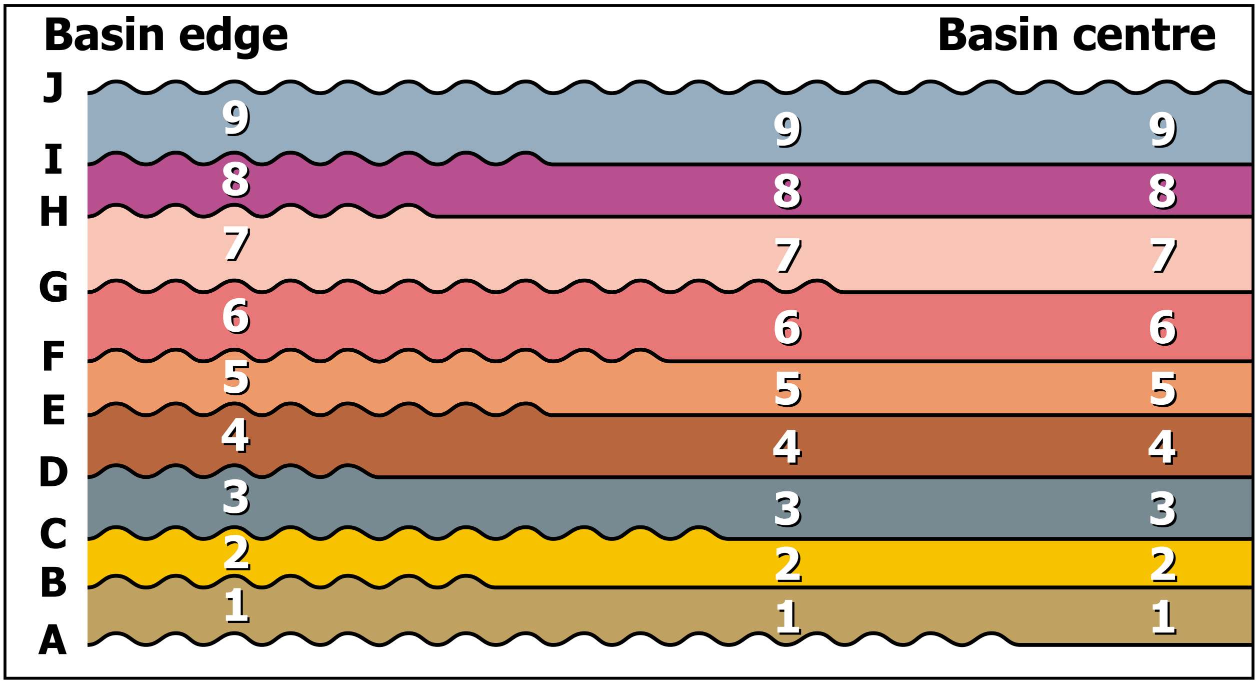


Fig. 2 The same 10 unconformities as shown on Fig 1 are present on the basin flank and the same 9 depositional sequences are delineated. With Mitchum et al's (1977) addition of the "correlative conformity" to the definition of a sequence boundary, the same 9 sequences can be extended over the entire basin. This resolved the nomenclatural nightmare of "unconformity-only" sequences.

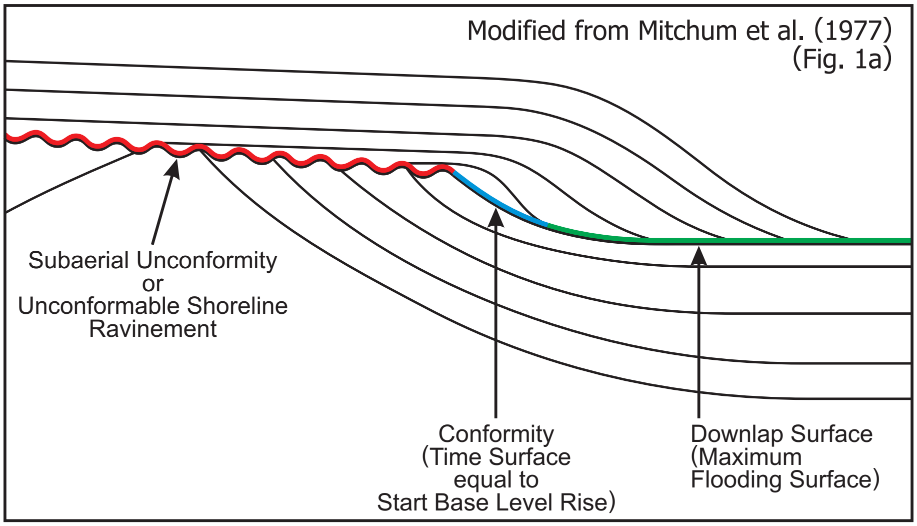


Fig. 3 A sequence boundary as interpreted by Mitchum et al (1977). The downlap surface (MFS) was interpreted to be the main correlative surface of the basin flank unconformity in basinward localities. Such an interpretation, which was based on low resolution seismic data, had been earlier shown to be in error by Frazier (1974) from studies of Pleistocene strata. It was eventually discarded by Exxon scientists.

boundary recognition and unit definition in sequence stratigraphy. It has also perhaps been the biggest factor in preventing sequence stratigraphy from being seen as a separate, reasonably objective, stratigraphic discipline on a par with lithostratigraphy and biostratigraphy. As discussed by Embry et al (in press), there is no doubt that a sequence stratigraphic analysis can contribute significantly to a chronostratigraphic interpretation but it is essential to keep these two very different types of stratigraphy separate.

Overall, the advances in sequence stratigraphy achieved by Vail et al (1977) were based on empirical seismic data and were the product of the inductive approach. Unfortunately the low vertical resolution of the seismic data resulted in a sequence stratigraphic model which was poorly constrained in terms of the types of actual stratigraphic surfaces which formed the sequence boundary. Furthermore, the low resolution led the Exxon scientists to correlate a subaerial unconformity to a submarine downlap surface, a stratigraphic relationship which had earlier been shown to be untenable by another Exxon scientist, Dave Frazier, in his seminal 1974 publication. Frazier (1974) clearly demonstrated on the basis of detailed stratigraphic sections from the Pleistocene of the USA Gulf Coast that subaerial unconformities and downlap surfaces (which he termed hiatal surfaces) do not join but rather they interleave on the basin margins. This fundamental error in the 1977 Exxon sequence boundary model, which was a consequence of the low vertical resolution of seismic data, was eventually corrected without any discussion of such an error (Vail et. al., 1984; Posamentier and Vail, 1988).

Model-Driven Sequence Stratigraphy

Vail et al (1977) took the liberty of interpreting that the base level changes that generated the multitude of sequence boundaries they recognized on seismic data in many parts of the world were due to eustatic sea level changes. Despite the lack of support by empirical data, this speculative interpretation subsequently formed the basis of a deductive model that has dominated sequence stratigraphy to the present day. This influential deductive model was developed by Mac Jervey of Exxon in 1979 and was published in the next watershed publication on sequence stratigraphy, SEPM Special Publication 42 (Jervey, 1988). The model used sinusoidal sea level change, hinged subsidence, which increased basinward, and a constant sediment supply as its *a priori* input parameters. Notably it predicted the occurrence of stacked, basin flank unconformities and basin central, downlap surfaces, the two main surfaces which had been interpreted from the seismic sections. Importantly the model had these surfaces interleaving rather than joining, just as Frazier (1974) had empirically determined years earlier. Van Wagoner et al (1988), Posamentier et al (1988) and Posamentier and Vail (1988) adopted the Jervey Model to provide the theoretical underpinning for sequence stratigraphy. Using the model in conjunction with low resolution seismic data, they deduced theoretical stratigraphic relationships for a sequence and these deductions formed the basis for their sequence stratigraphic models and their terminology for sequence stratigraphy.

Two different types of sequence boundaries were deduced by Exxon scientists (Van Wagoner et al, 1988; Posamentier et al, 1988). Their Type 1 sequence boundary incorporated a subaerial unconformity as the sequence boundary on the basin flank. For the correlative conformity they used a conceptual time surface representing the sea floor just after the start of base level fall. This time surface was interpreted to follow the base of deep water turbidite deposits which were thought to have been deposited during base level fall and exposure of the shelf. Such a sequence boundary was generated when sea level fell below the shelf edge (e.g. Fig. 2 in Posamentier and Vail, 1988). A Type 1 sequence was subdivided into three component units termed systems tracts and these were each bounded by sequence stratigraphic surfaces determined by the model (Fig 4).

The lowest systems tract is the lowstand systems tract (LST) and it was bound by the sequence boundary (time surface, base turbidites) below and the “transgressive surface” above. The transgressive surface marked the change from a regressive trend below to a transgressive one above. The middle systems tract is the transgressive systems tract (TST) and it is bounded by the transgressive surface below and the maximum flooding surface above. The maximum flooding surface marked the change from a transgressive trend below to a regressive one above and had been previously referred to as the downlap surface on seismic sections. Thus, in this revised sequence stratigraphic model, the Exxon scientists now had the subaerial unconformity separated from the downlap surface

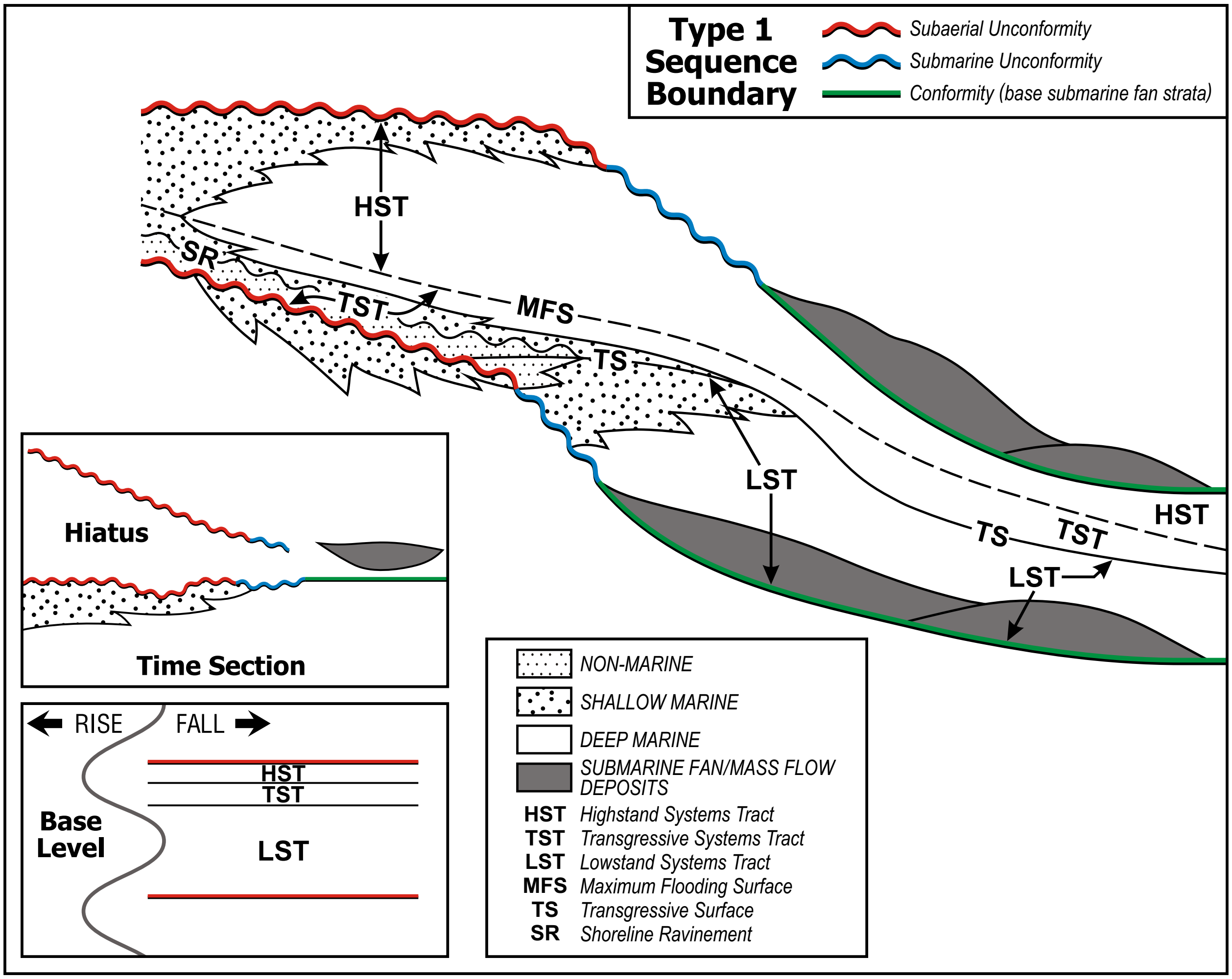


Fig. 4 A "Type 1" sequence boundary of Posamentier et al (1988). This composite boundary included a subaerial unconformity on the basin flanks and was extended along a submarine erosion surface and finally along the base of turbidite deposits. As discussed in the text, such a boundary is theoretically impossible because the basinward termination of the subaerial unconformity occurs at end base level fall whereas the interpreted basinward surface develops near the start of base level fall (see inset).

Three systems tracts, LST, TST and HST were proposed.

(maximum flooding surface) by the TST. The uppermost systems tract is the highstand systems tract (HST) and it is bound by the MFS below and the sequence boundary above.

Van Wagoner et al (1988) applied exactly the same terminology to siliciclastic sediments deposited in a ramp setting (see their Fig. 3). In this case the sequence boundary was extended basinward from the termination of the unconformity along the facies contact between shallow water sandstones above and deeper marine shales below. The inappropriateness of such a boundary will be discussed subsequently.

The Type 2 sequence boundary of Van Wagoner et al (1988) and Posamentier and Vail (1988) was generated when sea level did not fall below the shelf edge during base level fall. In this case the subaerial unconformity was again used as the sequence boundary on the basin flanks and a completely different correlative conformity was used for this boundary type - the time surface equal to the start of base level rise (Fig. 6 in Posamentier and Vail, 1988) (Fig. 5**).** This contrasted sharply with the time surface just after the start of fall which was used for the correlative conformity portion of a Type 1 boundary.

A Type 2 sequence was also divided into three systems tracts with the TST being defined as it was in a Type 1 sequence. Instead of an LST, the basal systems tract in a Type 2 sequence was termed a shelf margin systems tract (SMST). Whereas the LST of a Type 1 sequence represented almost all regressive strata deposited during base level fall and early rise, the SMST of a Type 2 sequence represented only regressive strata deposited during early rise. Regressive strata formed during base level fall were put into the HST in this sequence type, making the HST of a Type 2 sequence a very different unit than the HST of a Type 1 sequence. The significant differences between a Type 1 and a Type 2 sequence boundary/sequence of Posamentier and Vail (1988) (Fig. 4, 5) have not been understood or appreciated by many subsequent workers up to the present day (e.g. Catuneanu, 2006). Inexplicably, Posamentier and Allen (1999) claimed that the two boundary types are equivalent. Such a statement is clearly wrong given the completely different correlative conformities used to define the two boundary types in the first place,

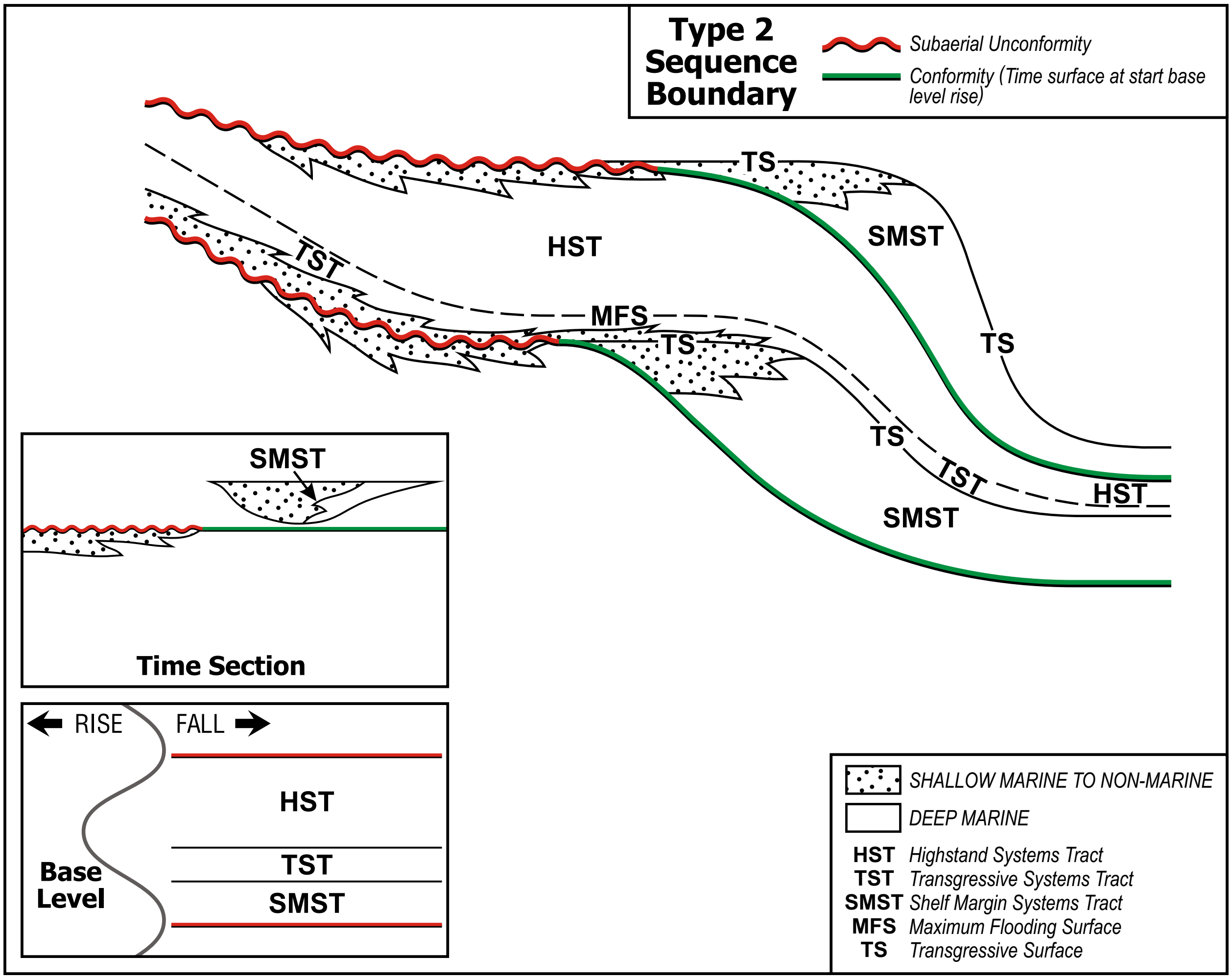


Fig. 5 A "Type 2" sequence boundary of Posamentier et al (1988). This composite boundary included the subaerial unconformity on the basin flank and a non-descript surface which represented the start of base level rise farther basinward. The main problem with this type of sequence boundary is the lack of objective criteria for recognizing the correlative "start of base level rise" surface.
Three systems tracts, SMST, TST and HST were proposed. To add to the confusion, the HST of a Type 2 sequence was different for the HST of a Type 1 sequence (see text).

the significant differences between an LST and a SMST, and the two different types of HSTs.

By 1990, sequence stratigraphy had advanced to the point where three distinct sequence stratigraphic surfaces, the subaerial unconformity, transgressive surface and maximum flooding surface, had been defined and, along with conceptual time surfaces, were used as the boundaries of a sequence and its component systems tracts. Unfortunately, the Exxon 1988 deductive sequence stratigraphic models contained some inconsistencies and non-actualistic aspects and these resulted in some difficulties in the application of the model to real-world successions. The biggest problem involved the Type 1 sequence model and it centred on the illogical nature of the Type 1 boundary. As mentioned above, the Type 1 boundary had a subaerial unconformity joining the time surface representing the sea floor just after the start of fall. Because the subaerial unconformity reaches its maximum basinward extent at the **end** of base level fall, it is impossible for it to join with the time surface just after the **start** of fall. Thus, although the 1988 Type 1 sequence boundary model corrected the untenable stratigraphic relationship (subaerial unconformity joining the MFS) of the 1977 Exxon sequence boundary model, it introduced a new, untenable relationship for both a shelf/basin and ramp settings. Because many workers are still not aware of the flawed nature of the 1988 model, the continued application of such a theoretically impossible boundary concept (e.g. Wynn and Reid, 2006) keeps causing problems and confusion, not to mention many illogical interpretations.

Hunt and Tucker (1992) recognized the fundamental error in the 1988 Exxon Type1 sequence boundary, which in effect placed strata deposited during base level fall below the sequence boundary on the basin flanks and above it in more basinward localities. To rectify this major flaw they suggested that the conformable portion of a sequence boundary for all sequence types be placed at the time surface that represented the start of base level rise. In theory, such a time surface, and not the one at or near the start of fall, should indeed merge with the basinward termination of the unconformity. Thus, although they apparently didn’t realize it, Hunt and Tucker (1992) were saying that the Type 2 sequence boundary of Van Wagoner et al (1988) and Posamentier and Vail (1988) is the only valid sequence boundary. Hunt and Tucker (1992) added a fourth and uppermost systems tract to the model and called it the forced regressive wedge systems tract (FRWST). It was defined as being bound by the “basal surface of forced regression” (equals the time surface at start base level fall) below and the sequence boundary (in part equal to the time surface at the start of base level rise) above. This new system tract encompassed all the strata deposited during base level fall. The LST of Hunt and Tucker (1992) was restricted to the strata between the time surface at the start of rise and the transgressive surface and thus is equivalent to the SMST of the 1988 Exxon Type 2 model. This four system tract model for a sequence (Fig.6**)** was elaborated on by Helland-Hansen and Gjelberg (1994) who ably demonstrated the theoretical logic of such a scheme. Notably, neither Hunt and Tucker (1992) nor Helland-Hansen and Gjelberg (1994) provided any examples of how such a theoretical scheme could be applied in the real world

Posamentier and Allen (1999) also recognized that the 1988 Type 1 boundary was theoretically impossible but they took a different approach than Hunt and Tucker (1992) to try to fix the problem. They proposed using the time surface at the start of fall as the correlative conformity but, instead of joining it to the end of the subaerial unconformity as was done in 1988, they properly illustrated that the time surface at the start of fall joined the unconformity well landward of its basinward termination (Fig. 2.31 in Posamentier and Allen, 1999). They also correctly showed that such a time surface was offset by the regressive surface of marine erosion and a short stretch of that surface was also included as part of the sequence boundary **(Fig. 7**). The use of such a sequence boundary resulted in much of the subaerial unconformity lying within the sequence rather than on its boundary, a relationship which violates the definition of a sequence. Because of this, such a proposal creates more problems than it solves as will be discussed later.

The end result of the model-driven exercises of the 80s and 90s was that two different ways of packaging a deductive sequence and its component systems tracts were being advocated. One used a portion of a subaerial unconformity on the basin flank and the

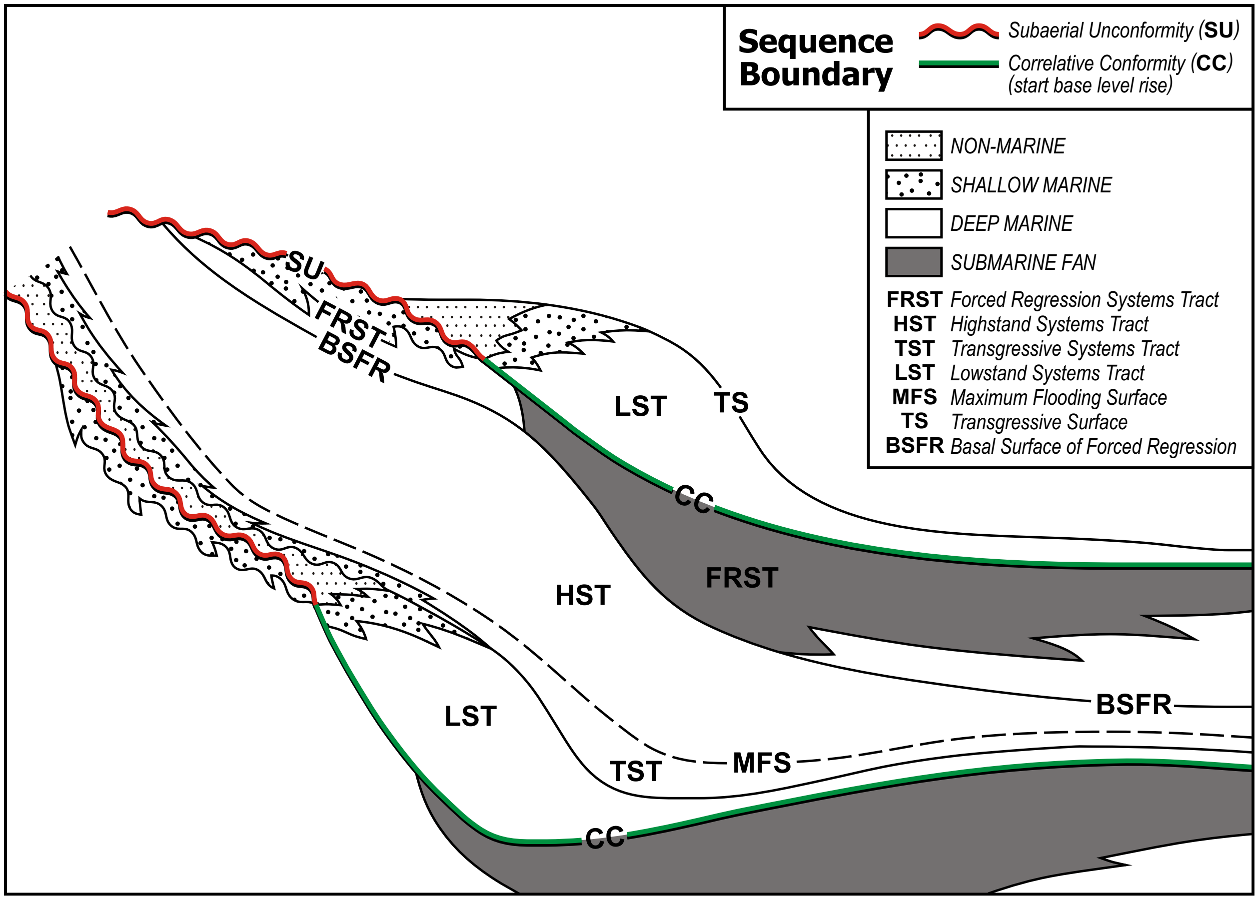


Fig. 6 The sequence model as proposed by Hunt and Tucker (1992). The sequence boundaries are exactly the same as those of the Type 2 sequence of Posamentier et al (1988) (subaerial unconformity and time surface equal to the start of base level rise (CC)). As opposed to Posamentier et al (1988), they advocated applying it to all physiographic settings.

This boundary suffers from the same serious problem as that of the Type 2 boundary the lack of objective criteria for recognizing the start of base level rise (CC) surface.

Hunt and Tucker proposed four systems tracts, LST, TST, HST and FRST.

time surface at the start of base level fall for the correlative conformity (Jervey, 1992, Posamentier and Allen, 1999). Such a sequence was divided into three systems tracts (LST, TST and HST) (Fig. 7). The other sequence model used the entire subaerial unconformity and the time surface at the start of base level rise (Hunt and Tucker, 1992; Plint and Nummedal, 2000) for its boundary. As previously described, this sequence model had four systems tracts (LST, TST, HST, FRST) (Fig.6). These two models basically represent a revised Type 1 model and a revised Type 2 model although few workers actually recognize this clear correspondence.

An added source of confusion with the model of Hunt and Tucker (1992) is that the forced regressive systems tract (FRST) is also referred to as falling stage systems tract (FSST) (Nummedal et al, 1993; Plint and Nummedal, 2000). Making a bad situation worse, this systems tract was later called the regressive systems tract by Naish and Kamp (1997). The Naish and Kamp (1997) proposal is a fine example of thoughtless nomenclature because, not only were there already two different names for the exact same unit, the term regressive systems tract was already in use for an entirely different type of sequence unit (Embry and Johannessen, 1992). Fortunately, the doubly problematic nomenclature of Naish and Kamp (1997) has been ignored by most workers.

Given these two distinctly different ways of delineating the boundaries for sequences and systems tracts through model-driven sequence stratigraphy, it is not surprising there was, and continues to be, considerable confusion and miscommunication in sequence stratigraphy. However, the occurrence of two overlapping but different ways of defining a sequence and its component systems tracts was not the only problem for the model-driven approach. As discussed below, model-driven methods and terminology suffer from a far more serious problem – the impossibility of being able to recognize some of the proposed, model-driven, bounding surfaces in an objective, scientific fashion. This critical problem is discussed in detail when the surfaces of sequence stratigraphy are described and evaluated and the different options for defining a sequence boundary are examined.

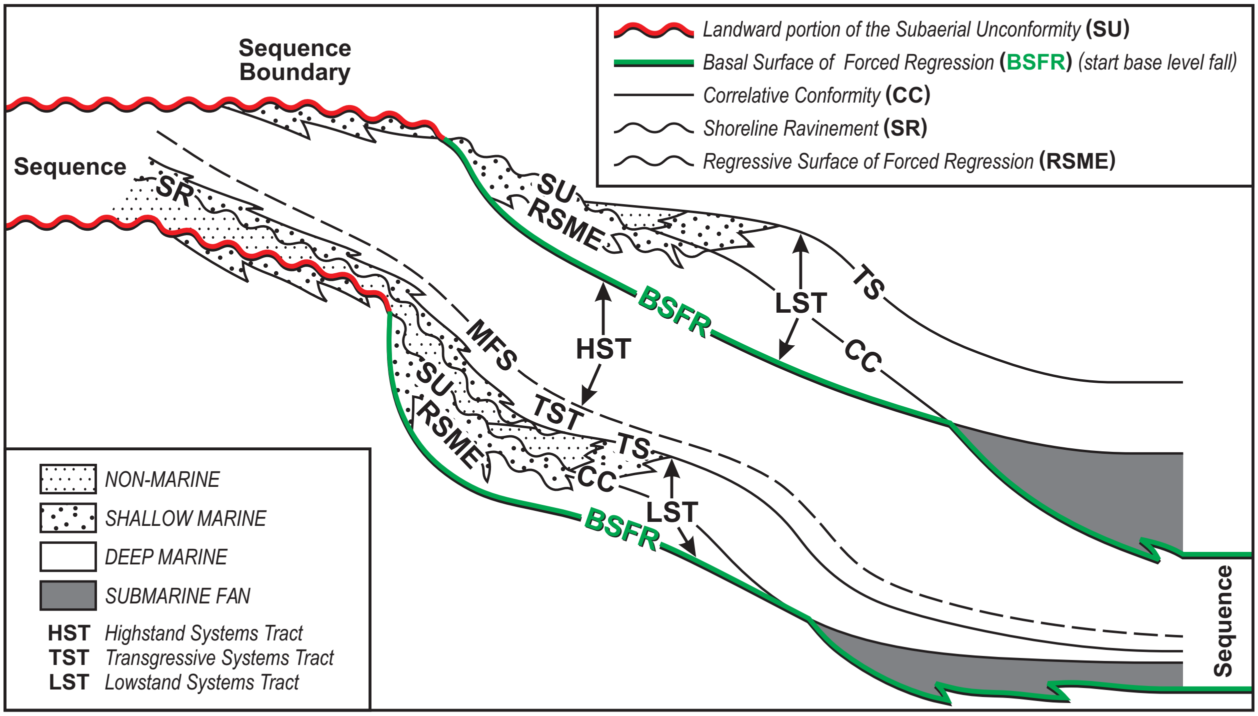


Fig. 7 The revised Type 1 sequence model of Posamentier and Allen (1999). To correct the "impossible boundary" of the 1988 Type 1 sequence model, Posamentier and Allen (1999) proposed the surface at the start of base level fall, which had been named the basal surface of forced regression (BSFR) by Hunt and Tucker (1992), be used as the conformable portion of a sequence boundary. This proposed boundary founders on the lack of any criteria for recognizing a "BSFR" and the inclusion of much of the subaerial unconformity within the sequence.

Empirical Sequence Stratigraphy

During the time the model-driven, sequence packaging schemes were being debated and revised, two other sequence models were proposed. Importantly, both of these were based on empirical data rather than on theoretical deductions, and thus they represented attempts to define sequences and systems tracts with a data-driven, inductive approach. Galloway (1989) proposed that a sequence be bound by maximum flooding surfaces ("downlap surfaces") and he named such a unit a genetic stratigraphic sequence (Fig. 8a). This methodology was based on Galloway's comprehensive subsurface work on the Tertiary strata of the Gulf of Mexico and built on the observations and interpretations of Frazier (1974). Frazier (1974) named a unit bounded by maximum flooding surfaces (calling them hiatal surfaces) a depositional complex.

The other inductive sequence model proposed at this time was the T-R sequence (Embry and Johannessen, 1992, Embry, 1993) and it was based on extensive fieldwork and subsurface analysis of the 9 km thick Mesozoic succession of the Sverdrup Basin of Arctic Canada. It had both similarities and differences with model-driven sequence stratigraphy. The T-R sequence used either a subaerial unconformity or an unconformable shoreline ravinement as the unconformable portion of the sequence boundary on the basin flank. This latter type of unconformity, which was not taken into account in the deductive models, developed during transgression and removed much or all of the subaerial unconformity which had formed during the preceding base level fall. Farther basinward, a surface, which marked the depositional change from coarsening upward to fining upward and which was interpreted to represent the change from regression to transgression, was employed as the correlative conformity portion of the boundary (Fig. 8b). This surface had been called the transgressive surface in model-driven sequence stratigraphy, but because the transgressive surface also included the shoreline ravinement, the name maximum regressive surface, first proposed by Helland-Hansen and Gjelberg (1994), is now commonly used for it (Embry, 2002; Catuneanu, 2006). Because the only sequence stratigraphic surface that could be empirically recognized within a T-R sequence was the maximum flooding surface, Embry and Johannessen (1992) subdivided the T-R sequence into two systems tracts: a transgressive

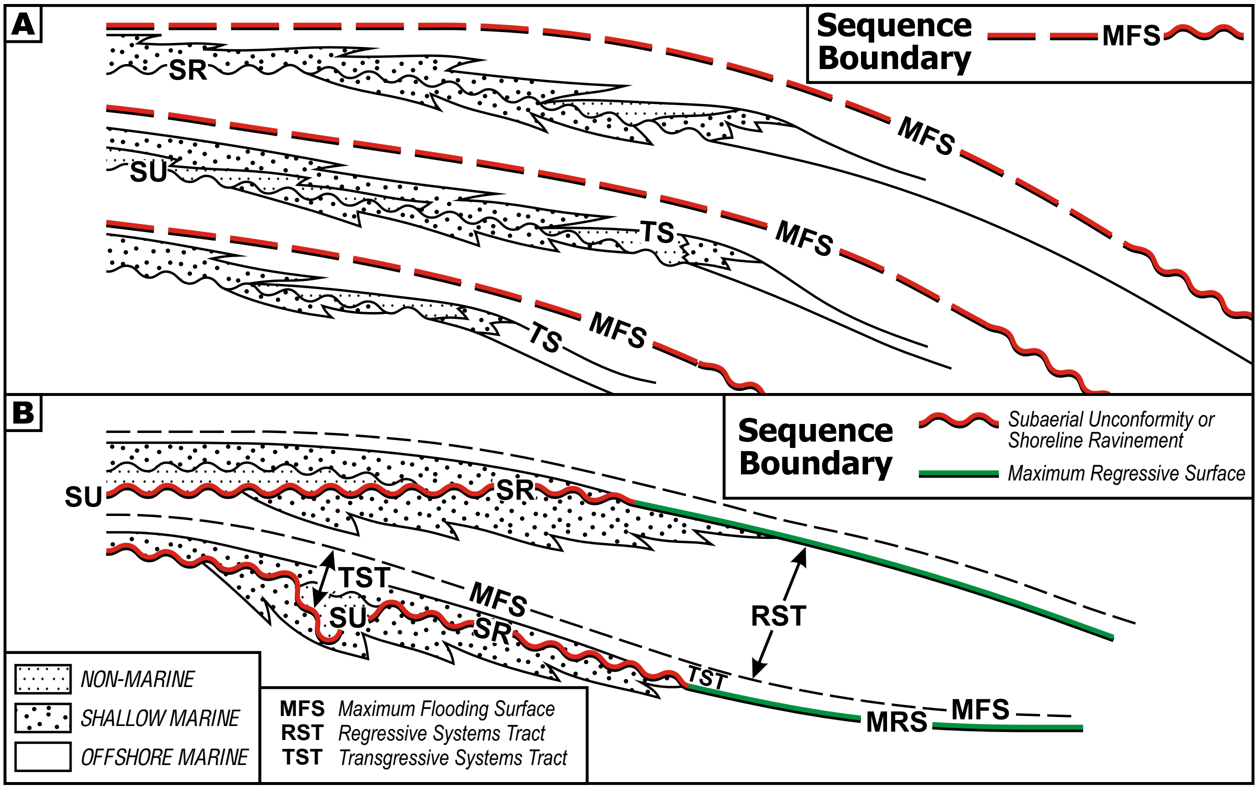


Fig. 8 The empirical sequence models.

A. The genetic stratigraphic sequence of Galloway (1989) used maximum flooding surfaces (MFS) for its boundaries. The one drawback of such a model was the inclusion of a subaerial unconformity within the sequence on the basin flanks.

B. The T-R sequence of Embry and Johannessen (1992) used the subaerial unconformity and the unconformable shoreline ravinement as the unconformable portion of the boundary and the maximum regressive surface (MRS) as the basinward, conformable extension of the boundary.

Two systems tracts, TST and RST, were proposed.

systems tract (TST) bounded by the sequence boundary below and the MFS above and a regressive systems tract (RST) bound by the MFS below and the sequence boundary above (Fig. 8b).

Carbonate Sequence Stratigraphy

The main concepts of sequence stratigraphy, which primarily concern the delineation and correlation of stratigraphic surfaces formed through the interaction of variations in sediment supply with base level change, were developed on the basis of either models (e.g. Posamentier et al, 1988) or empirical observations (e.g. Galloway, 1989) involving siliciclastic depositional systems. Given this, and the fact that, in comparison to siliciclastics systems, carbonate sedimentary systems react much differently to changes in base level (Schlager, 1991), it is reasonable to ask if siliciclastic-derived, sequence stratigraphic concepts can also be applied to carbonate strata.

The basic question is, “Are the sequence stratigraphic surfaces which are generated in siliciclastic strata during changes in base level also generated in a carbonate depositional regime?” The answer to the above question is an emphatic yes as has been demonstrated by a multitude of articles on carbonate sequence stratigraphy. Thus, the same sequence stratigraphic surfaces are used to define specific types of sequence stratigraphic units and to build a quasi-chronostratigraphic correlation framework in both carbonates and siliciclastics. There is no doubt the geometries of the various sequence stratigraphic units developed in carbonates differ substantially from their counterparts in siliciclastics due to the different responses of the two sediment types to base level changes. However, such geometrical differences have no bearing on the question of whether the basic concepts of sequence stratigraphy are equally applicable to both sediment types.

The evolution of sequence stratigraphic methods and terminology, as applied to carbonates, proceeded in tandem with that of siliciclastics. The same model-driven and data-driven approaches have been applied and the same spectrum of different sequence boundary types and system tract schemes is in the literature. All the comments regarding the history of sequence stratigraphy and the problems which have developed apply to carbonates just as well as they do to siliciclastics. Schlager (2005) provides a useful review of the evolving application of sequence stratigraphy to carbonate strata since 1977.

What tends to set carbonate sequence stratigraphy apart is the distinct nature of some of the sequence stratigraphic surfaces. Carbonate sediments, like siliciclastics, are deposited in both ramp and platform//basin settings. The sequence stratigraphic surfaces which are developed in a carbonate ramp setting have similar characteristics to those developed in siliciclastics strata (Schlager, 2005). However, because of the major differences in the response of carbonate sedimentation to base level changes as compared to siliciclastics, sequence stratigraphic surfaces developed in a carbonate platform/basin setting have somewhat different attributes than those of siliciclastics. For example, a maximum regressive surface in a siliciclastic setting (high sediment supply during late stage base level fall) has very different attributes than a maximum regressive surface in a carbonate platform/basin setting (minimal sediment supply during late stage base level fall). Consequently, when the surfaces are described in a following section, the attributes of each are discussed for both carbonate and siliciclastic settings.

Summary

There are currently four very different approaches to sequence analysis in siliciclastic and carbonate strata, two based on the deductive Jervey Model and two based on empirical data. Not surprisingly there is considerable ongoing debate concerning which ones are scientifically valid and of practical value and which are not (e.g. Embry, 2002; Catuneanu, 2006). In the sections below, we describe all the various types of surfaces that have been proposed by both the inductive and deductive approaches and evaluate each for its suitability to be used as a bounding surface for the units of sequence stratigraphy, sequences and systems tracts.

Sequence Stratigraphic Surfaces

Because sequence stratigraphy depends on specific types of stratigraphic surfaces for the definition of units rather than on characteristic properties of the units themselves, the most critical aspect of any attempt to develop methods and terminology for the discipline is the clear definition of useful and valid sequence-stratigraphic surfaces. This allows each surface to be empirically recognized in well exposed stratigraphic sections (or core) on the basis of its characteristic properties and those of the strata below and above the surface. Over the last two decades a number of sequence-stratigraphic surfaces have been described and named using either an inductive or deductive approach. Notably, during this time a specific type of surface has sometimes been given a number of different names and different types of surfaces have been given the same name. In this section we discuss each proposed surface, evaluate its potential worth in sequence stratigraphy and recommend a name for each one.

In order for sequence stratigraphy to be a valid and distinct stratigraphic discipline, any acceptable sequence stratigraphic surface used for unit boundaries and building a correlation framework must meet the following criteria:

1) The surface must represent a change in depositional trend and thus be a surface of sequence stratigraphy.
2) The surface must have various defining properties (i.e. physical features) which allow it to be recognized with reasonable objectivity in core or well-exposed strata and over a reasonable geographic extent so as to allow correlation to other sections and the establishment of mappable units.
3) The surface must either be of low diachroniety or be an approximate time barrier to allow it to be used as part of a quasi-chronostratigraphic framework for facies analysis and paleogeographic reconstruction (Embry et al, in press).
4) The surface must be developed in both siliciclastic and carbonate depositional regimes, in both ramp and shelf/slope/basin settings, and in strata of all ages. Furthermore it must be recognizable in deformed stratigraphic successions as well as undeformed ones so that sequence stratigraphy has widespread applicability.
5) The surface must be recognizable with an empirical approach so that sequence stratigraphy is on a par with the other established stratigraphic disciplines. The

surface should also have solid theoretical support to maximize its use in interpretation and prediction.

Any sequence stratigraphic surface which meets these criteria clearly can be confidently employed as a potential unit boundary and as a stand-alone correlation horizon. Proposed surfaces that do not meet these criteria need to be revised such that they do meet the criteria or they should not be used in sequence stratigraphy for unit delineation and correlation. Each surface which has been proposed for use is discussed separately below and its characteristics are summarized on Figure 9.

Subaerial Unconformity (SU)

A very important sequence stratigraphic surface is the subaerial unconformity, which was the surface used to empirically define a sequence in the first place (Sloss et al, 1949). It was first recognized through an inductive approach over 200 years ago. It represents a change from deposition to non-deposition and manifests itself as an abrupt, erosional and/or weathered contact (Fig. 9). Any type of strata or rock can underlie such a surface. In siliciclastic settings it is often found at the base of a channel scour or associated with a well developed paleosol. In carbonates a karst surface or calcrete most often represents a subaerial unconformity. An important characteristic of a subaerial unconformity is that non-marine strata overlie the surface. When marine strata overlie strata that had been formerly exposed and eroded, the surface marking the contact is not a subaerial unconformity because that surface was previously eroded with the passage of marine waters over it. Most often such a surface is a shoreline ravinement although maximum flooding surfaces and even regressive surfaces of marine erosion can erode through and thus replace a subaerial unconformity as the surface marking a major gap in the succession. Because sediments rarely accumulate above sea level in carbonate depositional systems, subaerial unconformities are rarely preserved in carbonate strata. This is discussed in more detail in the section on a shoreline ravinement. Shanmugan (1988) and Catuneanu (2006) have elaborated on the physical characteristics of a subaerial unconformity.

A subaerial unconformity represents a significant gap in the stratigraphic record as determined by its relationship to overlying (onlapping) and underlying (truncated) rocks. As discussed by Barrell (1917), it is interpreted to be formed during base level fall by subaerial erosional processes especially those connected to fluvial or chemical erosion. In regards to its relation to time surfaces, it is an approximate time barrier and time surfaces, for the most part, do not pass through it. In other words, almost all strata below the surface are older than almost all those above. There are definitely exceptions to this and these can be associated with migrating uplifts (Winker, 2002). Also, a small amount fluvial strata overlying an SU may have been deposited during base level fall (Suter et al, 1987; Galloway and Sylvia, 2002; Blum and Aslan, 2006) and is thus older than some of the down-dip strata below the unconformity).

As will be discussed below, a surface with all the above characteristics but with marine strata above is best classed as an unconformable shoreline ravinement rather than a subaerial unconformity. Importantly, the formation of a subaerial unconformity was deduced in the Wheeler (1958) and Jervey (1988) models and it expands basinward during base level fall. A subaerial unconformity meets all the criteria for a useful surface in sequence stratigraphy. Although the surface has been given other names besides subaerial unconformity such as lowstand unconformity (Schlager, 1992), regressive surface of fluvial erosion (Plint and Nummedal, 2000) and fluvial entrenchment/incision surface (Galloway and Sylvia, 2002), the term subaerial unconformity has the widest acceptance and is the best one to use for this surface.

Regressive Surface of Marine Erosion (RSME)

This surface was first empirically recognized and named by Plint (1988). It is a sharp, scoured surface which separates underlying offshore marine strata that coarsen and shallow upwards from overlying shoreface strata that also coarsen and shallow upwards (Fig. 9). Thus it lies within an overall regressive succession but can be considered as a change in depositional trend from deposition to non-deposition. It most cases erosion beneath the RSME is minor and localized and thus it can usually be considered a diastem rather than an unconformity. However the potential for more substantial erosion exists and in some situations it may be considered an unconformity (Bradshaw and Nelson, 2004; Cantalamessa and Celma, 2004). The RSME has very similar characteristics in carbonate strata with very shallow, high energy strata abruptly overlying much finer, lower energy deposits. Pomar (1993) and Wendte (1994) describe and illustrate an RSME in carbonate strata.

Plint (1988) interpreted the surface to be formed by scouring of the lowermost shoreface and adjacent inner shelf by waves and currents during a time of base level fall and such a surface is also part of the proposed deductive models (e.g. Catuneanu, 2006). Such scouring occurs due to the regrading of the shelf as it equilibrates with a lower base level. Notably, in many instances it does not form, and thus such a surface may be patchy or not even present in situations where it might be expected to form (Catuneanu, 2006).

As illustrated by Plint (1988), the regressive surface of marine erosion migrates basinward during the entire time of base level fall. It is a highly diachronous surface and time lines pass through it (offset) at a high angle (Embry, 2002; Catuneanu, 2006). Because of this, it is not suitable for use as a bounding surface for sequence stratigraphic units or for being part of a correlation framework. However, it is important to recognize such a surface when it is present and to use it as part of facies analysis inside the established sequence stratigraphic correlation framework. Galloway and Sylvia (2002) referred to this surface as the regressive ravinement surface. The term regressive surface of marine erosion is most commonly used and is adopted herein.

Shoreline Ravinement (SR)

A stratigraphic surface referred to herein as a shoreline ravinement has been empirically recognized for a long time. Excellent descriptions of the surface and its mode of origin were given by Stamp (1921), Bruun (1962), Swift et al (1972) and Swift (1975). One or more such surfaces form during transgression as wave and/or tidal processes erode previously deposited shoreface, beach and non-marine sediment as the shoreline moves landward. The eroded sediment is deposited both landward and seaward of the shoreline. This results in a surface characterized by an abrupt, scoured contact and overlain by

Surface	**Contact**	**Facies Below**	**Facies Above**	**Stratal Terminations**	**Relationship to Time**
Subaerial Unconformity	Scoured to weathered	Highly variable	Nonmarine	Major, regional truncation below and onlap above	Approximate time barrier
Regressive Surface of Marine Erosion	Scoured	Coarsening-upward offshore marine shelf	Coarsening- and shallowing-upward shoreface	Minor, local truncation below and downlap above	Highly diachronous
Unconformable Shoreline Ravinement	Scoured	Variable. Most commonly coarsening-upward marine shelf	Fining- and deepening-upward shallow marine shelf	Major, regional truncation below and onlap above	Time barrier
Normal Shoreline Ravinement	Scoured	Nonmarine	Fining- and deepening-upward marine shelf	Minor, local truncation below and onlap above	Highly diachronous
Maximum Regressive Surface	Conformable to scoured	Marine – Coarsening- and usually shallowing-upward. Nonmarine – increasing sandstone/ shale ratio.	Marine – Fining- and often deepening-upward. Nonmarine – decreasing sandstone/shale ratio.	Usually conformable. Rare truncation	Low diachroniety
Maximum Flooding Surface	Conformable to scoured	Marine – fining- and often deepening-upward. Nonmarine – decreasing sandstone/ shale ratio.	Marine – coarsening- and often shallowing-upward. Nonmarine – increasing sandstone/shale ratio.	Truncation or conformable below and downlap above	Low diachroniety
Basal Surface of Forced Regression	Abstract surface with no diagnostic attributes				Collection of time surfaces
Correlative Conformity	Abstract surface with no diagnostic attributes				Time surface
Within Trend Facies Contact	Lithostratigraphic Surface				Highly diachronous

Fig. 9 A summary of the characteristics of the proposed surfaces of sequence stratigraphy.

estuarine or marine strata which fine and deepen upwards. It thus represents a change in trend from deposition to non-deposition and can vary from being a minor diastem to a major unconformity.

When both tidal and wave processes are acting in a given area both a tidal shoreline ravinement and a wave shoreline ravinement can form (Dalrymple et al, 1994; Catuneanu, 2006). Because transgression usually occurs during an extended period of time, such shoreline ravinement surfaces are diachronous with time lines passing through them (offset) at a high angle (Embry, 2002). In such a case the shoreline ravinement is best regarded as a diastem which only minor time loss at any one locality. Given this high diachroniety and the diastemic nature, a shoreline ravinement would not be expected to be useful for bounding a sequence stratigraphic unit (Fig 10). However, in many cases a shoreline ravinement cuts down through the underlying subaerial unconformity which developed during the previous phase of base level fall (Suter et al, 1987). Where a tidal or wave shoreline ravinement has removed a subaerial unconformity it becomes an unconformity itself and is an approximate time barrier with most strata below being older than most strata above (Fig 10). In this case, the shoreline ravinement has all the qualities necessary to act as a bounding surface in sequence stratigraphy.

Following Embry (2002, in press), we refer to a shoreline ravinement which has not eroded through a subaerial unconformity as a normal shoreline ravinement. Such a surface is a sharp, scoured contact, is underlain by non-marine strata and is overlain by estuarine or marine strata that deepen upward (Fig. 9, 10). Importantly it only locally truncates the underlying strata and does not represent an unconformity. A shoreline ravinement that does erode through a subaerial unconformity is called an unconformable shoreline ravinement. It is similar to a normal shoreline ravinement in that it is a scoured contact which is overlain by deepening upward, estuarine or marine strata. Important differences are the underlying strata are, in most cases, marine rather than non-marine strata and the strata below are regionally truncated with the surface representing a significant gap in the succession (Fig 10). Many major unconformities in the stratigraphic

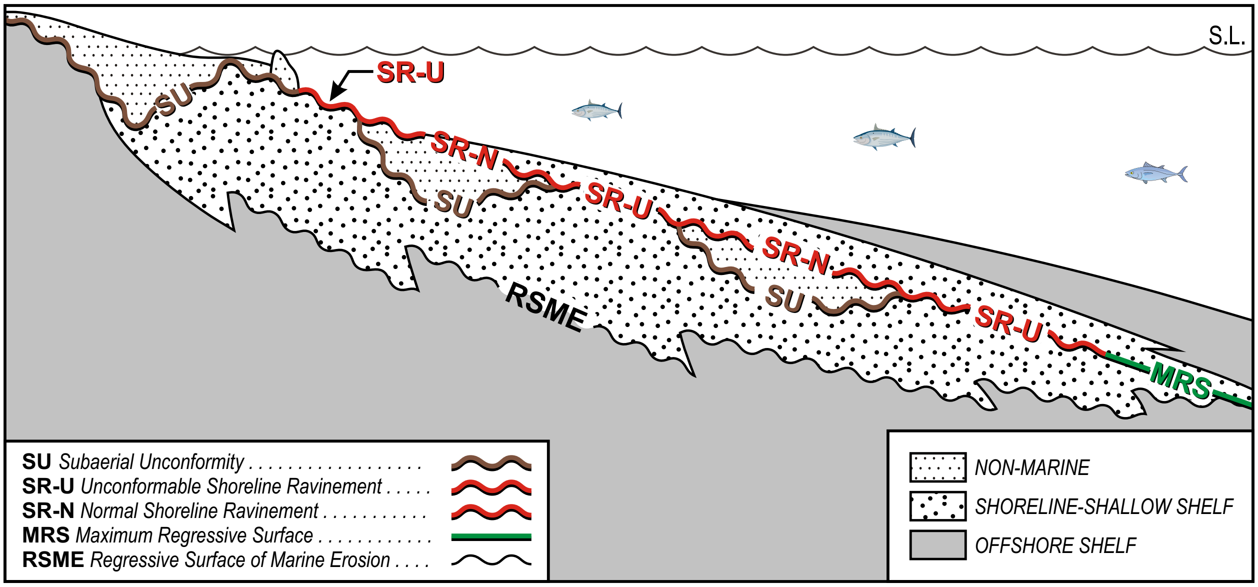


Fig. 10 The two different time relationships of a shoreline ravinement surface. A single shoreline ravinement surface is a highly diachronous surface (SR-N) when it has not eroded the underlying subaerial unconformity. However, when it has eroded the underlying subaerial unconformity, it is a time barrier (SU) with all strata below being older than all strata above. An SR-U is often used as part of a sequence boundary.

record, including some of those used by Sloss (1963) to define his major sequences, are unconformable shoreline ravinements rather than subaerial unconformities.

Most of the stratigraphic gap represented by an unconformable shoreline ravinement is formed during the time when a now-eroded subaerial unconformity developed. However the surface now remaining in the stratigraphic record is the unconformable shoreline ravinement and not a subaerial unconformity and it should be recognized as such. In carbonate rocks, a subaerial unconformity which develops during an episode of base level fall is not often preserved, in part because little sediment is deposited above high tide. The shoreline ravinement which develops during the following base level rise usually removes any thin veneer of supratidal sediment and erodes the subaerial unconformity such that marine strata occur on both sides of the surface. Admittedly, because carbonate strata tend to be cemented very early, especially in situations of exposure, such shoreline erosion during transgression may be extremely minor. However, for consistency and clarity, we use the term unconformable shoreline ravinement rather than subaerial unconformity in situations where marine carbonate strata overlie such an unconformable surface.

This distinctive surface has been given a variety of names including ravinement surface (Swift, 1975), transgressive ravinement surface (Galloway, 2001), transgressive surface (Van Wagoner et al, 1988), transgressive surface of erosion (Posamentier and Allen, 1999) and shoreface ravinement (Embry, 2002). We prefer to use the term shoreline ravinement for this very distinctive surface with the proviso that modifiers such as tidal and wave can be added to it. We would emphasize it is most important to add the modifier normal or unconformable to any stretch of shoreline ravinement surface to differentiate between the two very different relationships to time (highly diachronous or approximate time barrier) that exist for a given shoreline ravinement (Fig. 10).

Maximum Regressive Surface (MRS)

The maximum regressive surface has been recognized from empirical data for as long as transgressive-regressive cycles have been recorded (at least 150 years) (Donovan, in press). It is one of the more easily recognized sequence surfaces in clastic marine strata where it separates coarsening upward strata from fining upward strata (Fig. 9) (Embry, 2001) and represents a change from a regressive trend to a transgressive one. In such a setting it most often occurs in a conformable succession and simply marks the interpreted change in grain size trend. In shallow water areas, including the shoreline, the surface coincides with a change from a shallowing trend to a deepening trend, and thus detailed facies analysis is useful, and often essential, for its identification in these areas. In some cases the MRS is marked by minor scouring and is best regarded as a diastem. In slope environments the MRS can coincide with a surface of submarine erosion often related to scour beneath turbidite flows. In these cases the MRS is either a diastem or an unconformity. In submarine fan strata it again marks the change in trend from coarsening to fining and can be conformable to diastemic. The MRS sometimes is present in nonmarine clastic strata and is harder to recognize. It is best defined as the change in trend from increasing channel content to decreasing channel content and is approximated by a change from increasing sand content to decreasing sand content (Cross and Lessenger, 1997; Embry, in press).

In shallow water carbonate strata, the MRS is delineated as the horizon which marks a change from a coarsening upward trend which represents a shallowing trend to a fining/deepening one. In deeper water, high subsidence areas, the change from of shallowing to deepening may not coincide with the MRS (Vecsei and Duringer, 2003). In a carbonate ramp setting, the MRS in offshore areas is similar to that developed in siliciclastics and marks the change from coarsening upward to fining upward. In a carbonate platform/basin setting the MRS may be an unconformity related to significant sediment starvation in deep water slope and basin areas. This is due to the very low rate of carbonate sedimentation in the last phase of regression when the carbonate factory becomes areally very restricted (Schlager, 2005). In such unconformable cases, which can occur on the margins of a carbonate bank or reef, it is usually onlapped by transgressive strata.

The MRS is interpreted to form when transgression begins and areas in the marine environment become farther from the main source of sediment (the clastic shoreline or the main carbonate factory) and thus start to receive finer and finer sediments. Over much of the shallow water portion of the basin, such transgression initiates significant deepening and the MRS represents the horizon of shallowest water.

The MRS forms along a shore-perpendicular tract at the time when the shoreline movement changes from seaward (regression) to landward (transgression) due to the rate of base level rise exceeding sediment supply at the shoreline. Finer grainer sediment is then deposited at any given locality along the offshore transect and the MRS is marked by the change from coarsening upward to fining upward. In a shore-perpendicular direction, it is very close to a time line but usually exhibits diachroniety parallel to the shore because of along-strike variations in the rate of sediment supply. Previous analyses of the relationship between the MRS and time relied on a non-actualistic, sinusoidal base level curve and came to the interpretation that such a surface can be quite diachronous (Catuneanu et al, 1998; Catuneanu, 2006). However, when actualistic base level curves are employed (Embry, 2006, in press), it becomes apparent that such regional diachroniety is usually low because of high rates of base level rise soon after the start of rise. Thus time lines usually cross an MRS at a very low angle. This low diachroniety makes the MRS a very useful surface for bounding sequence-stratigraphic units (Embry, 2002; Catuneanu, 2006)

The MRS is laterally equivalent to the shoreline ravinement and it may be difficult to distinguish an MRS from an unconformable shoreline ravinement (SR-U) because both separate coarsening-upward marine strata from fining upward marine strata and both can be scoured contacts. However on the basin flanks the SR-U is an unconformity with truncation below whereas the MRS does not truncate underlying strata in this area of the basin. This surface has been called a variety of names including transgressive surface (Van Wagoner et al, 1988), conformable transgressive surface (Embry, 1993, 1995), maximum progradation surface (Emery and Myers, 1996) and sometimes by the more general term, flooding surface. Because there is considerable confusion associated with the above names, it seems best to use the more descriptive and less ambiguous term, maximum regressive surface, first introduced by Helland-Hansen and Gjelberg (1994) and adopted by Embry (2002) and Catuneanu (2006).

Maximum Flooding Surface (MFS)

Like the maximum regressive surface, the maximum flooding surface has been empirically recognized since transgressive-regressive cycles were delineated (Donovan , in press). Its value for correlating well log sections was recognized by the 1950s and many so called “markers” on published cross sections would be now designated as maximum flooding surfaces (e.g. Forgotson, 1957). Frazier (1974) called such a surface a hiatal surface and Vail et al (1977) called the seismic reflector which encompassed this surface a downlap surface.

In marine siliciclastic strata the surface marks the change in trend from a fining upward below to a coarsening upward above (Embry, 2001) (Fig. 9)**.** In nearshore areas this change in trend coincides with a change from deepening to shallowing. Farther offshore this relationship does not hold and the deepest water horizon lies above the MFS (Catuneanu, 2006).

In nonmarine siliciclastic strata the expression of the MFS is more subtle and interpretative and is drawn at the change from a decreasing fluvial channel content to one of increasing channel content and can be sometimes associated with a change from coarsening to one of fining (Cross and Lessenger, 1997). The MFS in nonmarine strata is sometimes associated with a prominent coal bed or even a nonmarine to brackish water limestone (Catuneanu, 2006**).**

In carbonate strata, the MFS also marks a change in trend from fining to coarsening. Notably in shallow water carbonate bank settings the MFS will mark the horizon of change between deepening upward to shallowing upward and this criterion, which employs facies analysis, can often be more reliable than grain size variation for its delineation in shallow water carbonate strata. In deeper water, carbonate ramp settings, the MFS marks a change from decreasing and/or finer carbonate material to increasing and/or coarser carbonate material. In platform, slope settings the MFS can be very subtle due to the high production of carbonate sediment on the outer platform and its shedding down slope when the shoreline reaches is maximum landward extent.

On the basin flanks the surface is either a minor scour surface (diastem) or conformity. In offshore areas it can be an unconformity that developed mainly due to starvation and minor scouring in both carbonate and clastic regimes. In these offshore areas, the MFS is often associated with condensed strata and in siliciclastics maybe associated with a chemical deposit such as a limestone or ironstone. The relationship to time surfaces is variable. In most cases it is a low diachroniety surface with maximum diachroniety being parallel to depositional strike. In a carbonate platform setting, the MFS can be very diachronous due to highly variable rates of carbonate production over the platform. Where the MFS is an unconformity, it is an approximate time barrier. Because of these relationships to time and its observable characteristics, it is most often a very useful surface for forming the boundary of a sequence stratigraphic unit. This surface has been called a hiatal surface (Frazier, 1974), a downlap surface (Vail et al, 1977; Van Wagoner et al, 1988), maximum transgressive surface (Helland-Hansen and Gjelberg, 1994) and a final transgressive surface (Nummedal et al, 1993). We recommend the name maximum flooding surface which is by far the most commonly used name for this surface.

Basal Surface of Forced Regression (BSFR)

This surface was initially defined as part of a deductive model of sequence stratigraphy proposed by Hunt and Tucker (1992). They defined it (p.5) as “a chronostratigraphic surface separating older sediments…deposited during slowing rates of relative sea level rise… from younger sediments deposited during base-level fall”. Most subsequent authors (e.g. Helland-Hansen and Gjelberg (1994), Plint and Nummedal (2000) and Catuneanu (2006)) have used the BSFR as the time at the start of base level fall at the shoreline and thus the start of forced regression at that locality. This revision was not well conceived because during much or even all of base level fall at the basin edge some stretches of the shoreline will be experiencing base level fall (forced regression) and others will be experiencing base level rise(normal regression). Thus the “start of forced regression” occurs at many different times during an interval of base level fall and the reason for this is that the shoreline along its extent occupies areas with markedly different rates of subsidence. In fact, forced regression may not even occur during some times of base level fall when the subaerial unconformity never extends beyond the coastal plain.

Plint and Nummedal (2000) and Catuneanu (2006) characterize the BSFR as the clinoform representing the start of offlap along a given transect perpendicular to the shoreline. Because offlap (forced regression) will begin at very different times along a shoreline, there will be many such clinoforms developed parallel to depositional strike. Notably such theoretical time surfaces were never recognized or even considered to be present in the stratigraphic record until the Jervey Model was published and thus have no empirical roots.

Unfortunately, it is impossible to recognize “the first clinoform associated with offlap” in almost every conceivable geological setting. Such a time surface has no observable characteristics which allow it to be recognized with any semblance of scientific objectivity. It occurs within a succession of coarsening-upward strata and no sedimentological variation or change in grain size trend, which might mark the surface occurs in the succession (Fig. 11). This lack of objective criteria for the recognition of such a surface over most of the basin has been noted by Posamentier and Allen (1999), Plint and Nummedal (2000) and Catuneanu (2006) among others. Posamentier and Allen (1999, p.90) state “it exists only as a chronohorizon, .. precise identification .. can be limited”. Plint and Nummedal (2000, p. 5) note that such a time surface is “difficult or impossible to recognize in outcrops or well logs”. Catuneanu (2006, p.129) admits “the basal surface of forced regression .. has no physical expression in a conformable succession of shallow water deposits”. Thus it is widely accepted that the BSFR is a theoretical surface (or set of surfaces) which has no physical attributes to allow its objective recognition in well exposed sections or in core.

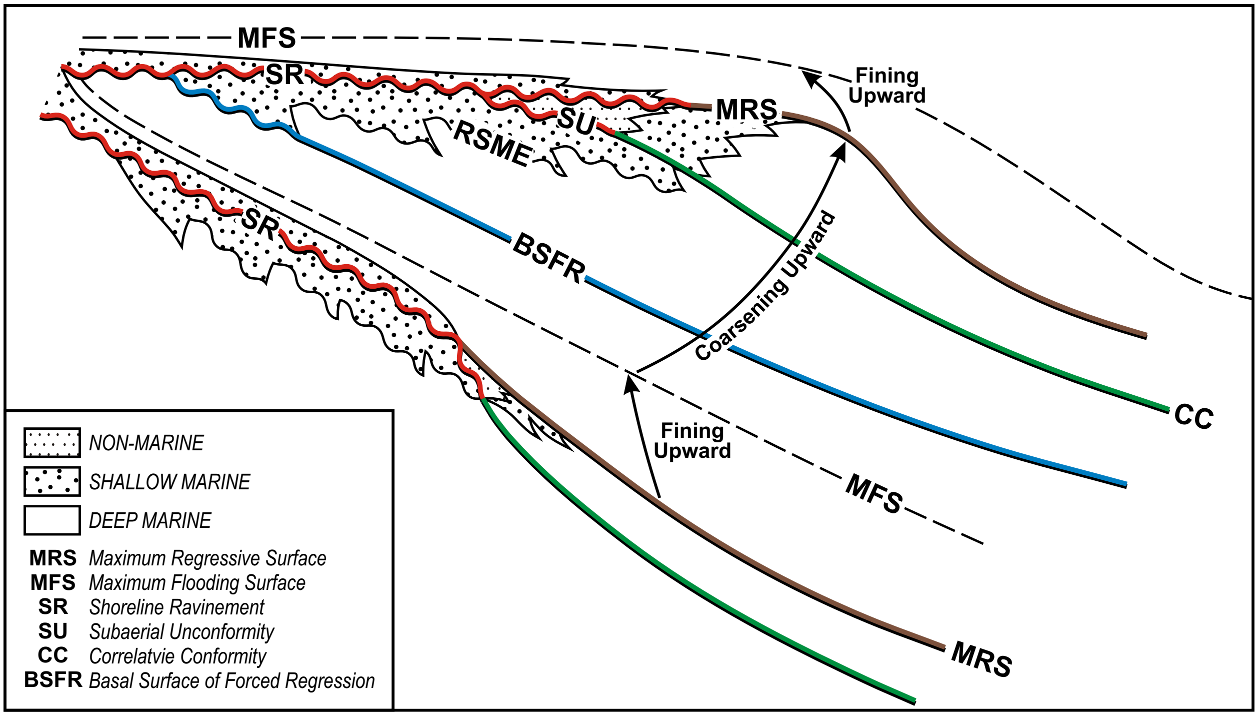


Fig. 11 The maximum regressive surface (MRS) and maximum flooding surface (MFS) are empirical surfaces which represent a change in depositional trend (e.g. from fining to coarsening for the MFS) as shown. These contrast sharply with the hypothetical and unrecognizable basal surface of forced regression (BSFR) and correlative conformity (CC) which are abstract time surfaces. Both the BSFR and CC occur within a coarsening upward trend and are not marked by any physical features. Proposals to use such "invisible surfaces" for unit definition (e.g. a portion of sequence or systems tract boundary) have no credence.

In some cases a lithostratigraphic surface at the base of turbidite strata or shallow water carbonate or clastic strata has been used as a proxy for the BSFR (e.g. Hunt and Tucker, 1992; Plint and Nummedal, 2000; Mellere and Steel, 2000; Coe, 2003; Catuneanu, 2006). However such a proposal has no merit because of the highly diachronous nature of such a contact and a lack of theoretical support for such an approximation. Catuneanu (2006, p.125-126) points out the obvious pitfall in using the base of submarine fan deposits as a proxy for the BSFR by noting that “the arrival of the first gravity flow deposits in the deeper water environment may not necessarily coincide with the start of base level fall but **may in fact happen any time during fall**”. The same logic applies to the misuse of the base of a shallow marine deposit (including a RSME) for the BSFR (e.g Burchette and Wright, 1992).

As discussed above, the BSFR of Plint and Nummedal (2000) and Catuneanu (2006) would be very diachronous because the shoreline occupies areas of greatly varying rates of subsidence. Thus in areas of low subsidence the BSFR would form much earlier (close to the start of base level fall) on the basin margin than in areas of high subsidence (close to the end of base level fall). This significant diachroniety would be avoided using the original definition of Hunt and Tucker (1992). Regardless, given that such a surface is unrecognizable by objective, scientific analysis in either case, the high diachroniety of it is moot.

Because no one has ever presented any defining characteristics for a BSFR, demonstrated how one might delineate such a surface in well exposed outcrops or in core, or illustrated the correlation of such an abstract surface on a regional cross section, we have to conclude it has no value as a bounding surface of a standard sequence-stratigraphic unit at this time.

Correlative Conformity (sensu Hunt and Tucker) (CC)

Another deductive surface which was derived from the Jervey Model for sequence stratigraphy is the correlative conformity as defined by Hunt and Tucker (1992). Like the BSFR, it was never recognized or even considered to exist as a distinct surface before such modelling was done. Helland-Hansen and Gjelberg(1994), Helland-Hansen and Martinsen (1996) and Catuneanu (2006) have elaborated on this surface and advocated its use in sequence stratigraphy. Hunt and Tucker (1992) defined the correlative conformity, which formed part of their sequence boundary, as a chronostratigraphic surface equivalent to the time at the end of base level fall (i.e. start base level rise) (Fig. 11). As noted previously, such a time surface was also used as part of the sequence boundary by Mitchum et al (1977) and Posamentier and Vail (1988). Unfortunately, Hunt and Tucker (1992) did not provide any specific criteria which would allow the recognition of such a deductive time surface except in areas of submarine fan deposition.

In the Jervey Model, the correlative conformity is interpreted to form before transgression begins and the MRS is generated. It represents the sea floor at the moment in time when forced regression related to base level fall gives way to normal regression related to initial slow base level rise dictated by a sinusoidal change in base level. Thus, like the basal surface of forced regression, the correlative conformity also occurs with an overall regressive succession (Fig. 11). Unfortunately, no one has ever published any observable criteria for recognizing the correlative conformity within the regressive succession over most of a basin. This is not surprising given that no change in sedimentation style or trend occurs over much of the marine area at the start of base level rise in the Jervey Model. This is recognized by Catuneanu (2006, p.122) who states “The main problem relates to the difficulty of recognizing it in most outcrop sections, core or wireline logs”. As Catuneanu explains, the correlative conformity “develops within a conformable prograding package (coarsening upward trends below and above); lacking any lithofacies and grading contrasts”. The main problem associated with the correlative conformity is clearly enunciated by Plint and Nummedal (2000, p.5) who succinctly state “From a practical point of view, this marine surface will be difficult to impossible to identify”. We could not agree more.

Hunt and Tucker (1992) suggested that the change from a coarsening upward succession of turbidites to a fining upward succession might approximate such a boundary and this has theoretical support (Catuneanu, 2006). Such a boundary also fits the empirical definition of the maximum regressive surface as discussed above and the apparent coincidence of the theoretical CC and the empirical MRS in deep basinal settings is not unreasonable, as will be discussed in more detail later.

To us, the deductive correlative conformity, although it has theoretical appeal, is not a bona fide sequence-stratigraphic surface because of the lack of any defining characteristics which would allow such a surface to be recognized with any semblance of scientific objectivity (i.e with empirical observations) in most data sets. We thus reject its use as either a potential unit boundary or correlation framework surface in sequence stratigraphy. As will be described later, it appears that the start of base level rise can in many instances be approximated by the MRS and, given this, the CC would be redundant in most cases.

Within-trend Facies Contact (WTFC)

Embry (2001, 2002) introduced the within-trend facies contact and this terminology has been adopted by Catuneanu (2006). This surface is defined as a conformable or diastemic contact between two distinct lithofacies and it occurs within a regressive or transgressive succession. It does not represent a change in depositional trend and thus it is a lithostratigraphic surface and not a sequence stratigraphic one. It forms most commonly as facies prograde and retrograde in response to the interaction of base level changes and sediment supply. In most cases it is a highly diachronous surface and time lines pass through it at a high angle. As discussed by Embry et al (in press), there are a few instances when such a contact has a low diachroniety. The contacts of an ash bed are the classic example of this. The basal boundary of individual turbidite flows and storm deposits can also have low diachroniety. However such specific contacts are of limited areal extent, and, on a regional scale, the base of the first turbidite or storm deposit is highly diachronous. Just as a magnetostratigraphic boundary would not be acceptable as a biostratigraphic boundary, a lithostratigraphic contact is not acceptable as a sequence stratigraphic contact. It is most important that within-trend facies contacts are not used to bound sequence stratigraphic units. Any attempt to do so violates basic stratigraphic principles.

Marine-Flooding Surface

A marine-flooding surface, which is also commonly called a flooding surface, was defined by Van Wagoner et al (1988) as “a surface separating younger from older strata across which there is an abrupt increase in water depth”. This definition does not provide much insight into what a marine-flooding surface actually is and how one would recognize one. All stratigraphic surfaces separate younger from older strata (Law of Superposition) leaving us with “an abrupt increase in water depth” as the only criteria for recognition. Given this is an interpretive feature rather than an observable one, it is not surprising there has been considerable confusion as to the nature of a marine flooding surface. An inspection of various diagrams, which illustrate marine-flooding surfaces (e.g. Figs 3b and 7 in Van Wagoner et al., 1990), reveals that what Van Wagoner et al (1988) meant by a marine-flooding surface is simply a contact between sandstone below and shale above. Going by the illustrations in Van Wagoner et al (1990), such a contact can be gradational (conformable) or scoured (diastem). It is clear that, in many cases, such a surface is a within-trend facies contact which is developed within a transgressive succession (Fig. 12). The use of such a lithostratigraphic contact as a boundary in sequence stratigraphy is wholly inappropriate.

The term has been also used for other types of surfaces including a maximum regressive surface, a maximum flooding surface and a shoreline ravinement and these terms, rather than the term “flooding surface”, should be applied in such cases. Following Catuneanu (2006), we also recommend the term flooding surface not be used in sequence stratigraphy due to its definition as a lithostratigraphic surface and the use of the term for a variety of surfaces which already have established names.

Other Unconformities

The surfaces described above are the ones that have been most commonly used as unit boundaries in sequence stratigraphic studies. Other surfaces which have potential as unit boundaries are marine unconformities that are developed on the shelf and/or slope area. Some of these may coincide with the MFS or MFS, and these terms can be used in such

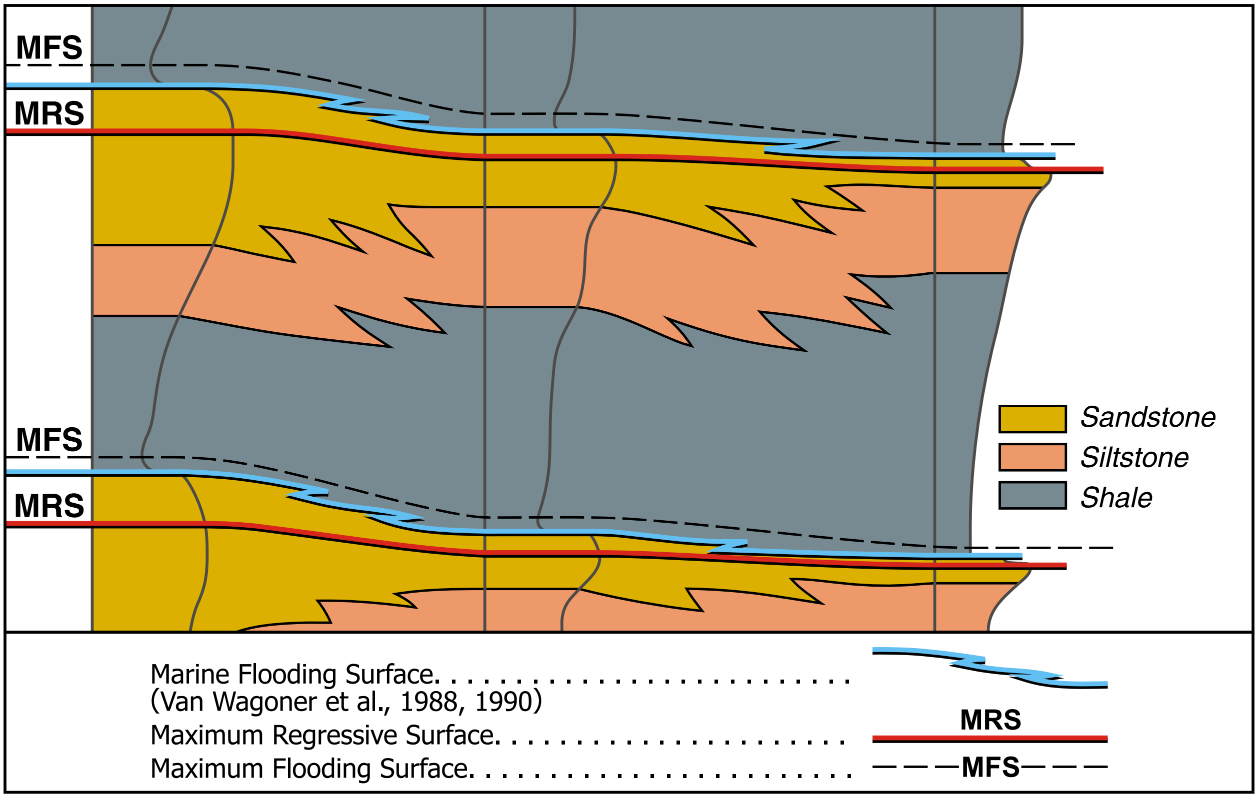


Figure 12 Van Wagoner et al (1988, 1990) defined (indirectly see text) a "marine flooding surface" as an upward, lithologic change from sandstone to shale (blue line). Such a surface is a highly diachronous, within-trend facies change and thus a marine flooding surface is a lithostratigraphic surface rather than a sequence stratigraphic one (e.g. MRS and MFS).

instances. However in cases where submarine unconformities are widely developed and recognizable by objective science, they can be potentially used as unit boundaries in sequence stratigraphy.

One unconformity surface which has recognized in carbonate strata is the “drowning unconformity” and its author suggested it as a Type 3 sequence boundary (Schlager, 1992, 1998). Inspection of the diagrams in Schlager (1992, 1998) reveals that a drowning unconformity is sometimes equivalent to an MFS and sometimes equivalent to an MRS. This redundancy was also noted by Catuneanu (2006) and was mentioned by Schlager (1999). Given the above, we recommend such a term not be used in sequence stratigraphy.

Summary of Surface Evaluation

In the preceding sections eleven different surface types have been described and discussed. It is critical to decide which ones are appropriate for use for defining and bounding various types of sequence stratigraphic units and which ones are not. Once the appropriate ones are identified, then various units of sequence stratigraphy can be defined and named.

Using the criteria at the beginning of this section as a guide, the following empirical surfaces appear to be useful as potential unit boundaries:

1) Subaerial unconformity (empirical, approximate time barrier)
2) Unconformable shoreline ravinement (empirical, approximate time barrier)
3) Maximum regressive surface (empirical, low diachroniety surface)
4) Maximum flooding surface (empirical, low diachroniety surface or approximate time barrier)
5) Offshore marine unconformities (empirical, approximate time barrier)

The following empirical and theoretical surfaces are not appropriate for use in sequence stratigraphic unit definition and as boundaries for one or more reasons.

1) Regressive surface of marine erosion (highly diachronous diastem)

2) Normal shoreline ravinement (highly diachronous diastem)
3) Basal surface of forced regression (Deductive time surface with no defining characteristics, cannot be recognized by empirical analysis and highly diachronous)
4) Correlative conformity (Deductive time surface with no defining characteristics over most of the basin and cannot be recognized by empirical analysis)
5) Within-trend facies contact (Highly diachronous, lithostratigraphic surface)
6) Marine-flooding surface (Highly diachronous, lithostratigraphic surface or covered by other recognized surfaces)

From the above analysis we are left with five different surfaces from which to define various units of sequence stratigraphy.

Sequence Stratigraphic Units

A variety of units have been described for sequence stratigraphy and in this section each one is evaluated in terms of its definition and its validity. The basic premise we have used to assess the validity of a given unit is that its boundaries must be one of the five acceptable surfaces of sequence stratigraphy listed above. Any proposed unit which has an inappropriate boundary, such as a highly diachronous surface or a deductive time surface which cannot be empirically recognized, is rejected for use in sequence stratigraphy. As mentioned earlier, if sequence stratigraphy is to be on par with other established stratigraphic disciplines, its units must be relatively objective with recognizable, reproducible contacts.

The three categories of sequence stratigraphic units so far discussed in the literature over the past 57 years are sequence (Sloss et al, 1949; Mitchum et al, 1977), systems tract (Posamentier et al, 1988) and parasequence (Van Wagoner at al 1988). Each of these units is discussed below and recommendations are made concerning the validity and terminology for each.

Sequence

Introduction - We see the sequence as the primary unit category in sequence stratigraphy and favour its use in a generic sense. Thus, its use would be similar to the use of the term biozone in biostratigraphy, and each specific type of sequence will require a modifier for its name. The term sequence has evolved from being a stratigraphic unit bounded by unconformities (Sloss et al, 1949) to one which is bounded by unconformities or their correlative conformities (Mitchum et al, 1977). As emphasized previously, the addition of correlative conformities to the definition was needed to make a sequence a practical unit in a variety of tectonic-sedimentary settings. We suggest the definition of a sequence be slightly modified to "a stratigraphic unit bounded by a specific type of unconformity or its correlative surfaces". This minor revision will allow a variety of sequence types to be clearly defined while still retaining the meaning and spirit of the Mitchum et al (1977) definition.

Once a specific type of unconformity is identified, a specific sequence type can be defined using the unconformity and correlative sequence stratigraphic surfaces as the bounding surfaces. Correlative surfaces are those which join with the end(s) of the unconformity and with each other so as to form a single, through going boundary. Such surfaces can be conformities, diastems and/or other types of unconformities. We would further recommend that the same type of surface or combination of surfaces be used for both the upper and lower boundaries of a given type of sequence. Thus using a subaerial unconformity as the defining unconformity for the lower boundary and a marine shelf unconformity as the upper defining unconformity would not be acceptable. On the basis of the above, only two different types of sequences have been defined in the literature and are in common use. One type uses the subaerial unconformity as its primary unconformity type and the other type uses the unconformable portion of the maximum flooding surface as its primary unconformity. These two types are discussed below.

R-T Sequence - The sequence type which uses the MFS unconformity as its bounding unconformity was introduced by Galloway (1989) and termed a genetic stratigraphic sequence. The correlative surfaces which join with the unconformable portion of the

MFS are the conformable and diastemic portions of the MFS, which are present in both marine and non-marine strata (Fig. 8a). These empirically recognizable surfaces all have low diachroniety or are approximate time barriers and thus such a sequence is valid and potentially has much utility.

As discussed by Embry (1993, 2002), the one serious drawback of such a sequence type is that it commonly encloses a subaerial unconformity or an unconformable shoreline ravinement on the flanks of a basin (Fig. 8A). Given that a major time gap can be associated with such surfaces, not to mention a notable structural discordance, such a sequence type is really two very different genetic units on the basin flanks. This can cause a lot of problems for mapping and communication in these areas. On the plus side, MFSs are the most readily recognizable and objective sequence-surfaces in the offshore and deep-marine areas on both logs and seismic sections. In these areas, such a sequence clearly has great value for mapping and communication. Its utility has been demonstrated by studies in the North Sea (Partington et al, 1993) and Middle East (Sharland et al, 2003).

To us, Galloway's (1989) name for such a sequence, "genetic stratigraphic sequence", is rather unwieldy and not indicative of what such a sequence represents. The modifiers genetic and stratigraphic apply to any sequence type. We suggest that such a sequence be called an "R-T (regressive-transgressive) Sequence" to emphasize that the boundaries coincide with the start of regression and to provide a more euphonious name. Furthermore we recommend that it be used mainly in offshore marine areas where subaerial unconformities and unconformable shoreline ravinements are rare or absent. An R-T sequence can be most useful in deep-water areas dominated by stacked submarine fans.

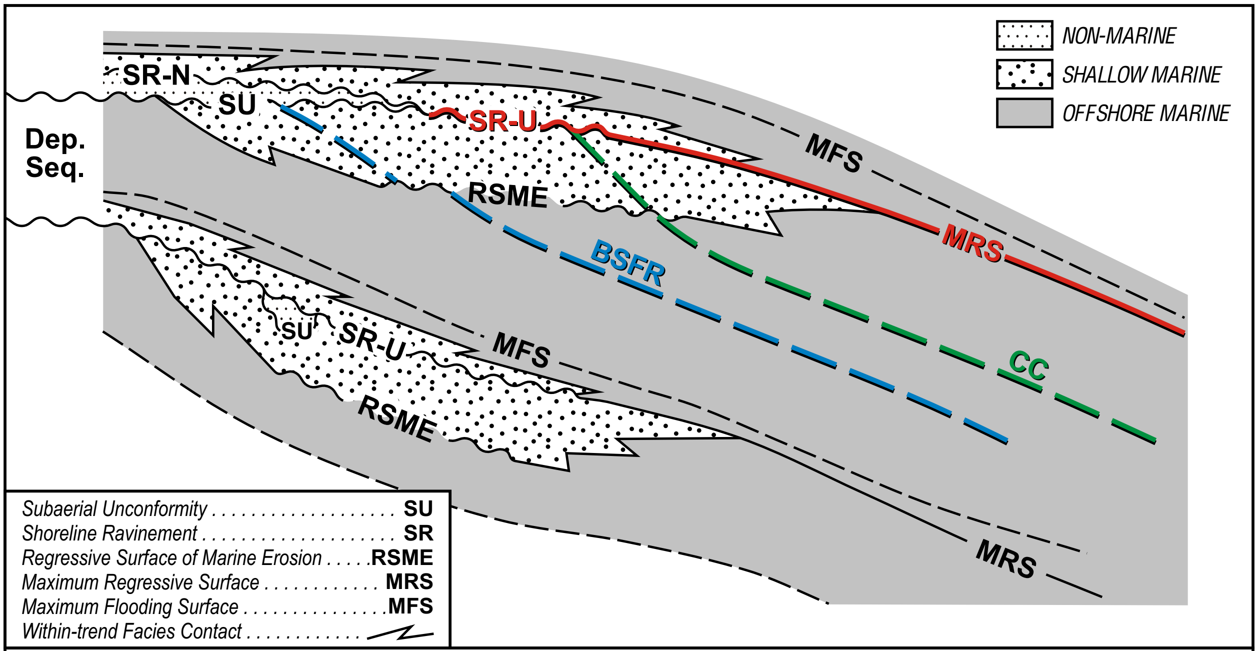
Depositional Sequence – The other type of sequence which has been defined and commonly applied is one which has a subaerial unconformity as the primary unconformity type. The name depositional sequence was used by Vail et al (1977) for such a sequence and we accept this name. To us a depositional sequence is "a sequence stratigraphic unit bounded by subaerial unconformities or their correlative surfaces". This is almost exactly how Van Wagoner et al (1988, 1990) defined a sequence although they wanted to restrict the term sequence to only such a unit. As mentioned above, we think a much more flexible and utilitarian system for sequence terminology is to add a modifier to the term sequence so as to define a specific type of sequence and to reserve the term sequence for a generic unit of wider applicability.

Despite the obvious usefulness of using a subaerial unconformity to define a specific type of sequence, there currently is significant confusion and debate as to what types of sequence-stratigraphic surfaces can combine with the subaerial unconformity (i.e. correlative surfaces) to form a valid and practical sequence boundary and consequent depositional sequence. To us, it is essential that a depositional sequence be defined such that its boundaries are valid, recognizable sequence stratigraphic surfaces which all join together to form a continuous, unbroken boundary over much or all of a basin.

Numerous surfaces have been proposed to be used in combination with a subaerial unconformity to form a depositional sequence boundary and to consequently define a depositional sequence. The first attempt to do so was by Mitchum et al (1977, Fig 1) who proposed both a time surface at the start of base level rise and the downlap surface (now the maximum flooding surface) as correlative surfaces of the subaerial unconformity (Fig.3). After it was recognized that the downlap surface (MFS) was not a correlative surface of an SU in most cases, Posamentier and Vail (1988) proposed two different correlative surfaces for a subaerial unconformity. The first one, which was incorporated into their 'Type 1 boundary", was a time surface which represented the sea floor soon after the start of base level fall. As part of this boundary, the facies contact at the base of deep water turbidites was interpreted to approximate such a time surface in deep water settings (Fig. 4). Unfortunately such a boundary was not acceptable because, as previously discussed, it is not theoretically possible for the basinward termination of a subaerial unconformity which formed at the end of base level fall to join with a time surface which formed just after the start of base level fall. Furthermore, the use of a highly diachronous, within trend facies contact (base turbidite facies) is also unacceptable.

As discussed earlier, Hunt and Tucker (1992) pointed out this illogical “disconnect”. In response to this, Posamentier and Allen (1999) and Posamentier and Morris (2000) revised the boundary of a depositional sequence to a subaerial unconformity and the time surface at the start of base level fall (the basal surface of forced regression) as the main correlative surface and included a small portion of the regressive surface of marine erosion as an additional correlative surface (Fig. 7). Such a proposal is not acceptable for various reasons. First of all, as acknowledged by Posamentier and Allen (1999), the BSFR does not join with the basinward end of the SU (Fig. 13) and thus does not form a single through going boundary (see Catuneanu (2006) for an elaboration of this point). Thus a BSFR cannot be considered as a correlative surface of a subaerial unconformity. Furthermore, as discussed above and acknowledged by numerous workers, the BSFR has no defining characteristics and cannot be recognized by objective scientific analysis in well exposed sections or in core. Consequently there is no question that the time surface at the start of fall, either at the basin edge or the shoreline (BSFR), is not a valid correlative surface for an SU and for bounding a portion of a depositional sequence. Any attempt to follow such a practice (e.g. Coe and Church, 2003) results in the subaerial unconformity being inside the sequence rather than on the boundaries, a result which completely violates the widely accepted definition of a depositional sequence.

Another proposed surface for a correlative surface of a subaerial unconformity is the time surface which represents the start of base level rise - the correlative conformity (sensu Hunt and Tucker). Such a time surface was used as part of a Type 2 sequence boundary by Posamentier and Vail (1988) as well as the original Exxon sequence model (Mitchum et al, 1977). On the basis of the Jervey Model, this time surface is assumed to form well before the start of transgression and the generation of the MRS (Fig.5). The use of such a time surface as a part of a depositional sequence boundary was advocated by Hunt and Tucker (1992), Helland-Hansen and Gjelberg (1994), Plint and Nummedal (2000) and Catuneanu (2006). One attractive aspect of such a proposal is that the time surface at the



Options for correlative surfaces for a subaerial unconformity (SU)

1. Basal Surface of Forced Regression .... BSFR
   (time surface at start base level fall)
2. Correlative Conformity CC
   (time surface at start base level rise)
3. Unconformable Shoreline Ravinement .... SR-U
   and Maximum Regressive Surface .... MRS

Figure 13 The three proposed options for the correlative surfaces of a subaerial unconformity to allow a depositional sequence boundary to be defined.

Posamentier and Allen (1999) suggested the BSFR (time surface equal to start base level fall) (blue line) be used but the lack of any objective criteria for its recognition combined with the fact it does not join with the basinward end of the unconformity negate this proposal.

Hunt and Tucker (1992) proposed the time surface at the start of base level rise (green line) as a suitable correlative surface for a depositional sequence boundary. The lack of any criteria for recognizing such a hypothetical surface prevents its adoption as part of the depositional sequence boundary.

Embry and Johannessen (1992) suggested that the unconformable shoreline ravinement and maximum regressive surface (red line) would be appropriate correlative surfaces for a subaerial unconformity. This combination of empirical surfaces for a depositional sequence boundary has no obvious drawbacks.

start of base level rise theoretically joins with the basinward end of the subaerial unconformity and the two surfaces would thus form a single, unbroken boundary (Fig. 13). However, as discussed in detail above, such an abstract time surface is not a valid or acceptable surface for bounding part of a sequence due to the lack of any reasonably objective criteria for its recognition. There is no discernable change in depositional trend over most of a basin at the start of base level rise and a surface, which represents such an event, cannot be recognized on an empirical basis in a given stratigraphic section or core. Thus, such a model-driven surface, which is theoretically pleasing but empirically invisible, is not acceptable for use as part of a depositional sequence boundary.

Embry and Johannessen (1992) proposed that a sequence be bound by a subaerial unconformity and/or an unconformable shoreline ravinement on the basin flanks and by the maximum regressive surface in the marine areas beyond the extent of the unconformity. They referred to such a sequence as a transgressive-regressive (T-R) sequence. However, because the subaerial unconformity is the primary defining surface of such a sequence type, the term depositional sequence is applicable for such a unit. A shoreline ravinement can and often does erode through a subaerial unconformity in clastic strata and essentially always in carbonate strata. Thus an unconformable portion of a shoreline ravinement (SR-U) is a correlative surface of the SU (Suter et al, 1987). At its seaward edge, the SR-U joins the MRS which would then be a correlative surface over much of the marine portion of the basin. Finally, in distal areas, a combination of very low sediment supply during transgression and erosion associated with the MFS sometimes results in the MFS replacing the MRS. This is a common occurrence in carbonate strata. In such a situation the MFS also becomes a correlative surface of the SU. Thus in situations where a shoreline ravinement erodes the basinward end of the SU, the MRS and sometimes a small portion of the MFS combine with the SU and SR-U to form a single, continuous boundary for a depositional sequence over much or all of a basin (Fig. 13).

Given that all these surfaces are empirically recognizable sequence stratigraphic surfaces, such a combination of surfaces forms a practical and valid boundary for a depositional sequence. The determination of the age of the MRS by biostratigraphic analysis provides a convenient and objective way to assign an age to the sequence boundary. Thus, although the ages of the other surfaces will differ somewhat from that of the MRS, a single age can be used when referring to the age of a depositional sequence boundary. Empirical studies demonstrate the existence and practical application of such a thorough going sequence boundary in a variety of geological settings (e.g. Embry, 1993; Beauchamp and Henderson, 1994).

The one, oft-quoted objection to the use of the maximum regressive surface and shoreline ravinement as correlative surfaces of a subaerial unconformity has not been based on empirical evidence but rather on theoretical grounds. On the basis of the Jervey Model, the MRS and SR do not **theoretically** join with the basinward termination of the subaerial unconformity in many situations because of the substantial time lag between the end of base level fall and the start of transgression (Helland-Hansen and Martinsen, 1994; Catuneanu, 2006) (Fig. 14). If one accepts the Jervey Model as a valid representation of real world stratigraphic relationships, then the MRS would sometimes not be a correlative surface of the SU and, in such cases, would not be appropriate for extending the depositional sequence boundary basinward from the end of the subaerial unconformity.

As noted above, many empirical observations demonstrate that the three types of surfaces do indeed join and form one continuous boundary. In fact, a scrutiny of many published stratigraphic and seismic cross sections reveals this is the case in most situations (e.g. Thrana and Talbot, 2006). Thus, we are left with a discordance between what is observed and what is predicted by the Jervey Model. One possible explanation for this lack of agreement of theory with observation is that the Jervey Model is too simplistic and that one or more of the input parameters is substantially non-actualistic. It is important to note that the Jervey Model employs a sinusoidal base level curve as a key input parameter. With sinusoidal change, early rates of base level rise are slow and consequently there is a substantial lag time between the start of base level rise when the subaerial unconformity reaches its basinward extent and the start of transgression when the MRS and SR are generated. Thus in the Jervey Model, the MRS and the SR (previously called the

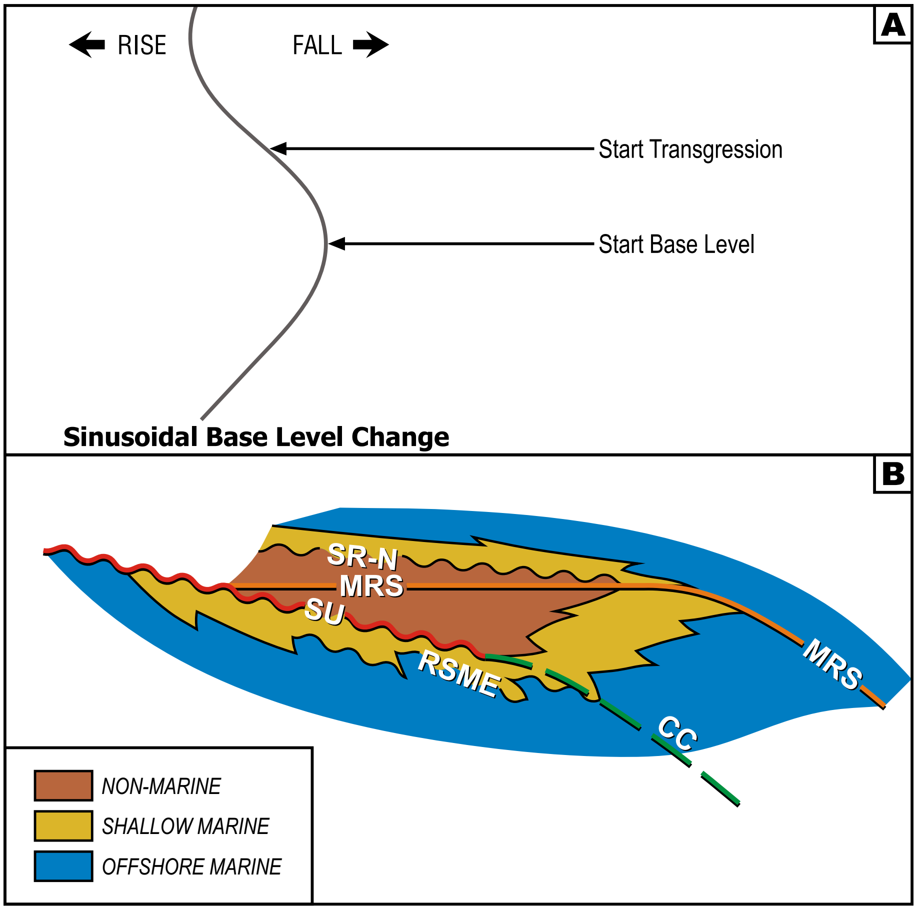


Fig. 14 Sequence stratigraphic relationships for a sinusoidal change in base level and a relatively high supply of sediment. In such a model ("Jervey Model"), the time surface at the start of base level rise (CC) forms substantially earlier than the start of transgression when the MRS is generated. In this situation the MRS does not join with the basinward end of the unconformity. There is no empirical or theoretical support for sinusoidal changes in base level and the above described stratigraphic relationships have never been documented with actual data.

transgressive surface) are stratigraphically higher than the termination of the SU and thus do not join with the SU (Fig 14). As discussed by Embry (2006, in press) there is no evidence whatsoever that base level changes in a such a gradual, sinusoidal manner in the real world and thus such a curve is considered to be non-actualistic.

Given that either eustasy or tectonics is the primary driver of base level change, Embry (2006, in press) suggested that an input base level curve based on eustasy (Shackleton, 1987) or tectonism (Gawthorpe et al, 1994; Embry, 1997) is more appropriate for a sequence stratigraphic model. Each of these base level curves is punctuated by pulses of fast rises followed by either slow rise or standstill. This results in a rapid rate of rise (initial tectonic or eustatic pulse) initiating the start of the rising phase of the base level cycle (Immenhauser and Scott, 2002). The use of such actualistic base level curves in a sequence stratigraphic model results in the coincidence of the start of base level rise with the start of transgression in both siliciclastic and carbonate regimes (Fig. 15). This is due to a combination of a high rate of base level rise and decreasing (siliciclastics) or very low (carbonates) rate of sedimentation at the shoreline very soon after the start of base level rise. The coincidence of the initiation of base level rise with the onset of transgression results in the MRS and SR joining with the terminal end of the SU as has been empirically observed (e.g. Embry, 1993). Thus with the use of much more actualistic base level curves in an inductive sequence stratigraphic model, the proposed depositional sequence boundary which employs a subaerial unconformity, an unconformable shoreline ravinement and a maximum regressive surface has robust theoretical support to complement the abundant empirical observations.

There may well be geological settings where initial base level rise is slow and the onset of transgression will be considerably later than the initiation of base level rise. In such a case there will be no practical way to extend the sequence boundary basinward of the termination of the subaerial unconformity because no valid correlative surfaces will exist. The rarity of such an occurrence is underscored by the lack of such a situation being well documented in the literature.

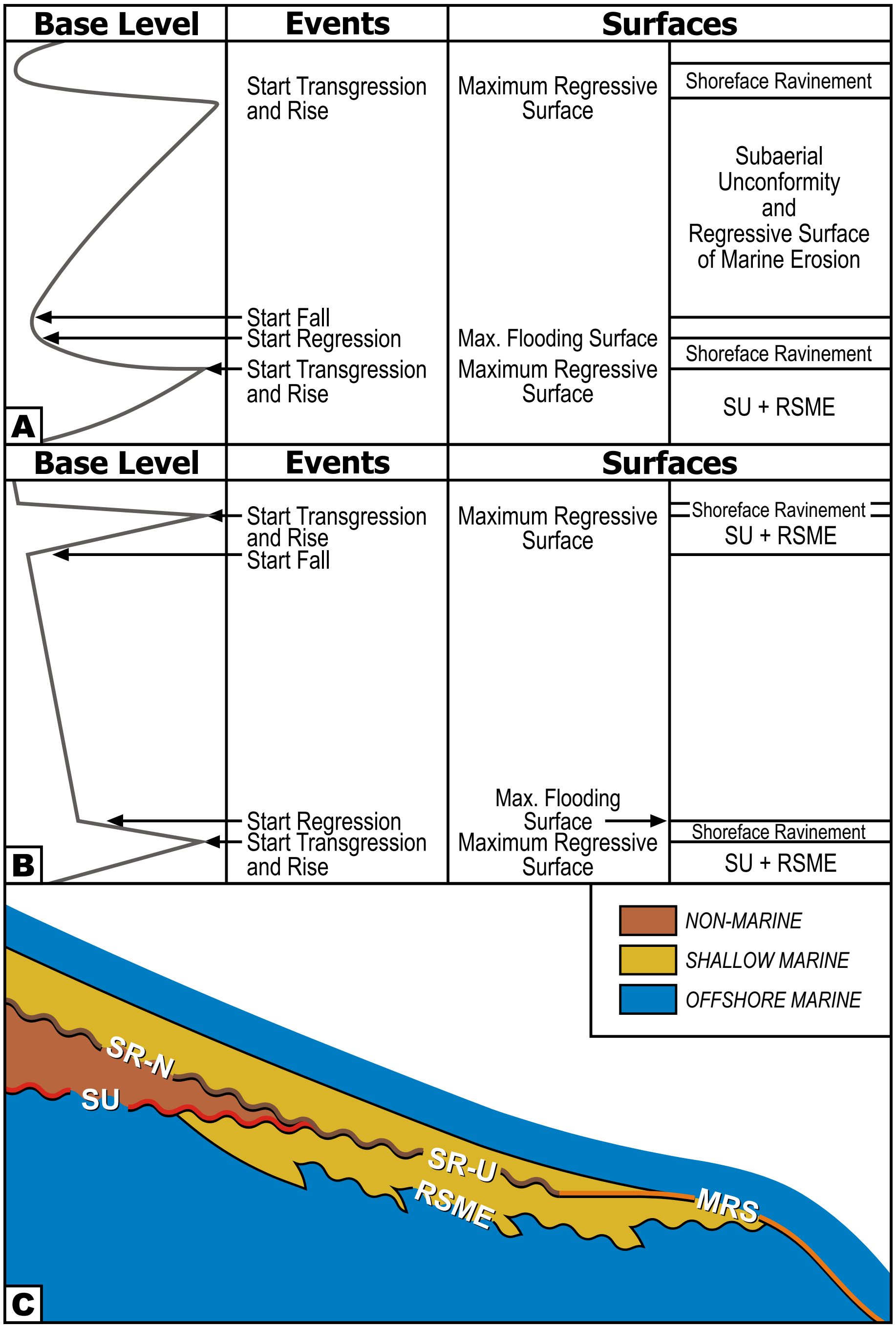


Fig. 15 Actualistic changes in base level and sequence stratigraphic surfaces.

A. Eustatic sea level driven base level change and consequent sequence stratigraphic surfaces. Note that in this case the start of base level rise coincides with the start of transgression which results in the MRS joining with the subaerial unconformity (C) as has been empirically observed.

B. Tectonically-driven base level change and sequence stratigraphic surfaces. Once again the very early, rapid rise in base level results in the start of base level rise coinciding with the start of transgression. This again agrees with the observed correlation of the MRS with the SU as illustrated in C.

In summary, we recommend that a depositional sequence boundary be defined by a subaerial unconformity, an unconformable shoreline ravinement, a maximum regressive surface and occasionally part of the MFS (Fig.16, 17). Such a through going and recognizable boundary is well supported by empirical observations and by a revised, base level/sediment supply model which employs actualistic base level curves (Fig 18).

***Other Sequence Types* -** Given that there are other types of unconformities besides a subaerial unconformity or an unconformity associated with an MFS, there is no reason that other types of sequences besides the depositional sequence and the R-T sequence cannot be defined. We would suggest that any new type of sequence have a defining type of unconformity and that it be demonstrable that such an unconformity and its correlative sequence stratigraphic surfaces be potentially delineated and correlated by objective science over a reasonable portion of a basin. This will avoid the nomenclature problems experienced by a unit bounded by “unconformities only” and by a unit bound in part by theoretically appealing, but empirically invisible, abstract surfaces.

Systems Tracts

Introduction - Posamentier and Vail (1988) advanced sequence stratigraphy with the innovation that a sequence can be subdivided into component units on the basis of sequence- stratigraphic surfaces which occur within a sequence. This enhances mapping and communication and adds to the resolution capability of sequence stratigraphy. To us, a systems tract is best defined as “a component unit of a sequence which is bound by sequence-stratigraphic surfaces”. Like other sequence-stratigraphic units, it is defined by its bounding surfaces and not by some characteristic property of the unit with the exception of overall depositional trend. As discussed in the history section of this article, a number of systems tract schemes have been proposed. In this section we look at each proposed systems tract and evaluate it regarding its usefulness and validity. Again, because sequence stratigraphic units are primarily defined by their bounding surfaces and not internal properties, we will focus on the nature of the defining surfaces for each systems tract.

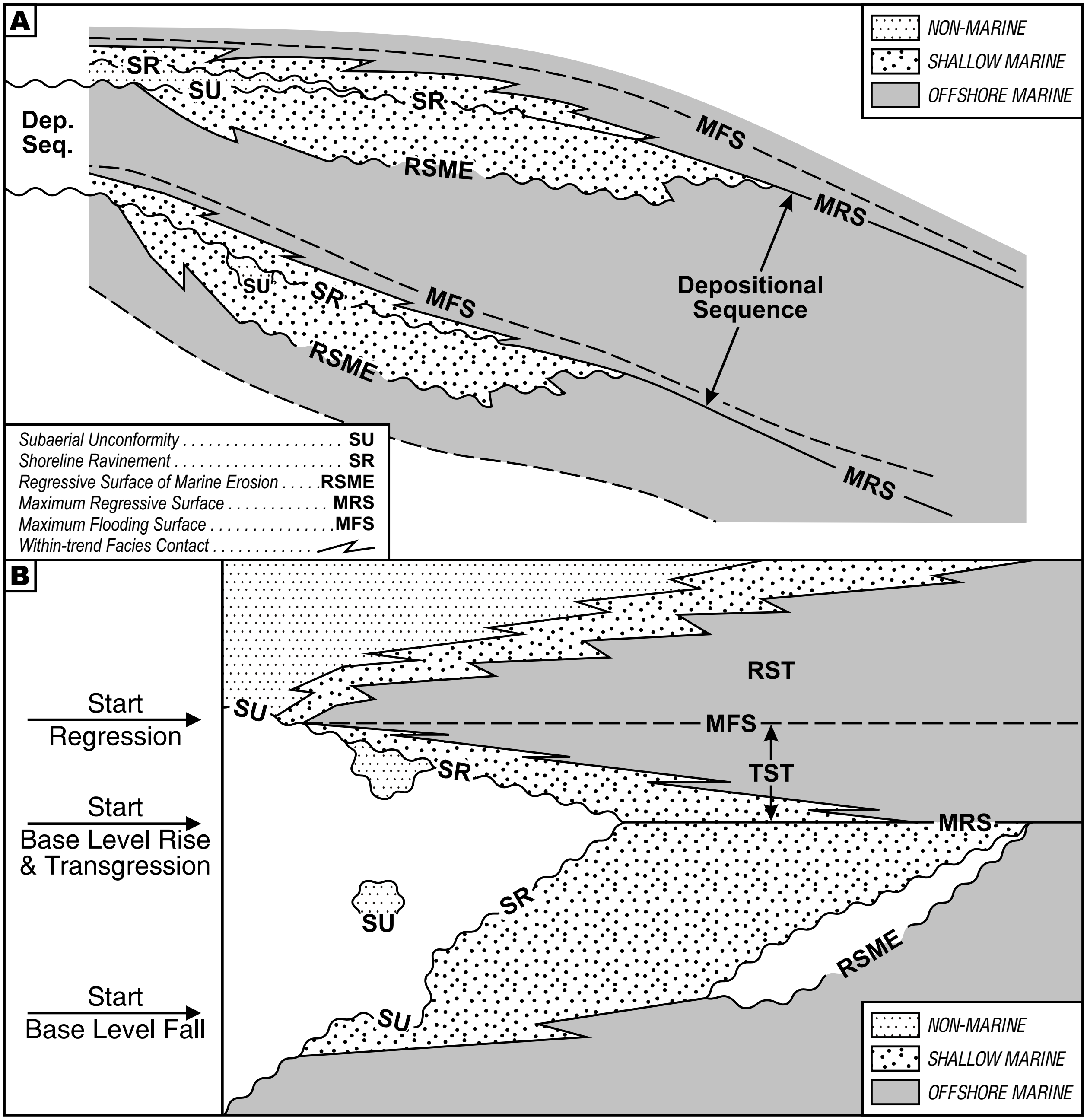


Fig. 16 The depositional sequence model in both time and space for a ramp setting. On the basin margins the unconformity (SU or SR-U) form the boundaries whereas in the basin the MRS forms the boundaries. A depositional sequence can be subdivided into a transgressive systems tract (TST) and a regressive systems tract (RST) with the MFS forming the mutual boundary.

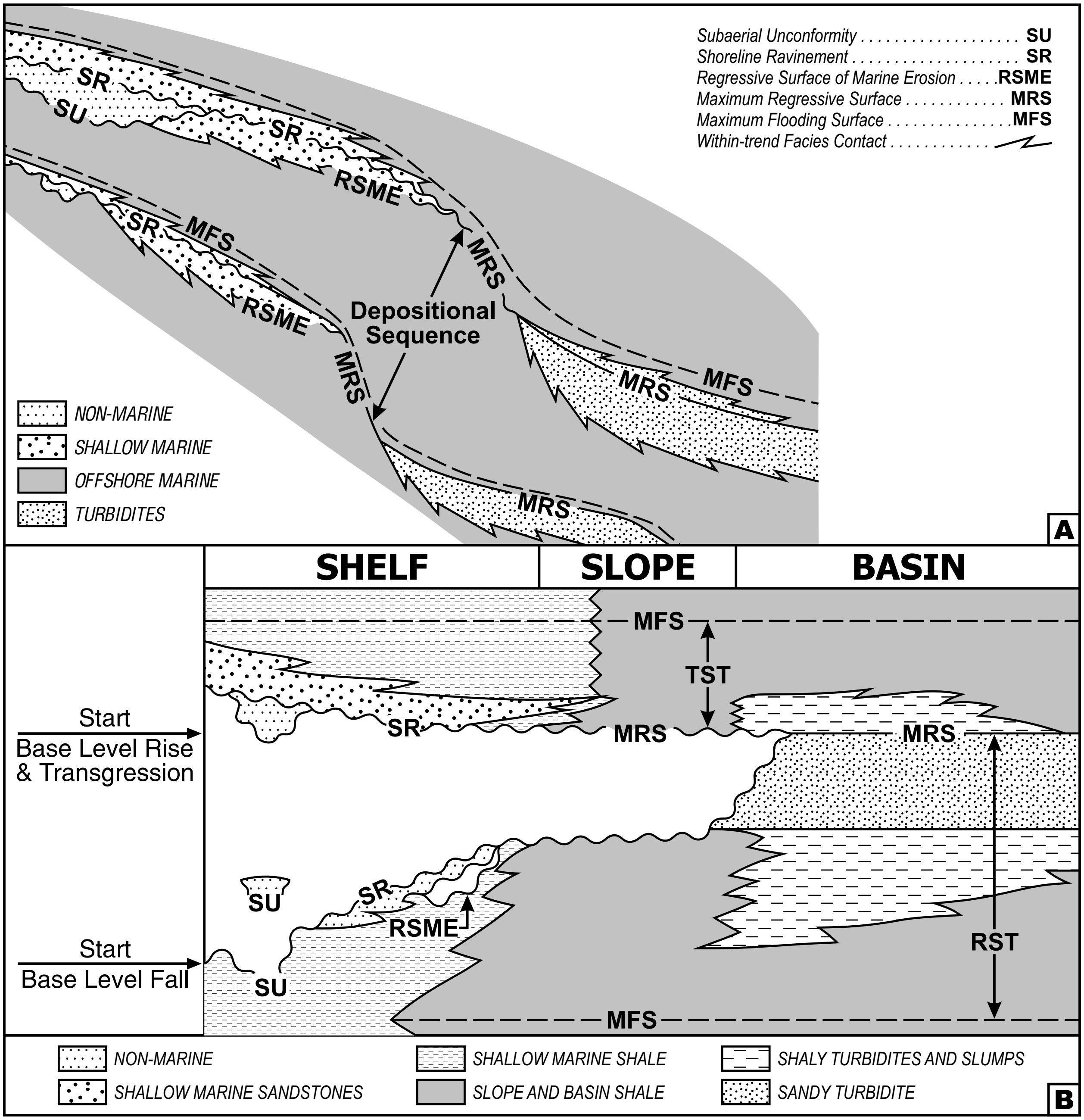


Fig. 17 The depositional sequence model in both time and space for a shelf/slope/basin setting. The SR-U, SU and MRS from the boundaries of the sequence and the internal MFS allows a depositional sequence to be subdivided into a transgressive systems tract (TST) and an overlying regressive systems tract (RST).

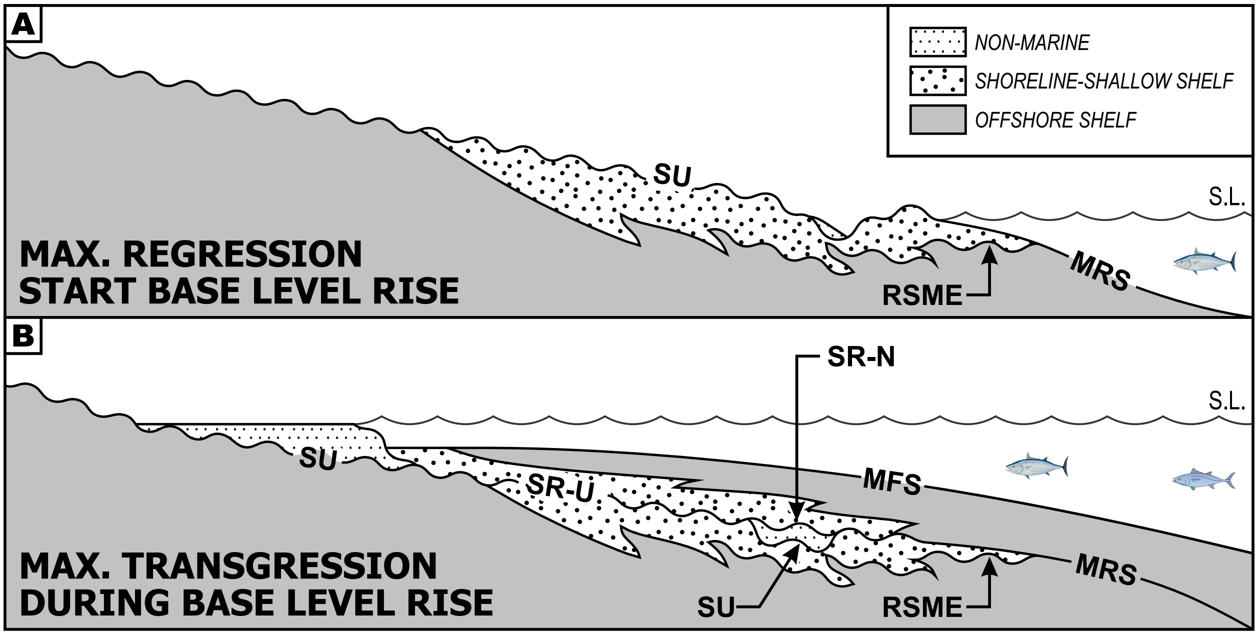


Fig. 18 The development of a depositional sequence boundary.

A. The end of base level fall coincides with time of maximum regression when actualistic base level curves are applied. At this time a subaerial unconformity (SU) extends to the shoreline and joins with a maximum regressive surface (MRS).

B. During the subsequent transgression, the shoreline ravinement (SR-U) extends from the landward termination of the MRS and erodes a portion of the subaerial unconformity. This results in the SU, SR-U and MRS forming a continuous boundary that meets the definition of a depositional sequence boundary (subaerial unconformity and correlative surfaces).

Lowstand Systems Tract (sensu Posamentier and Allen, 1999) **-** The lowstand system tract was first defined by Van Wagoner et al (1988) and Posamentier and Vail (1988) as the basal systems tract in a Type 1 sequence and the definition was slightly modified by Posamentier and Allen (1999). The LST was defined as being bound by the sequence boundary (SU and BSFR) below and the transgressive surface (MRS) above (Fig. 19). Such a unit was intended to encapsulate all the strata deposited during base level fall and those deposited during early base level rise but before the onset of transgression. The transgressive surface (the maximum regressive surface) is a valid sequence stratigraphic surface, but the conformable portion of the sequence boundary in the revised Type 1 sequence (the time surface at the start of base level fall or BSFR) is not a valid surface because there are no criteria to allow its recognition as previously discussed. Thus, the lowstand systems tract as defined by Posamentier and Vail (1988) and modified by Posamentier and Allen (1999) is not an acceptable sequence stratigraphic unit because of its unrecognizable lower contact.

Transgressive Systems Tract (TST) **-** The transgressive systems tract was defined by Van Wagoner et al (1988) and Posamentier and Vail (1988) as being bound by the transgressive surface (MRS) below and the maximum flooding surface above (Fig. 19). This systems tract comprises all the strata deposited during transgression. Both bounding surfaces are valid sequence stratigraphic surfaces and thus the TST is a valid sequence stratigraphic unit. In areas where the depositional sequence boundary is an unconformity (SU or SR-U), Embry (1993) defined the TST as being bound by the unconformity at the base and the MFS at the top. When the underlying boundary is an SU, it is acknowledged that the TST may contain some fluvial strata that were deposited before transgression began (i.e. during base level fall). However, as discussed by Suter et al (1987) and Embry (2002), there is no objective methodology for separating such pre-transgression, fluvial beds from overlying fluvial strata which were deposited during transgression. The practice of labeling fluvial strata overlying a SU as LST, and overlying brackish or marine beds as TST, is in effect drawing a system tract boundary at a highly diachronous facies contact (e.g. Van Wagoner et. al., 1990; Posamentier and Allen, 1999; Catuneanu, 2006) – an unacceptable sequence stratigraphic practice.

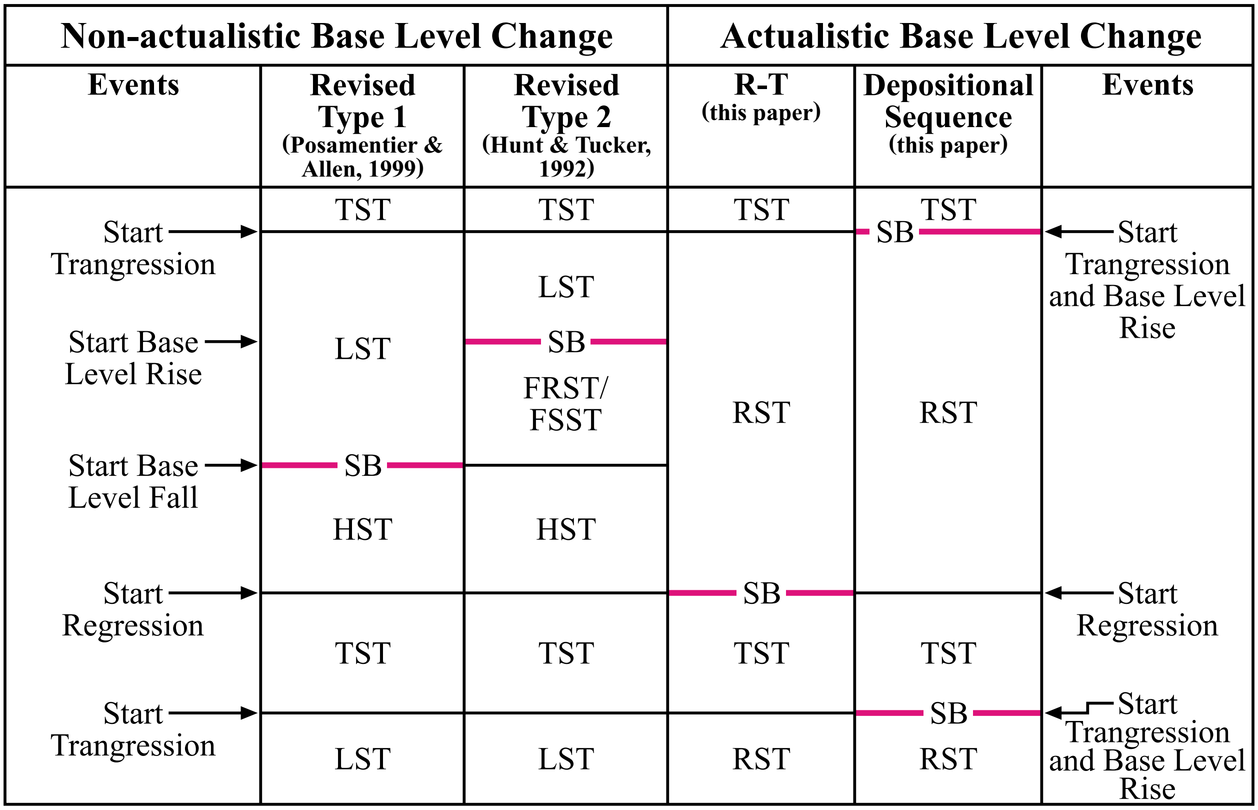


Fig. 19 A comparison of proposed sequence boundaries and systems tracts for the depositional sequence models based on the Jervey Model of non-actualistic sinusoidal base level change (Posamentier and Allen, 1999; Hunt and Tucker, 1992) and the empirical sequence models based on actualistic eustatic and tectonic base level change as described in this paper.

The boundaries of most of the units based on the Jervey Model are hypothetical time surfaces (start base level fall and start base level rise) which have no physical characteristics to allow their recognition by scientific methods. Such units have no validity.

The empirical R-T and depositional sequence models have units with recognizable boundaries.

Highstand Systems Tract (HST) - The highstand systems tract as defined by Van Wagoner et al (1988) and Posamentier and Vail (1988) is bound by the MFS below and the sequence boundary above. In a Type 1 sequence it included all strata deposited after the cessation of transgression and up to the start of base level fall (Fig. 19). However, for a Type 2 sequence, its meaning was expanded to also include strata deposited during the fall (Fig. 19). Because the HST, like the LST, uses an unrecognizable time surface (start base level fall = BSFR, in Type 1; start base level rise = CC, in Type 2) as part of its upper boundary, it cannot be delineated in a scientific manner and is thus also not an acceptable or valid sequence-stratigraphic unit.

Shelf Margin Systems Tract (SMST) - In a type 2 sequence, Van Wagoner et al (1988) and Posamentier and Vail (1988) included a shelf margin systems tract (SMST). It had the time surface at the start of base level rise (CC) as the lower boundary and the transgressive surface (MRS) as the upper boundary and thus comprised strata deposited from the start of base level rise to the start of transgression. Given that the time surface at the start of base level rise (CC) is not a valid sequence stratigraphic surface, the SMST is also not an acceptable sequence stratigraphic unit. It has rarely been applied.

Lowstand Systems Tract (sensu Hunt and Tucker, 1992 (LST) - Hunt and Tucker (1992) changed the definition of the LST by revising the lower contact to the time surface at the start of base level rise (as opposed to the time surface just after the start of base level fall as proposed by Posamentier and Vail (1988)) (Fig. 19). Like the SMST, the revised LST comprised strata deposited from the start of base level rise to the start of transgression. Helland-Hansen and Martinson (1994), Plint and Nummedal (2000) and Catuneanu (2006) use the term lowstand systems tract in this way. This revised version of an LST is also not an acceptable sequence stratigraphic unit because the revised lower boundary is an abstract, unrecognizable time surface rather than a valid surface of sequence stratigraphy. Furthermore, because it appears that, in most cases, the start of transgression coincides with the start of base level rise, such a theoretical unit does not exist in many stratigraphic successions even in an abstract sense (Fig. 19).

Forced Regressive Systems Tract (FRST)/Falling Stage Systems Tract (FSST) - Hunt and Tucker (1992) proposed a new systems tract, the forced regressive wedge systems tract, which was subsequently shortened to forced regressive systems tract. Unfortunately it was defined as having abstract, time surfaces for both the lower and upper boundaries (start and end of base level fall) (Fig. 19) and thus there is little hope of recognizing such a unit with objective scientific analysis in most instances. The FRST is also called the falling stage systems tract (FSST) (Plint and Nummedal, 2000). These authors used the regressive surface of marine erosion (RSME) as the basal boundary of the FSST on the concept that such a surface approximated the start of base level fall. The RSME in fact is highly diachronous and develops over the entire time of base level fall. As Plint and Nummedal (2000, p.11) candidly state "In this offshore setting it is impossible to place the lower boundary of the FSST at a single surface". In summary both contacts of the FRST/FSST are not valid boundaries and the FRST/FSST is not a valid unit of sequence stratigraphy.

Regressive Systems Tract (RST) – Embry and Johannessen (1992) defined the RST as being bound by the MFS at the base and the sequence boundary above. In this case the sequence boundary was defined as a combination of the subaerial unconformity, the unconformable shoreline ravinement and the maximum regressive surface (then called a transgressive surface) (Fig. 19). Thus it encapsulates the strata deposited during regression. Given that all the bounding surfaces are valid sequence stratigraphic surfaces, the RST is considered to be a valid sequence stratigraphic unit

Low and High Accommodation Systems Tracts - The low accommodation systems tract and the high accommodation systems tract were introduced for non-marine strata which are not known to be connected to a marine basin in an abstract by Dahle et al (1997). They have been rarely applied but recently their use has been strongly advocated by Catuneanu (2006). Because accommodation increases from low to high as base level rises in a nonmarine basin, there is no change in depositional trend which would support the establishment of a new sequence stratigraphic surface to be used to define units such as the low- and high accommodation systems tracts. Catuneanu (2006, p.230) avoids discussing how one might draw a contact between these two proposed systems tract and notes that “it is common that the change from the low- to the high accommodation systems tract is gradational”. Such gradation within the same trend of increasing accommodation would be expected and this underscores the futility in trying to establish a valid sequence stratigraphic contact between a low and high accommodation systems tract.

If one wanted to establish accommodation-related systems tracts, it would be necessary to define the physical properties in non-marine strata which reflect a change in trend from increasing accommodation to decreasing accommodation and vice –versa. This is basically how the MFS and MRS are usually recognized in nonmarine strata (Cross and Lessenger,1997). We recommend the terms transgressive systems tract (bound by an SU below and MFS above) and regressive systems tract (bound but MFS below and the SU above) be used in nonmarine basins which appear not to be connected to marine areas despite the apparent lack of transgressions and regressions in such a setting. This avoids the introduction of new, overlapping jargon such as “increasing accommodation systems tract” and “decreasing accommodation systems tract”. Furthermore there is always the chance that further work will establish a marine connection for a given nonmarine basin and it is not reasonable to have systems tract nomenclature depend on such information.

In summary, the increase from low to high accommodation, advocated by Catuneanu (2006) for use in defining two new sequence stratigraphic units, is part of the same trend (increasing accommodation) and thus cannot be used to determine a sequence stratigraphic surface which could act as a systems tract boundary. Consequently, the low- and high accommodation systems tracts are anything but a “conceptual breakthrough” as claimed by Catuneanu (2006), and have no empirical or theoretical support as sequence stratigraphic units.

Summary – Although numerous system tracts have been proposed over the last few decades, most of them have no validity as a sequence stratigraphic unit because one or both of the surfaces used to define them is not a valid surface of sequence stratigraphy.

Only two systems tracts, the transgressive systems tract and the regressive systems tract, are valid sequence stratigraphic units because they both are defined on the basis of sequence-stratigraphic surfaces which can be empirically recognized. These systems tracts are valid component units of both a depositional sequence and an R-T sequence (Fig. 19).

It is worth noting that, while the highly interpretive terms, lowstand, highstand, falling stage and forced regressive cannot be applied to specific systems tracts, they can be used as descriptive adjectives for strata interpreted to be deposited during a specific portion of the base level curve. An example would be a “forced regressive sandstone”. In this case it is not possible to draw a stratigraphic boundary equivalent to the start of base level fall so as to define the base of a FRST, but it often is reasonable to interpret that a sandstone facies between a RSME and an SU was deposited when base level was falling.

When other types of sequences are properly defined, component systems tracts can be defined for them. The only proviso for defining a new systems tract is that its boundaries are valid sequence-stratigraphic surfaces which fulfill the requirements listed at the beginning of this section. If additional valid sequence-stratigraphic surfaces are defined in the future, additional systems tracts may be recognizable within both the depositional sequence and the R-T sequence.

Parasequence

In keeping with sequence stratigraphic practice, Van Wagoner et al (1988) defined a parasequence by means of its bounding surfaces - “a relatively conformable succession of beds or bedsets bound by marine-flooding surfaces”. To understand the definition of a parasequence, one needs a definition of a marine-flooding surface, its defining bounding surface. Van Wagoner et al (1988) defined a marine-flooding surface as “a surface separating younger from older strata across which there is an abrupt increase in water depth”. As discussed in the section on surfaces, the marine-flooding surface, as defined and used by Van Wagoner et al (1988;1990), is in most cases a diachronous, within-trend facies contact, which is a lithostratigraphic surface rather than a sequence stratigraphic one (Fig. 12). Given this, a parasequence as defined by Van Wagoner et al (1988) is not a valid unit of sequence stratigraphy.

The question then arises whether or not a parasequence can be redefined so that it becomes a valid sequence stratigraphic unit. Sometimes the sandstone /shale contact, which Van Wagoner et al (1988, 1990) used as the defining bounding surface of a parasequence, coincides with either the MRS or the MFS. However, if either of these valid surfaces of sequence stratigraphy is used as the unit boundary, a parasequence would be equivalent with either a depositional sequence (MRS for a boundary) or an R-T sequence (MFS as the boundary). Thus a parasequence is either invalid or redundant and in either case is not needed in sequence stratigraphy. We recommend that a parasequence not be used as sequence stratigraphic unit. A case could be made for adopting it as an informal lithostratigraphic unit if the boundaries as defined and illustrated by Van Wagoner et al (1988, 1990) are used.

Sequence Hierarchy

Introduction

As emphasized by Embry (1993, 1995), it is most important that sequence stratigraphic surfaces be assigned to a hierarchy if individual sequences are delineated and mapped or if numerous sequence stratigraphic surfaces are used for regional correlation. The main reason for this is that very many sequence stratigraphic surfaces of greatly varying magnitude occur in a given succession and, without a hierarchy, any two recognized sequence boundaries, regardless of their magnitude, (e.g. two MFSs in the case of R-T sequences and any combination of two SU, SR-U or MRSs in the case of a depositional sequence) could, in theory, be used to form the boundaries of a sequence (Fig. 20). This would result in a huge number of potential sequences and the only way to escape such madness is to establish a hierarchy of surfaces. It is widely recognized that there is a great variation in the magnitude of sequence stratigraphic surfaces and that there is a need to separate large magnitude sequences/sequence boundaries from much smaller scale ones. This is a natural consequence of the recognition that sequence boundaries and the enclosed sequences are not scale dependent (Posamentier and Allen, 1999; Catuneanu,

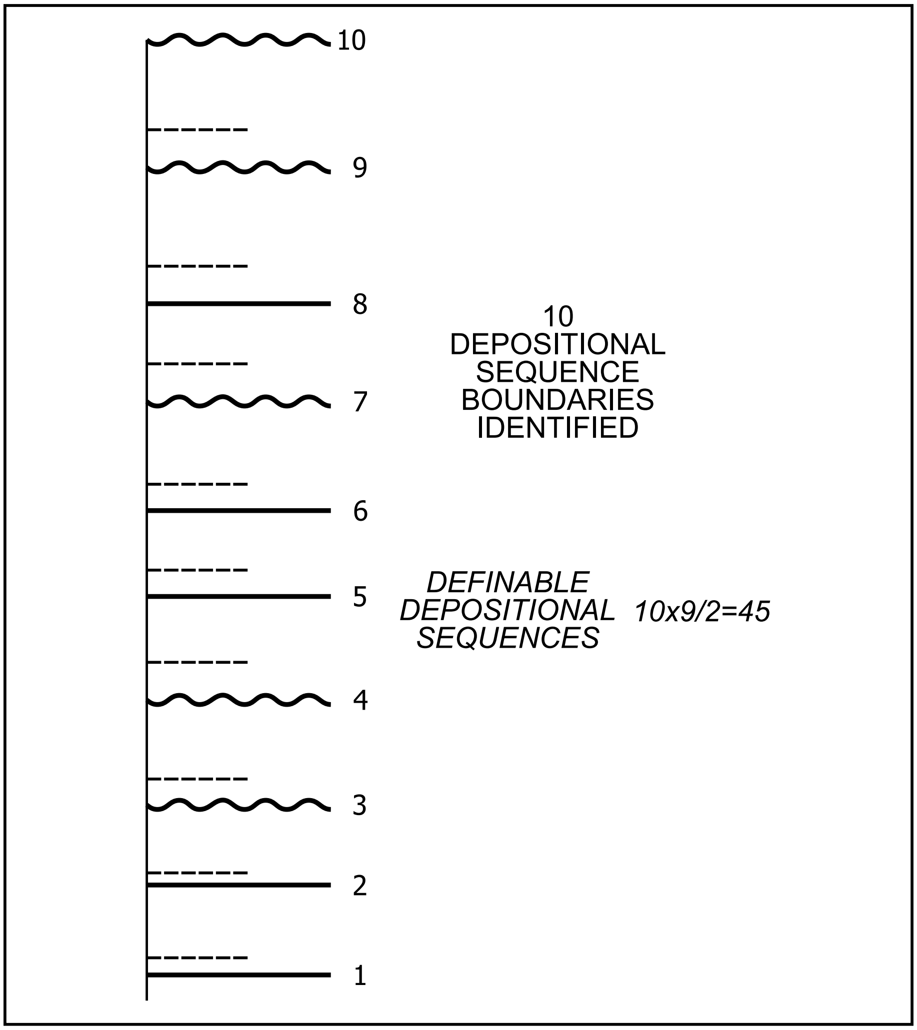


Fig. 20 Because a depositional sequence is defined as a unit bound by subaerial unconformities (wavy line) and correlative surfaces (solid line), it is essential that a hierarchy of sequence boundaries be defined. If a hierarchical system is not used, up to 45 sequences could be defined in the above schematic succession with 10 recognized sequence boundaries (e.g. 1-2 1-3, 1-4, 1-5 etc). Such a chaotic and unacceptable situation is avoidable only by separating the sequence boundaries into different classes (orders) and arranging them into a hierarchy.

2006). Notably two very different methodologies for developing such a hierarchy of sequences and sequence boundaries have been proposed - a model-driven method and a data-driven method.

Model-Driven Hierarchy

The model-driven approach has been championed by Exxon scientists (e.g. Vail et al, 1977; Mitchum and Van Wagoner, 1991; Vail et al, 1991; Posamentier and Allen, 1999). Such an approach postulates *a priori* that sequence stratigraphic surfaces are generated by eustasy-driven, sinusoidal base level changes and that such eustatic cycles increase in amplitude with decreasing frequency. Thus very large amplitude changes driven by tectono-eustasy (changes in volume of ocean basins), occur rarely and the resulting sequence boundaries are assigned to either a 1st or 2nd order category. Such orders are usually referred to as low order boundaries although Catuneanu (2006) has gone against convention and called such boundaries high order boundaries. Throughout this section we follow the conventional practice of referring to 1st, 2nd and 3rd order boundaries as low order boundaries and 4th, 5th and 6th order boundaries as high order boundaries. In the model-driven hierarchy, such high order boundaries are related to climate-driven, Milankovitch cycles, which drive high frequency eustatic changes in the 20 ky to 400 ky band. In such a model-driven approach, a sequence is assigned to a given order based on the amount of time represented by the sequence, that is the amount of time which lapsed between the development of each of its bounding surfaces.

Vail et al (1977) assumed *a priori* that three distinct orders of sea level variation existed with the largest changes occurring every 200-300 million years (first order), intermediate changes occurring every 10-80 million years (second order) and smaller ones occurring every 1-10 million years (third order). This model-driven approach was refined and culminated in a publication by Vail et al (1991) in which six orders of boundaries were defined solely on boundary frequency. The six orders and their characteristic boundary frequencies in this hierarchical scheme are:

1st order - 50 Ma
2nd order – 3-50 MA

3rd order - .5 – 3 MA
4th order - .08 - .5 MA
5th order - .03 - 08 MA
6th order - .01- .03 MA

Such a model-driven approach to establishing a hierarchy of sequences is basically unworkable and is highly prone to circular reasoning. Because any stratigraphic section contains numerous depositional sequence boundaries (unconformities and MRSs), any desired frequency of boundary occurrence can be determined simply by selecting only the boundaries that fit the desired result. For example, if fourteen sequence boundaries were recognized within a succession spanning 20 MA, there are many combinations of boundaries that could be chosen to delineate a sequence with a boundary frequency of 10 MA (Fig. 21). Which one is a 3rd order sequence? Catuneanu (2006) has elaborated on the fatal flaws of such a model-driven method for determining a sequence hierarchy.

It simply comes down to the premise that, if one wants to determine the frequency of 3rd order sequence boundaries, one must be able to empirically recognize 3rd order boundaries in the first place. Boundary frequency is a conclusion that can be only be reached once the different orders of boundaries are defined with reasonable objectivity. Frequency is not an observable characteristic of a sequence boundary.

Data-Driven Hierarchy

Embry (1993, 1995) advocated for the use of a data-driven methodology for establishing a hierarchy of sequence stratigraphic boundaries and enclosed units. Such an approach is based on objective scientific criteria rather than on *a priori* assumptions, as is the case for the model-driven approach described above. The data-driven approach has recently also been advocated by Catuneanu (2006).

In the data-driven approach, a hierarchy of boundaries is established on the basis of the interpreted relative magnitude of the boundaries. The interpreted relative magnitude of a boundary would reflect the relative magnitude of base level shift which generated the

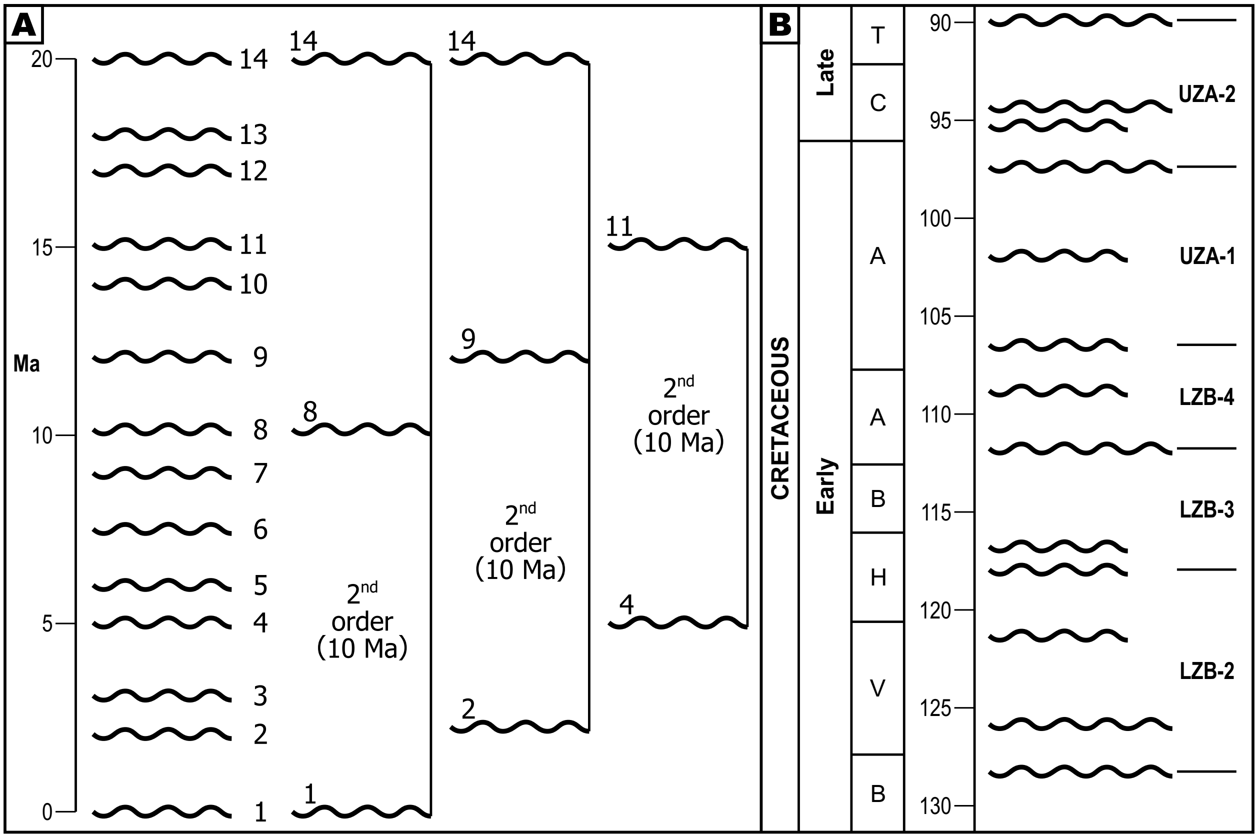


Fig. 21 On the left (A) is a schematic diagram which illustrates the faulty logic of using boundary frequency, as suggested by Exxon workers, for the establishment of a sequence hierarchy. In a succession which spans 20 Ma and contains 14 sequence boundaries, many combinations of boundaries (only 3 shown) can be used to create second order sequences with a 10 Ma year frequency.

On the right (B) is a diagram from Haq et al (1988) which illustrates the use of the concept of boundary frequency to define a series of second order sequences. It is clear that the boundaries of the second order sequences have been subjectively selected to fit the desired result (sequences of 10 Ma duration), while ignoring others which did not “fit”. Such a methodology is not acceptable scientific practice.

boundary in the first place. A base level change of 500 m is going to result in a relatively large magnitude sequence boundary that has different attributes than a smaller magnitude sequence boundary that was generated by a base level change of 10 m or less. In a given basin, the largest magnitude boundaries (i.e. the sequence boundaries generated by the largest interpreted base level changes) are assigned to the 1st order category in the hierarchy and smallest magnitude boundaries recognized (i.e. those generated by the smallest interpreted base level changes) would be assigned to the highest order established (e.g. 4, 5 or 6).

To apply such a methodology, it is necessary to find objective, scientific criteria which allow the characterization of the relative magnitude of a sequence boundary. Such criteria would reflect the magnitude of the base level change which generated the boundaries. The attributes of a sequence boundary we have found useful to estimate the relative magnitude of a sequence boundary, and indirectly the amount of base level change that generated the boundary in the first place, are listed below. Such observable characteristics are placed in order of their importance for assessing the relative magnitude of a given depositional sequence boundary with the first one being most important.

1) The degree of change of the tectonic setting across the boundary
2) The degree of change of the depositional regime and sediment composition across the boundary.
3) The amount of section missing below the unconformity at as many localities as possible. Localities close to the basin edge are very helpful.
4) The estimated amount of deepening at the maximum flooding surface above the sequence boundary where it is an unconformity.
5) How far the subaerial unconformity and associated shoreline facies penetrate into the basin.

It is important to note that not all these characteristics can be applied for each boundary but in many cases most of them can be. In many instances, the largest magnitude boundaries in a basin, which would be 1st order boundaries **for that basin**, mark a significant change in tectonic and sedimentary regime and are associated with large amounts of erosion and significant deepening. The unconformity and shoreline facies usually penetrate far into the basin. Such sequence boundaries are most often readily apparent and correlatable and would bound 1st order depositional sequences. Because of the tectonic and sedimentary regime changes, there is little doubt that such boundaries were generated by tectonics.

Sequence boundaries which exhibit no change in tectonic or depositional regime, are associated with little erosion and subsequent drowning, and the unconformity and shoreline facies do not extend past the basin margin, would be high order, low magnitude boundaries (e.g. 5th and 6th order).

For sequence boundaries generated during “Greenhouse” conditions (i.e. no continental glaciers), there tends to be a consistency for each of the five criteria to point to the same result and the magnitude of the boundary correlates closely with the basinward extent the unconformity, with the amount of section eroded and with the amount of subsequent deepening. Those large magnitude boundaries in which the unconformity extends far into the basin and for which significant erosion and subsequent drowning are present almost always also have a significant change in depositional regime, if not also tectonic regime.

Problems with assignment sometimes occur for sequence boundaries formed during “Icehouse” conditions when continental glaciers were intermittently present. During such times, relatively large base level changes (up to ~ 120 m) due to climate-driven eustatic sea level changes were often accompanied by essentially no change in depositional and tectonic regimes. Experience has taught us that changes in these latter two criteria most often reflect major base level change episodes and should be used as the final arbiters for recognizing the greatest magnitude boundaries. Thus a boundary with a substantial amount of change of depositional regime and /or tectonic regime would be ranked higher (lower order) than one with no change in these regimes, even if it seemed that the one with no regime change had similar properties on the basis of the last three criteria.

It must be emphasized that for each basin the interpreter must establish his or her own hierarchy based on the listed criteria. Thus there is no characteristic first order sequence boundary that can be defined. First order boundaries in a given study are those that are interpreted to have the largest magnitude in the basin. Thus a first order boundary recognized in one basin may be somewhat different from a first order boundary recognized in another. Once a hierarchy has been established for a basin, that is each recognized order has been assigned a specific set of characteristics, the assignment of a given boundary to a given order can involve some subjectivity but in general can be done with reasonable consistency and objectivity.

This methodology emphasizes the establishment of a hierarchy based on the interpreted relative magnitude of the depositional sequence boundaries. Thus if one wants to establish a hierarchy for sequences rather than boundaries, the various sequence boundaries must be ranked first. The order of a sequence is equal to the order of its lowest magnitude (highest order) boundary. Thus a sequence with a fourth order boundary at the base and a first order boundary on top is a fourth order sequence.

This brings us back to our original problem of trying to avoid a chaotic and senseless delineation of sequences in a succession with multiple sequence boundaries of varying magnitude. With the establishment of a hierarchy of sequence boundaries as described above, one simple rule of hierarchies now allows us to recognize a sensible and orderly succession of sequences. This rule states that **a sequence cannot contain within it a sequence boundary that has an equal or greater magnitude (equal or lower order) than that of its lowest magnitude (highest order) boundary**. For example a second order sequence cannot contain a second or first order boundary. It can contain many higher order (3 -6) boundaries. This is of most importance and is the only way that a chaotic delineation of sequences can be avoided and an orderly one produced (Fig. 22).

Naming Individual Units in Sequence Stratigraphy

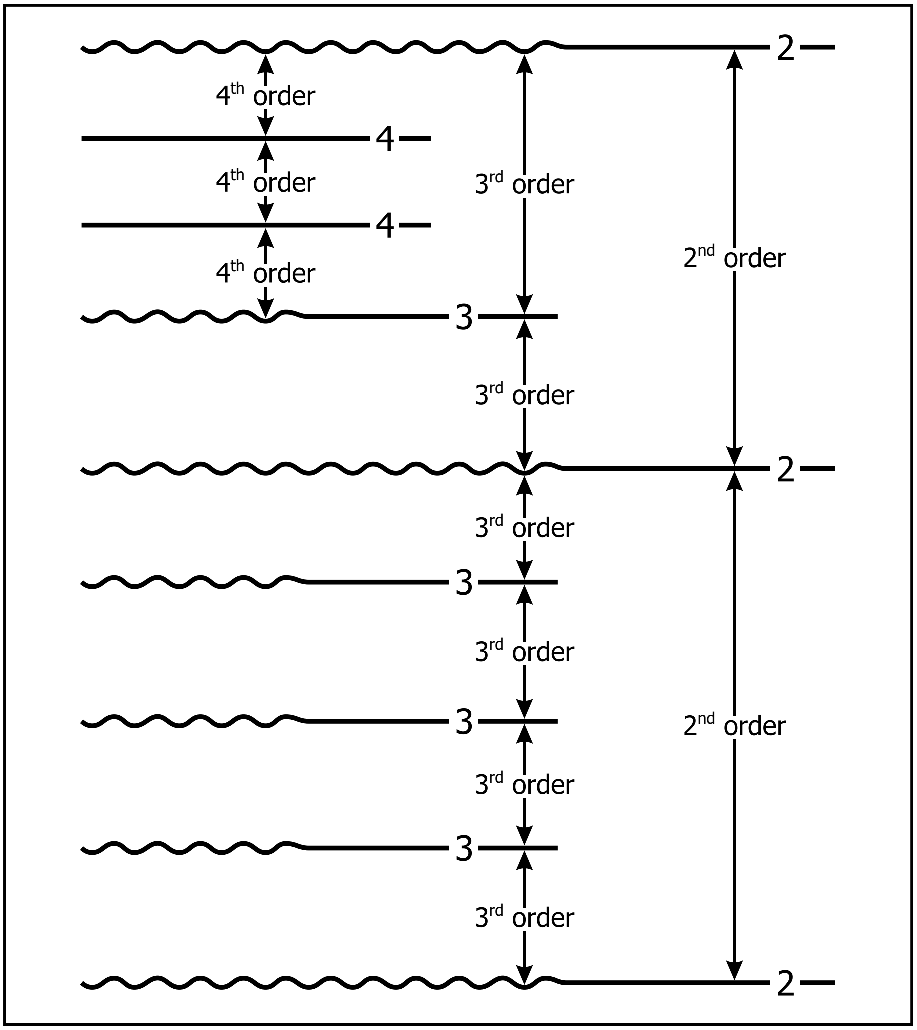


Fig. 22 Principles of determining the order of a sequence based on hierarchical rules. A sequence cannot contain a sequence boundary with the same or larger magnitude (same or lower order) as its smallest magnitude (highest order) boundary. Thus a 2nd order sequence cannot contain any 1st or 2nd order boundaries. In this way the chaos described in Fig. 20 can be avoided.

The above sections focused on the types of units which are recognized in sequence stratigraphy, and how each is defined. This resulted in four different types of sequence stratigraphic units being available for delineation and mapping: a depositional sequence, an R-T sequence, a transgressive systems tract and a regressive systems tract. Of course, in a specific succession in a given basin many such units of various orders can be delineated and mapped and this begs the questions of how to name individual units and whether or not such names should be formal or informal.

We have taken the position that, at this time, names for sequence stratigraphic units should remain informal and that there should not yet be any prescribed way in which informal names should be assigned to the units. We have chosen this route for two reasons. The first is the reality that sequence methodology and terminology is still a hotly debated topic and only time will determine if the methods and units advocated herein are widely accepted. It would seem only reasonable that the question of formalization not be examined until there is wide agreement on the various types of sequence stratigraphic units and how to recognize them.

Secondly, because sequence boundaries are somewhat interpretive and sequence designation depends to an extent on the establishment of a hierarchy which also has elements of subjectivity, revisions of boundaries and sequence order are going to happen frequently, especially as more data are collected. Thus it may be best if formalization is never instituted so as to allow the easy and possibly frequent reinterpretation of sequence boundaries and their enclosed sequences. To us, an informal nomenclature system can be just as effective for mapping and communication as a formal system and has the advantage of being much more flexible and easy to change.

In terms of how individual sequence stratigraphic units might be informally named, we feel most comfortable with allowing the interpreters to devise their own nomenclatural scheme, be it lettering, numbering or using the interpreted age of the unit. We would discourage the use of geographic names which might cause confusion with lithostratigraphic units. Because each sequence will contain a TST and an RST, systems tracts would not need informal names and are best referred to as the TST or RST of depositional sequence X or R-T sequence Y. It is possible that one or more convenient methods of informal nomenclature will become apparent and will eventually be widely adopted. Currently we do not have any preferred method to recommend.

Relationship between Sequence Stratigraphy and Other Stratigraphic Methodologies

With the proposed methodologies, surfaces and units, sequence stratigraphy can join the other “concrete” stratigraphies, lithostratigraphy, biostratigraphy, magnetostratigraphy and chemostratigraphy, as a useful and scientifically valid stratigraphic discipline. Lithostratigraphy is mainly used to create a very objective and stable nomenclatural framework for the strata of a basin. This acts as a reference framework for all studies carried out in the basin and is critical for communication. Formalization of lithostratigraphic units is essential to ensure effective communication and stability. Biostratigraphy, magnetostratigraphy, chemostratigraphy and, to a minor extent, lithostratigraphy supply low diachroniety, empirically-based, stratigraphic surfaces to allow the construction of an approximate chronostratigraphic framework for the succession. Sequence stratigraphy can also be an important contributor to such a quasi-chronostratigraphic framework through the addition of both low diachroniety surfaces (MFS, MRS) and approximate time barriers (SU, SR-U). Embry (in press) discusses correlation using sequence stratigraphic surfaces and the utility of integrating correlation surfaces from other disciplines, especially biostratigraphy, to corroborate sequence stratigraphic correlations and to allow a reliable chronostratigraphic interpretation.

Chronostratigraphy is not a “concrete” stratigraphic discipline because the designated unit boundaries are time surfaces and cannot be identified by one or more physical features. Rather, it is mainly a stratigraphic methodology which encompasses the practice of converting the reasonably objective correlation framework based on surfaces from the five “concrete”, stratigraphic disciplines into a time framework and correlating this framework to the global time scale. Thus, it is again emphasized that sequence stratigraphy should not been confused with chronostratigraphy as has often occurred in the past. Rather, sequence stratigraphy is best seen in the same light as the other four, “concrete”, stratigraphic disciplines - an important contributor to chronostratigraphic analysis.

Cyclostratigraphy, like chronostratigraphy, is also not a concrete stratigraphic discipline in which specific types of units and surfaces are recognized and correlated on the basis or physical criteria (Embry et al. in press). It is a methodology for testing if a succession of stratigraphic surfaces, delineated through one or more of the five stratigraphic disciplines, was generated by changes ultimately related astronomical cycles (Strasser et al, in press). The recognized stratigraphic surfaces are tuned to the periodicities of the precession, obliquity and eccentricity orbital cycles and, if a match is obtained, time resolution down to 20,000 years can be obtained. Sequence stratigraphic surfaces are well suited for cyclostratigraphic analysis with MRSs and MFSs being obvious candidates for such an analysis. The use of SUs and SR-Us for cyclostratigraphy might be somewhat problematic given the loss of section below such boundaries.

Real World Examples

Introduction

In this final section we present two examples of the application of depositional sequence stratigraphy to various stratigraphic successions in siliciclastic ramp and siliciclastic shelf/slope/basin settings. These examples are taken from published studies so are only briefly described and illustrated. The reader is referred to the references for more details on each example. Because maximum flooding surfaces are delineated as part of the analyses these examples also can be also considered examples of the application of R-T sequence analysis. Both depositional and R-T sequences use the same delineated sequence stratigraphic surfaces. They simply differ on what combination of surfaces is designated as sequence boundaries, and which are internal to the sequence so as to act as systems tract boundaries.

Siliciclastic Ramp

We have chosen the application of sequence stratigraphy to a succession of latest Triassic to earliest Jurassic (Rhaetian – Sinemurian) strata of the Sverdrup Basin, an extensional basin located in the Canadian Arctic Archipelago, to illustrate a siliciclastic ramp setting. The Sverdrup Basin underwent extension and high subsidence rates during the Carboniferous and early Permian. In Late Permian and all of the Mesozoic, the basin was dominated by regional subsidence which increased basinward and reflected regional sagging over the rift-dominated deposits. The physiography of the Mesozoic depositional setting evolved from a shelf/slope/basin during much of the Triassic to a ramp setting in latest Triassic to Cretaceous following the filling of the deep, central basin by the early Late Triassic. Embry (1991, 1993, 1997) summarized the Mesozoic sequence stratigraphy and depositional history of the basin. Available data for sequence analysis in the basin includes many measured sections, 120 wells with cuttings and core and reflection seismic data (Embry, 1991).

During the latest Triassic to Early Jurassic a major delta occupied the eastern portion of basin and, to the west, a shoreline- to offshore-shelf regime was present (Embry, 1982). Siliciclastic sediments were supplied to the western portion of the basin by longshore drift from the deltaic centre and by small rivers flowing into that part of the basin. The Rhaetian to Sinemurian succession throughout the basin comprises a second order sequence bound at the base by a first order boundary near the Norian/Rhaetian boundary and a second order boundary which formed near the Sinemurian/Pliensbachian boundary (Embry and Johannessen, 1992). The near-base Rhaetian sequence boundary is classified as a 1st order boundary because of the major tectonic and sedimentary shifts which occur across the boundary in combination with a very widespread unconformable portion and the loss through erosion of hundreds of metres of section on the basin flanks. The near base Pliensbachian boundary is classed as a 2nd order and is characterized by a widespread unconformable portion of the boundary and a major sedimentary regime shift across the boundary. There was no shift in tectonic regime across this boundary.

In the western Sverdrup Basin the Rhaetian-Sinemurian second order sequence is subdivided into three, third order sequences with the boundaries of each being dated as being close to an Age boundary. The near-base Hettangian and near-base Sinemurian boundaries are classed as being lower magnitude (3^{rd} order) because of the relatively minor change of depositional regime across each of the boundaries and the restriction of the unconformable portion of the boundaries to the basin flank. The three third order sequences have been informally named the Rhaetian sequence, the Hettangian sequence and the Sinemurian sequence. Only the Sinemurian sequence crops out on the southwestern and northwestern edges of the basin and the other two sequences are restricted to the subsurface in this area of the basin. Thus sequence- stratigraphic analysis in this area depends mainly on mechanical well log data supplemented by cuttings and cores. Available seismic data do not add any additional insights due to relatively low resolution. These sequences are described and illustrated in Embry and Johannessen (1992), Embry (1993) and Embry and Suneby (1994).

The Rhaetian sequence is illustrated in Figure 23, a stratigraphic cross section which runs from the southwestern margin (non-deltaic) of the basin to the center of the offshore shelf. As can be seen, prominent unconformable shoreline ravinements bound the sequence on the basin flank and basinward these give way to conformable maximum regressive surfaces. The lack of preservation of a subaerial unconformity is a common phenomenon for extensional basins which have low rates of subsidence on the basin margins. Note the truncation below the upper bounding unconformity which approximates the Triassic/Jurassic boundary. The MRSs represent the horizons of coarsest grain size, and log calibration with core (Embry and Johannessen, 1992) indicates this horizon coincides with the lowest gamma ray count. The MFS, which occurs within the Rhaetian sequence, coincides with the highest gamma ray values (also calibrated with core) and is easy to delineate and correlate throughout the area. The MFS allows the sequence to be subdivided into a TST and RST. The TST consists mainly of oolitic ironstone and the RST consists of a prograding shoreline to shallow-shelf sandstone unit which overlies and interdigitates with offshore shelf shale and siltstone.

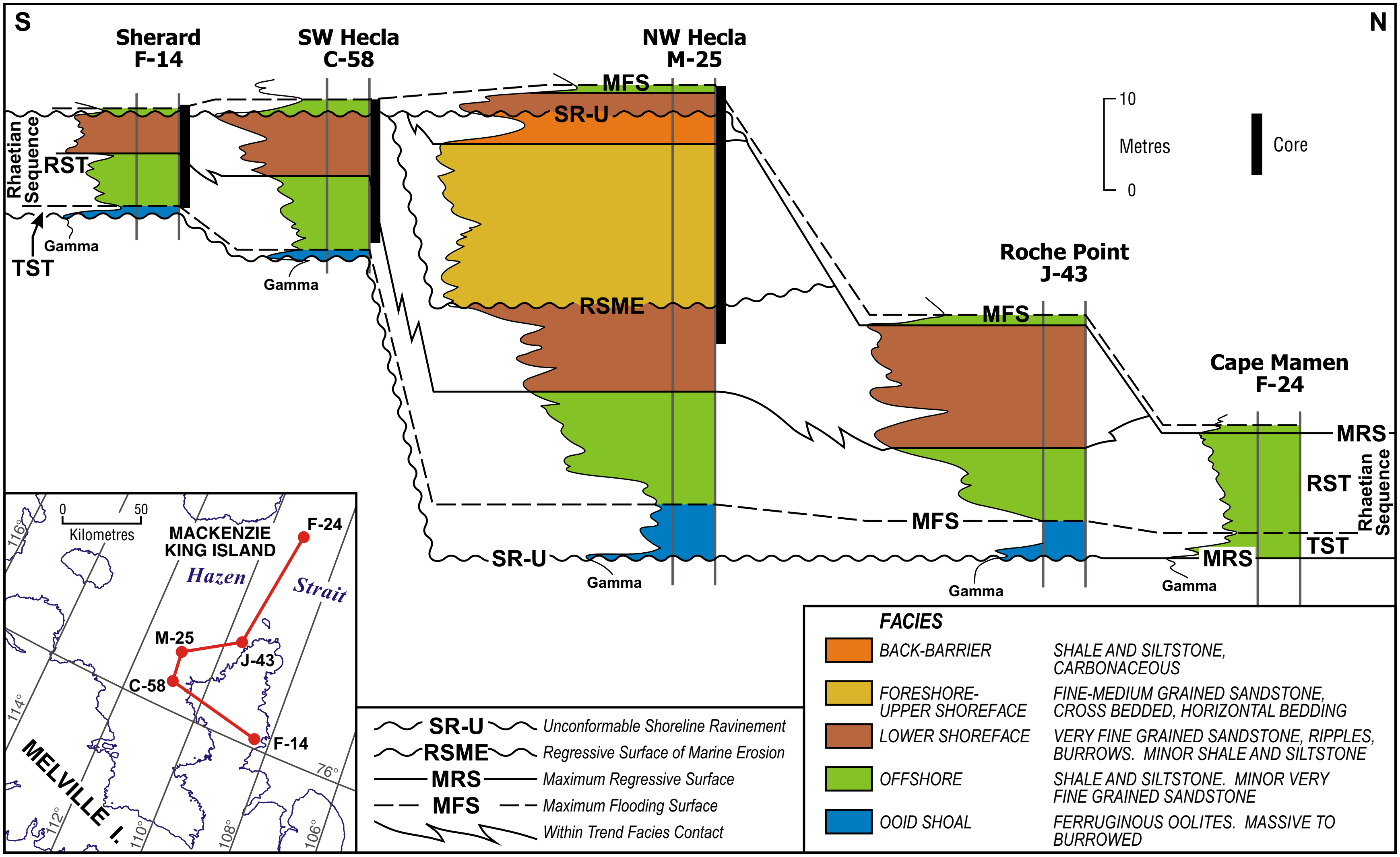


Fig. 23 A stratigraphic cross section of the Rhaetian depositional sequence in the western Sverdrup Basin of Arctic Canada (see Embry and Johannessen (1992) for details). The unconformable portion of the sequence boundaries are unconformable shoreface ravinements which cut down section to the south. Basinward, both SR-Us correlate with readily recognizable MRSs allowing the sequence boundaries to be extended from basin edge (Sherard well) to basin centre (Cape Mamen well). The MFS allows both a TST and RST to be delineated. Note that it is impossible to draw either a BSFR or a CC within the succession.

The Sinemurian depositional sequence is illustrated in Figure 24, a cross section that runs from the edge of the delta plain in the east westward to the centre of the offshore shelf in the southwest. Due to the influence of the delta, the Sinemurian sequence in this area is much thicker than the Rhaetian sequence illustrated in Figure 23. Again, unconformable shoreline ravinements form the unconformable portion of the depositional sequence boundaries and they correlate with prominent MRSs which are easily traced westward over the extent of the cross section. A MFS is also easily delineated and correlated and it subdivides the Sinemurian sequence into a TST and a RST.

In this sequence the TST consists of a relatively thick interval of alternating shallow-water sandstones and offshore shales in the east (higher order depositional sequences) and a thinner succession of offshore shales and siltstones in the west. The RST consists of a prograding succession of offshore to prodelta shale and silt overlain by delta front sandstones which thin and disappear basinward. Note that it is not possible to scientifically subdivide the RST in either the Rhaetian or Sinemurian depositional sequence into a HST, FSST and LST because, as noted by other authors (e.g. Catuneanu, 2006), recognition of the “basal surface of forced regression” is impossible and the time surface equivalent to the start of base level rise is approximated by the MRS. This again illustrates that these model-based, hypothetical surfaces (BSFR, CC) and units (HST, LST, FSST) have no scientific validity for use in sequence stratigraphy.

In this study area the use of depositional sequence analysis rather than R-T sequence analysis is warranted given the common occurrence of the unconformable shoreline ravinements. The delineation and correlation of the sequences each with two systems tracts allows the reservoir and trapping potential to be evaluated for each of the six systems tracts recognized (Embry and Johannessen, 1992). This provides a far better assessment of these aspects of petroleum geology than a lithostratigraphic approach would.

Siliciclastic Shelf/Slope/Basin

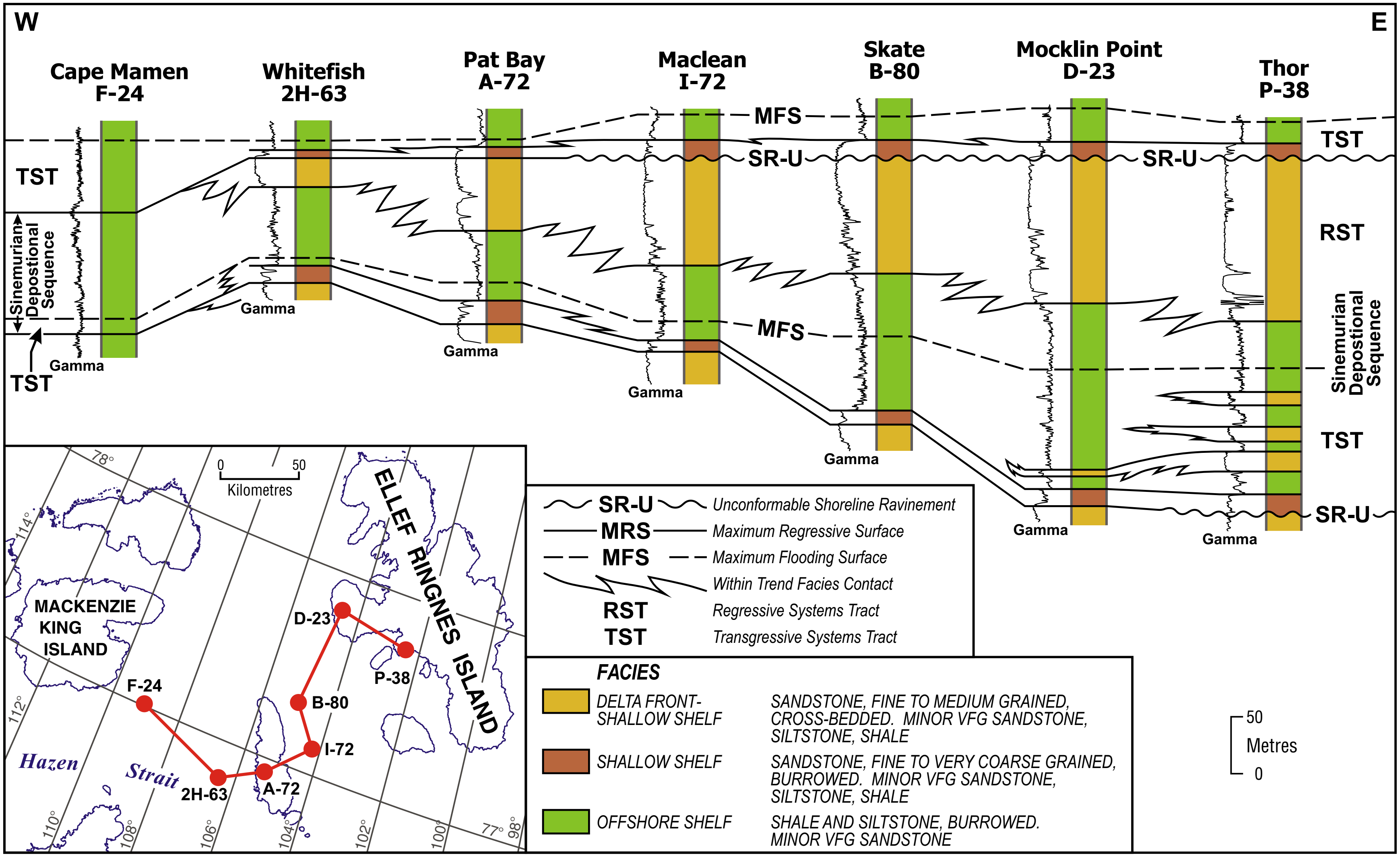


Fig. 24 A stratigraphic cross section of the Sinemurian depositional sequence in the western Sverdrup Basin of Arctic Canada (see Embry and Johannessen (1992) for details). Over most of the section easily recognizable MRSs in a variety of facies form the sequence boundaries and these correlate with shoreface ravinement unconformities to the east. The MFS is easily delineated, allowing a TST and RST to be recognized. Again any attempt to recognize a hypothetical BSFR or CC would be fruitless ad unscientific.

We have chosen the well exposed and intensely studied, Eocene succession from Spitsbergen, an island located north of Norway on the northwest corner of the Barents Shelf, to illustrate the application of sequence stratigraphy to a siliciclastic shelf to basin setting,. The Eocene strata were deposited within a large, north-to-south trending foreland or transpressional basin, the Central Tertiary Basin of Spitsbergen. This basin formed during the late Palaeocene and early Eocene, contemporaneous with the development of the West Spitsbergen Orogenic Belt, along the western coast of Spitsbergen, as the Eurasian and Greenland plates slid past each other (Steel et al, 1985).

The Paleocene-Eocene section on Spitsbergen comprises several 2nd order sequences, bound at the base by a first order boundary at the Cretaceous-Tertiary transition. This boundary represents a major tectonic event and the Tertiary strata unconfomably overlie Early Cretaceous strata. The studied 2nd order sequence has its lower boundary near the Paleocene –Eocene boundary, which represents a large tectonic event with a major change in depositional direction from easterly derivation to westerly derivation as the Spitsbergen Orogenic Belt developed (Steel et al, 1985). The Eocene 2nd order sequence is about 1.5 km thick and about 6 my in duration. The upper boundary is truncated by the present erosion surface. Seismic scale, 2D mountainsides (2-10 km long and 1000 meter high) provide excellent exposures of the strata which consist of a long series of clinoforms (10s of km of basinward accretion) that migrate across the basin (Johannessen and Steel, 2005). The shelf margin style is low shelf-to-basin relief/sediment overfilled basin with shelf-edge clinoforms and associated attached deep water sands (Hadler-Jacobsen et al., 2005). The definition and application of clinoforms and shelf-edge trajectories are described in Steel and Olsen (2002) and Johannessen and Steel (2005).

During the early Eocene, the Central Basin filled (>2 km) west to east with marine and non-marine clastic sediment. The clinoforms, reflecting a basinward accretion of the Eocene shelf margin, can be followed through the coastal-plain, marine- shelf, slope and basin- floor stratigraphy (Johannessen and Steel, 2005). This overall progradation has a variation of trajectory style through time, from flat to rising. The 2nd order sequence is thus divided into 3rd order sequences based on significant changes in the trajectory pattern (flat to rise and back to flat trajectory pattern) of shelf margin accretion. Each 3rd order sequences is built up of 4th order clinoforms that stand out as 20-30 m thick amalgamated sandstone benches on the shelf but with thick shale packages above and below in their outer shelf and slope segments (fig 14 in Johannessen and Steel, 2005).

The clinothems have a variable amount of sandstone associated with the slope and basinal settings. Some are very shale prone (type 4 clinothems of Steel et al., 2000 and figure 3 in Mellere et al., 2002) and can be recognized on the mountainside only by the presence of heterolithic units of thin-bedded sandstones and siltstones that stand out from the uniform slope shales. Other clinothems are sand-prone across much of the storm- and wave-dominated shelves, but evidently delivered little sand onto the slope because the shoreline did not reach the shelf-edge during its development (type 3 clinothem in figure 3 in Mellere et al., 2002). Type 2 clinothems (figure 3 in Mellere et al., 2002) were generated when the shoreline approached the shelf margin and shelf-edge deltas formed. These are sand-prone along both shelf and slope segments but with insignificant sand volumes on the time-equivalent basin floor. The three clinothem types described above all developed during rising shelf margin trajectories which signify long term base level rise.

Type 1 clinothems (figure 3 in Mellere et al., 2002) are associated with basin-floor fans as well as upper slope channels and major slope collapse features. These clinothems were deposited during flat shoreline trajectory, signifying a dominance of base level fall (Steel et al., 2001; Johannessen and Steel, 2005). The sequence stratigraphic surfaces and units recognized in type 1 clinothems are illustrated in Figures 25 and 26.

Figure 25 is a sketch from the Storvola Mountain and illustrates deposition during a slight rising trajectory progradation. On the shelf there is a marked change from delta mouth bars and shoreline sandstones to tidal reworked coarser sandstone, and the surface separating these different facies is interpreted as an unconformable shoreline (tidal) ravinement surface (SR-U). This SR-U surface joins to a maximum regression surface

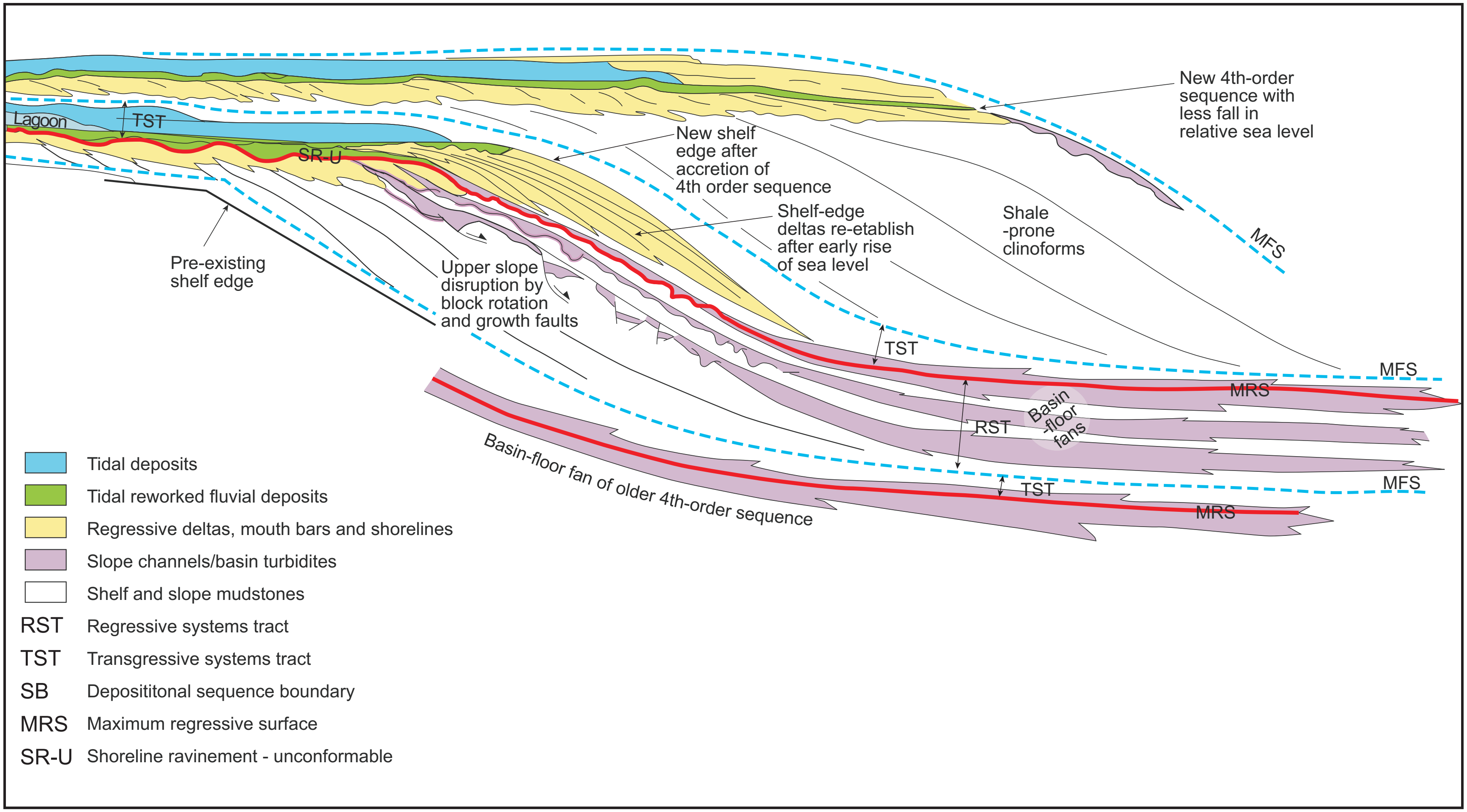


Fig. 25 Stratigraphic cross section on a clinothem with a slightly rising shelf margin trajectory on Storvola Mountain, Spitsbergen (see Johannessen and Steel, 2005) for details). On the shelf the depositional sequence boundary coincides with an unconformable shoreline ravinement. This surface correlates with a prominent MRS which is an erosional surface on the slope and a conformable surface near the top of the turbidite strata in the basin.

Following a major transgression, a shelf edge delta built seaward and is part of an expanded TST (see text). An MFS can be followed from the basin far onto the shelf and subdivides the depositional sequence into a TST and overlying RST.

(MRS) at the base of slope channels. In the basinal setting the MRS is placed at the maximum progradation of a basin floor fan, at the top of an upward increasing bed thickness trend, and where the fan starts to retreat. Both delta progradation to the shelf edge and the deep water fan progradation occurred during regression, and the resulting deposits are placed in the regressive system tract (RST). Above the depositional sequence boundary is a relative thick transgressive system tracts (TST) deposited during the overall relative rising trajectory. In the basal portion of the TST a thin marine shale unit extends onto the outer shelf and is sometimes followed by shelf-edge delta deposits which build basinward. Such local shelf-edge delta deposits are sometimes mistakenly referred to as LST deposits. The underlying transgressive marine strata and the restricted occurrence of such deposits to high input centres, demonstrate they are clearly part of the TST. A maximum flooding surface (MFS), located low within a shale-dominated package, can be traced from the basin onto the shelf (Fig. 25) and separates the TST from the overlying RST.

Figure 26 illustrates the stratigraphic relationships which resulted from deposition during a flat trajectory progradation. Overall they are very similar to those described above with a SR-U on the shelf and a correlative MRS farther basinward on the slope and in the basin. Notably the TST is much thinner due to less accommodation space at the shelf edge and again an MFS can be correlated from the basin to far onto the shelf. Both these examples illustrate that transgression happened essentially at the start of base level rise and there is no evidence of any strata being deposited after base level rise but before the start of transgression (the LST of the Jervey Model). Furthermore, it is impossible to delineate a surface which equates to the start of base level rise (BSFR), despite almost continuous exposure, and thus any attempt to separate out an FSST is fruitless.

These beautifully exposed shelf to deep basin strata nicely demonstrate how the unconformities on the shelf correlate with MRSs on the outer shelf, slope and basin and allow depositional sequences to be objectively determined. Given the widespread, shelf unconformities, R-T sequences would not be applicable in this setting. The readily recognized MFS in the depositional sequences allows them to be divided into a TST and

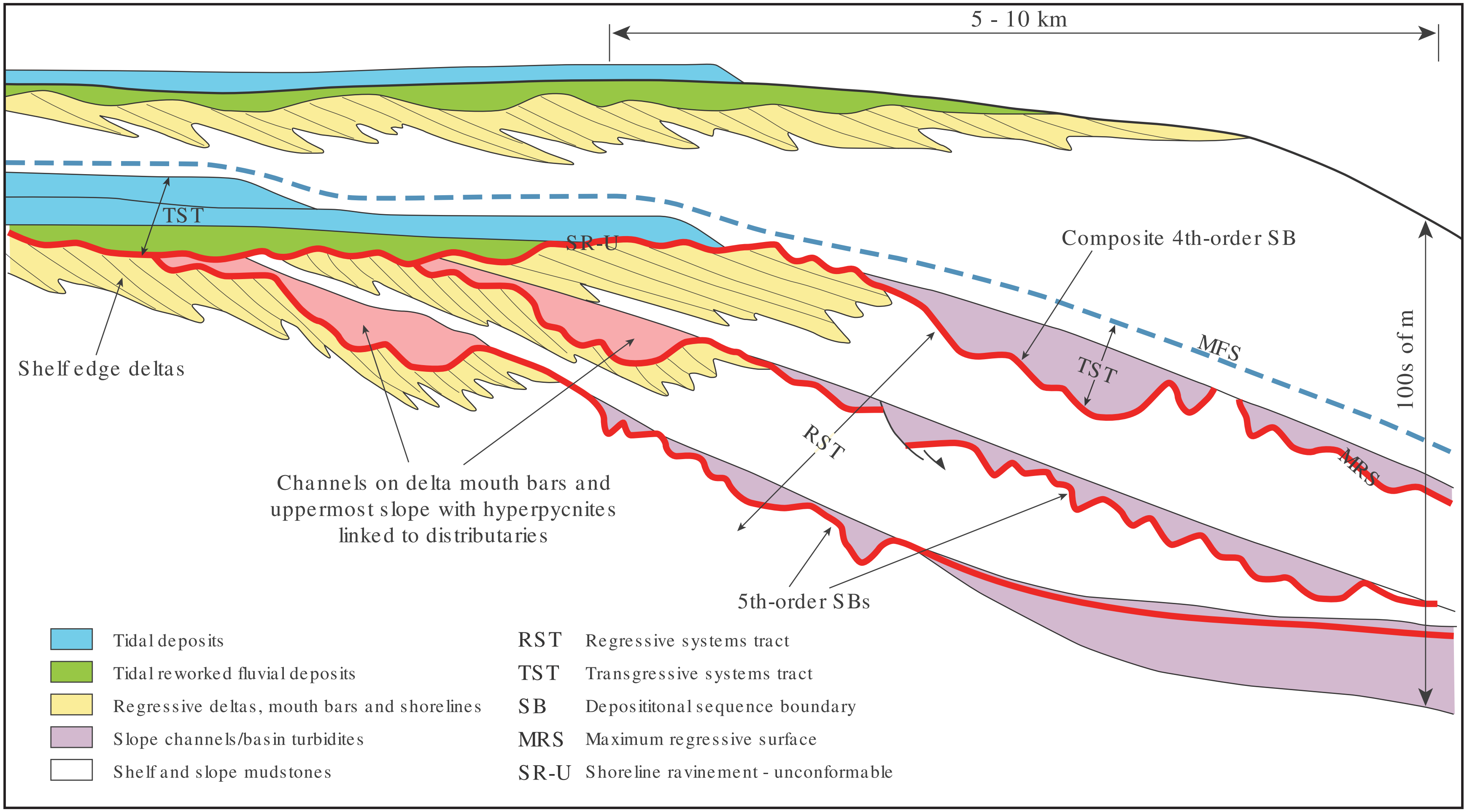


Fig. 26 Stratigraphic cross section of a clinothem with a flat shelf margin trajectory from Brogniartfjellet, Spitsbergen (see Johannessen and Steel, 2005) for details). The stratigraphic relationships are very similar to those illustrated on Fig. 25 with the SR-U and correlative MRS forming a depositional sequence boundary and an MFS allowing both a TST and RST to be delineated. The TST is much thinner in this case with no development of a shelf edge delta. A widespread MFS allows a TST and RST to be recognized.

overlying RST. Like the previous example, these strata demonstrate the impossibility of trying to delineate model-driven, hypothetical units such as FSSTs and LSTs.

Recommendations

Based on the guiding principles, the historical development, the available data, and actualistic and logical interpretations for sequence stratigraphy, we have formulated twenty recommendations for sequence stratigraphic methodology and terminology.
We recommend:

1) That sequence stratigraphy be accepted as a concrete, stratigraphic discipline in which stratigraphic surfaces are defined and delineated on the basis of observable changes in depositional trend. Such surfaces must have physical features which allow them to be considered objective and reproducible as demanded by the NACSN Code and to be recognizable in most instances in well exposed strata.
2) That surfaces defined on criteria other than changes in depositional trend, that is, surfaces from other stratigraphic disciplines, should not be used as unit boundaries in sequence stratigraphy. This especially includes lithostratigraphic surfaces such as within-trend facies changes (e.g. base of turbidities or base shallow marine facies) and marine flooding surfaces.
3) That the four main surfaces of sequence stratigraphy be named subaerial unconformity, shoreline ravinement, maximum regressive surface and maximum flooding surface, and that these surfaces, because of their relationship to time, be used for bounding units of sequence stratigraphy.
4) That surfaces in sequence stratigraphy which are consistently highly diachronous (normal shoreline ravinement and regressive surface of marine erosion) not be used for unit boundaries except in rare cases (e.g. RSME cuts through an SU).
5) That hypothetical time surfaces, such as the start of base level fall (the “basal surface of forced regression” and correlative conformity of some authors) and the start of base level rise (the “correlative conformity” of Hunt and Tucker, 1992)), not be considered as surfaces of sequence stratigraphy due to a lack of any observable physical features and objective criteria for their recognition in most

instances. Such abstract time surfaces should not be used as boundaries of units of sequence stratigraphy.

6) That a sequence be the primary unit of sequence stratigraphy and that it be a generic unit defined as “a unit bound by a specific type of unconformity and its correlative surfaces”.
7) That specific types of sequences be defined and named on the basis of specific types of unconformities as demonstrated in recommendations 8 and 10.
8) That the sequence type, which employs a subaerial unconformity as its defining type of unconformity, be named a depositional sequence.
9) That an unconformable shoreline ravinement and a maximum regressive surface, which are the correlative surfaces of a subaerial unconformity, be part of the boundary of a depositional sequence. With this recommendation the term T-R sequence becomes equal to a depositional sequence and thus redundant.
10) That the sequence type, which employs a maximum flooding surface as its defining type of unconformity, be named an R-T sequence.
11) That sequences be divided into component units called systems tracts on the basis of the occurrence of bona fide sequence stratigraphic surfaces within a sequence.
12) That a transgressive systems tract (TST) be defined as a unit bound by a subaerial unconformity, unconformable shoreline ravinement and/or maximum regressive surface below and a maximum flooding surface above.
13) That a regressive systems tract (RST) be defined as a unit bound by a maximum flooding surface below and a subaerial unconformity, unconformable shoreline ravinement and/or maximum regressive surface above.
14) That proposed systems tracts such as lowstand systems tract, highstand systems tract and falling stage systems tract (forced regressive systems tract) not be considered units of sequence stratigraphy because one or both of the proposed boundaries of these units are either a hypothetical, unrecognizable, time surface or a highly diachronous, lithostratigraphic surface.
15) That subjective terms such as lowstand, highstand and forced regressive be used as descriptive adjectives for facies interpreted to be deposited during a specific interval of a base level cycle.

16) That, in the future, any new type of sequence or systems tract be defined on the basis of bona fide, sequence stratigraphic surfaces.
17) That a parasequence not be considered a sequence stratigraphic unit because, depending on its definition, it is either a lithostratigraphic unit or an already defined sequence type.
18) That sequence boundaries and sequences in a given basin be organized into different classes (orders) on the basis of the interpreted relative magnitude of the boundaries. The largest magnitude boundaries would be assigned to the first order.
19) That a sequence hierarchy not be based on the boundary frequency which is an interpretation resulting from an established hierarchy rather than a descriptive characteristic of a boundary
20) That sequence stratigraphic units not be formalized.

Concluding Remarks

Sequence stratigraphy has evolved a great deal since Sloss et al (1949) first defined a sequence and thus initiated the discipline of sequence stratigraphy. Vail et al (1977) brought sequence stratigraphy into mainstream stratigraphic practice by defining a sequence as a unit bound by an unconformity or its correlative conformity. This allowed sequence boundaries to be correlated over much or all of a basin, thus greatly increasing the utility of such a stratigraphic methodology. Vail et al (1977 also emphasized the recognition of specific types of sequence stratigraphic surfaces such as a subaerial unconformity and maximum flooding surface and the use of these in defining specific types of sequence stratigraphic units. Work has progressed such that four sequence stratigraphic surfaces, subaerial unconformity, shoreline ravinement, maximum regressive surface and maximum flooding surface, have been well characterized for different types of sedimentary input and for different physiographic settings. Two types of sequences, depositional sequence and R-T sequence, are defined on the basis of these four, empirically recognizable, sequence stratigraphic surfaces. Each of these sequence types can be subdivided into two systems tracts, a transgressive systems tract and a regressive systems tract. These empirical surfaces and units allow sequence stratigraphy to be a very useful and scientifically acceptable “concrete” discipline that is of much value for establishing a quasi-chronostratigraphic framework and for mapping basin wide units. Sequence stratigraphy can now take its place beside the other time-honoured stratigraphic disciplines.

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