CHAPTER THREE

Two Approaches to Sequence Stratigraphy

Ashton F. Embry*,[1] and Erik P. Johannessen[†]
*Embry Corp, Calgary, AB, Canada
[†]EP Skolithos, Stavanger, Norway
[1]Corresponding author: e-mail address: ashtonfoxembry@gmail.com

Contents

Abstract

Sequence stratigraphy is a stratigraphic discipline in which the defined stratigraphic surfaces represent either breaks in deposition or changes in depositional trend. Two approaches for defining sequence stratigraphic surfaces and units have evolved, with one being inductive and the other deductive.

The empirical, inductive approach defines surfaces based on observable, physical characteristics. Five surfaces, subaerial unconformity (SU), unconformable shoreline ravinement (SR-U), slope onlap surface (SOS), maximum regressive surface (MRS), and maximum flooding surface (MFS), are used to define inductive sequence units and to construct a correlation framework. Two different types of sequences (depositional T-R, genetic stratigraphic) and two systems tracts (transgressive systems tract, regressive systems tract) are employed in the inductive approach.

In contrast, the deductive approach defines sequence stratigraphic surfaces in terms of theoretical events on a base-level curve (e.g., start base-level fall). Three

Stratigraphy & Timescales, Volume 2
ISSN 2468-5178
http://dx.doi.org/10.1016/bs.sats.2017.08.001

deductive surfaces (SU, MRS, and MFS) used for unit definition and correlation are the same as those employed by the inductive approach. Two surfaces, not recognized in the inductive approach, are also used to delineate units and for correlation. Notably, both are chronostratigraphic surfaces which display no diagnostic physical characteristics. These surfaces include the basal surface of forced regression (BSFR), the depositional surface at the start of base-level fall, and the correlative conformity (CC), the depositional surface at the start of base-level rise. A sequence is defined as a succession of strata deposited during a full base-level cycle and associated change in accommodation or sediment supply. Recognition of the five surfaces has allowed the definition of four types of sequences (depositional sequence type 1 and 2, T-R, genetic stratigraphic), with each type being divided into four systems tracts (lowstand, transgressive, highstand, and falling stage).

The decision as to what approach to use—inductive or deductive—depends on the robustness of the available data and whether the BSFR and CC can be recognized with reasonable objectivity and consistency over the study area. Caution must be exercised to avoid the pitfall of trying to force fit data into the deductive approach by interpreting an inappropriate surface (e.g., facies change) as either the BSFR or CC. In many situations, especially when seismic data are not available, it is not possible to recognize and correlate the BSFR and/or the CC with objectivity. In these cases, the inductive approach is required for unit delineation and correlation.

1. INTRODUCTION

Sequence stratigraphy has become a popular methodology for correlating sedimentary strata and constructing a quasi-chronostratigraphic framework for a basin. Such a framework, in conjunction with the sedimentology of the strata, is fundamental for interpreting paleogeography and depositional history in terms of changes of base level, shoreline movement, and/or sediment supply.

As significant as sequence stratigraphy has become over the past 30 years, controversies regarding sequence stratigraphic terminology and methodology exist (Burgess and Prince, 2015; Catuneanu et al., 2009, 2011; Embry, 1995, 2002, 2009; Embry and Johannessen, 1993; Madof et al., 2016). Such controversies seem in part to be rooted in stratigraphic classification problems addressed by Hedberg (1958) who stressed the need for precise definitions of stratigraphic terms so as "to allow ready communication and clear understanding." He elaborated, "Confusion results from ill-defined terms which are used with a certain meaning by one man and with a different meaning by another." Hedberg (1958) also highlighted the need to avoid "the mixing of the objective and the subjective in our terminology" and lamented "the millions of hours wasted in stratigraphic controversy" merely as a result of such a mixture.

We have used sequence stratigraphy in our basin analysis studies since 1977, when the modern era of sequence stratigraphy began with the watershed publication of the Exxon definitions and methodology (Payton, 1977). By 1990, it was apparent to us that two different approaches to sequence stratigraphic methodology and classification were in use and that the existence of two different approaches might well be contributing to methodological and communication problems associated with sequence stratigraphy. Miall and Miall (2004) drew attention to the two approaches which they termed inductive and deductive. Regarding sequence stratigraphy, Miall (2004) commented that, "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."

The inductive approach to sequence stratigraphy requires a methodology and classification system similar to the other empirical and material-based, stratigraphic disciplines (Embry, 2002, 2010; Embry and Johannessen, 1993). The deductive approach, conceptual and somewhat model-driven (Miall, 2004; Miall and Miall, 2004), has dominated sequence stratigraphic methodology and terminology for the past 30 years (Catuneanu, 2006; Catuneanu et al., 2009, 2011; Helland-Hansen and Gjelberg, 1994; Hunt and Tucker, 1992; Jervey, 1988; Posamentier and Allen, 1999; Van Wagoner et al., 1990). The deductive approach to sequence stratigraphy differs from other stratigraphic disciplines as expressed by Helland-Hansen (2009): "Sequence stratigraphy is and will necessarily remain interpretive in its philosophical essence, far more so than these other methodological branches of stratigraphy."

As demonstrated below, the inductive approach to sequence stratigraphy, which is empirical and material-based, is readily applied using a wide variety of data sets. This contrasts with the deductive approach, which generally relies on very specialized data in order to be applied in a scientific and reliable manner. It is critical that those engaged in sequence stratigraphic investigations are aware of the existence of the two distinctly different approaches to the discipline, and of the problems that might arise if one does not apply that approach most appropriate to their study. This contribution describes both sequence stratigraphic methodologies emphasizing the strengths and weaknesses of each so as to allow the practitioner to make an informed choice as to which approach is best suited to his or her work.

2. INDUCTIVE APPROACH TO SEQUENCE STRATIGRAPHY

2.1 Sequence Stratigraphy as an Inductive Stratigraphic Discipline

Wikipedia defines stratigraphy as "a branch of geology which studies rock layers (strata) and layering (stratification)." We would add that such layers must obey Steno's Law of Superposition (younger strata overlie older strata). Stratigraphic analysis includes the description and interpretation of physical, biological, and chemical properties of strata and the recognition of a variety of stratigraphic surfaces and units on the basis of vertical changes of the aforementioned properties (Hedberg, 1959).

Inductive stratigraphy seeks to define and delineate surfaces on the basis of observable, physical features. Each inductive, stratigraphic discipline concentrates on vertical variations of a specific property of strata. Inductively defined stratigraphic surfaces serve as surfaces of correlation and define the boundaries of stratigraphic units of the discipline. Established, inductive, stratigraphic disciplines and their characteristic, observable properties include lithostratigraphy (changes in lithology), biostratigraphy (changes in fossil content), magnetostratigraphy (changes in magnetic properties such as polarity), and chemostratigraphy (changes in chemical properties such as isotope ratios).

Two types of changes in sedimentation leave a record in the form of sequence stratigraphic surfaces—breaks in deposition (unconformities, diastems) and changes in depositional trend, including fining-upward or coarsening-upward trends. Given the above, we define sequence stratigraphy as the recognition and correlation of stratigraphic surfaces which represent depositional breaks and changes in sedimentation trend in the rock record. Such changes are recognized by sedimentological criteria and geometric relationships.

Finally, it is useful, but not essential, to have a solid theoretical foundation linking the generation of the various surfaces of a given stratigraphic discipline to phenomena that occur on our planet. For example, biostratigraphic surfaces represent changes in fossil content that are due mainly to a combination of evolution and shifting environments of deposition. It is noteworthy that biostratigraphy flourished long before the theory of evolution was developed. Similarly, most sequence stratigraphic surfaces were recognized in the rock record and used for correlation before a model was developed to explain their existence. It is now generally accepted that surfaces included in sequence stratigraphy are generated by the interaction of changing rates of sedimentation and base-level movement (Barrell, 1917; Burgess and Prince, 2015; Catuneanu, 2006; Embry, 2002; Jervey, 1988, 1993; Wheeler, 1958, 1959, 1964).

2.2 Inductive Sequence Stratigraphic Surfaces

It is essential that inductive sequence stratigraphic surfaces are material-based and guided by objectivity and reproducibility. It is also important that such surfaces (1) can be recognized in diverse stratigraphic successions, from undisturbed basin fill to tectonically disrupted strata with only fragmentary continuity, and (2) can be potentially delineated in outcrop sections, mechanical well logs supported by analysis of chip samples and discontinuous core, seismic data, and any combination of these data types.

Seven inductive surfaces of sequence stratigraphy have been described in the literature and are most commonly referred to as: (1) subaerial unconformity (SU), (2) unconformable shoreline ravinement (SR-U), (3) diastemic shoreline ravinement (SR-D), (4) maximum regressive surface (MRS), (5) maximum flooding surface (MFS), (6) slope onlap surface (SOS), and (7) regressive surface of marine erosion (RSME). Each of these surfaces is characterized by a combination of observable attributes that allow it to be distinguished from other surfaces. Reliable recognition of inductive surfaces requires adequate and reliable sedimentological information from outcrop and/or the subsurface as well as geometric relationships from outcrop exposures, correlated cross sections, and/or seismic data. Finally, it must be emphasized that although the surfaces tend to have names which have a genetic overtone (e.g., MRS), their definitions and criteria of recognition in the inductive approach are devoid of any genetic relationships, that is, they are objective.

Embry (2009, 2010) discussed the inductive surfaces, including their various sedimentological and stratigraphic attributes (Fig. 1), their inferred relationships with base-level changes (Figs. 2–4), their relationships with each other (Figs. 3 and 4), their significance as indicators of time (Fig. 1), and their value to regional correlation. Five of the seven surfaces (SU, SR-U, SOS, MRS, MFS) are, by virtue of their low diachroneity, especially useful for establishing a chronostratigraphic relationships and as bounding surfaces of sequence stratigraphic units. The highly diachronous SR-D and RSME surfaces are useful for facies analysis within an established sequence stratigraphic framework (Embry, 2010).

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 C.U. marine shelf	Fining and deepening upward shallow marine shelf	Major, regional truncation below and onlap above	Time barrier
Diastemic 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 diachroneity
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 diachroneity
Slope Onlap Surface	Scoured	Marine Slope Deposits. Often coarsening - upward	Marine Slope to Basin Deposits. Often coarsening - upward	Truncation to conformable below and onlap above	Time barrier

Fig. 1 A summary of the characteristics of the surfaces of sequence stratigraphy recognized by the inductive approach. *Modified from Figure 5 of Embry, A.F., 2010. Correlating siliciclastic successions with sequence stratigraphy. In: Ratcliffe, K., Zaitlin, B. (Eds.), Application of Modern Stratigraphic Techniques: Theory and Case Histories, SEPM Special Publication 94. pp. 35–53.*

2.3 Inductive Sequence Stratigraphic Units

Sequence stratigraphy relies upon three types of units—sequence, systems tract, and parasequence. However, the inductive approach to sequence stratigraphy utilizes only sequences and systems tracts with the parasequence being classified as a lithostratigraphic unit on the basis of its accepted definition (see discussion below). Inductive sequences and

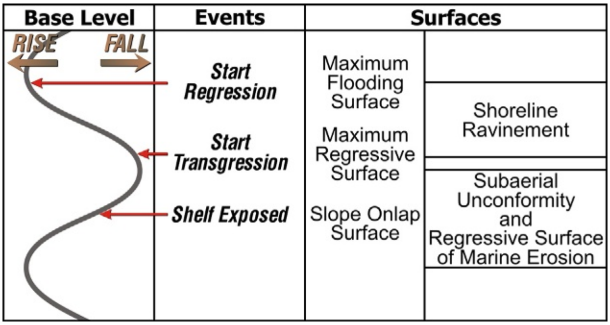

Fig. 2 Base-level change model for the generation of the inductive surfaces of sequence stratigraphy. Each surface is generated during a specific time interval of a base-level cycle as a consequence of the interaction of rates of change of accommodation space and sedimentation. *Modified from Figure 1 of Embry, A., 2002. Transgressive-regressive (T-R) sequence stratigraphy. In: Armentrout, J., Rosen, N. (Eds.), Sequence stratigraphic models for exploration and production. Gulf Coast SEPM Conference Proceedings, Houston, pp. 151–172.*

systems tracts are primarily defined by the inductive, sequence stratigraphic surfaces which bound them.

2.3.1 Sequence

The primary unit of sequence stratigraphy is the sequence, initially defined in an empirical manner by Sloss et al. (1949) as a stratigraphic unit bound by large-scale, regional unconformities. Wheeler (1958) retained this overall definition but extended the term sequence to units bounded by smaller-scale unconformities. Although a particular type of bounding unconformity was not specified by either Sloss et al. (1949) or Wheeler (1958), applications of this concept in the 1950s and 1960s used either SUs or unconformable shoreline ravinements as sequence bounding surfaces (e.g., Sloss, 1963; Wheeler, 1958). These types of unconformities are mainly confined to the flanks of a basin, limiting their correlation over much of the central portions of a basin and therefore their practical application to basin analysis.

In 1977, Exxon researchers demonstrated in a series of articles (Payton, 1977) that the seismic reflectors encompassing basin flank unconformities could be traced basinward into submarine unconformities and conformable surfaces. Thus, the definition of a sequence was modified to include a unit "bounded by unconformities or their correlative conformities" (Mitchum et al., 1977). Accordingly, a sequence boundary was recognized as a combination of surfaces rather than just an unconformity and, importantly, it permitted the correlation of sequence boundaries and their contained

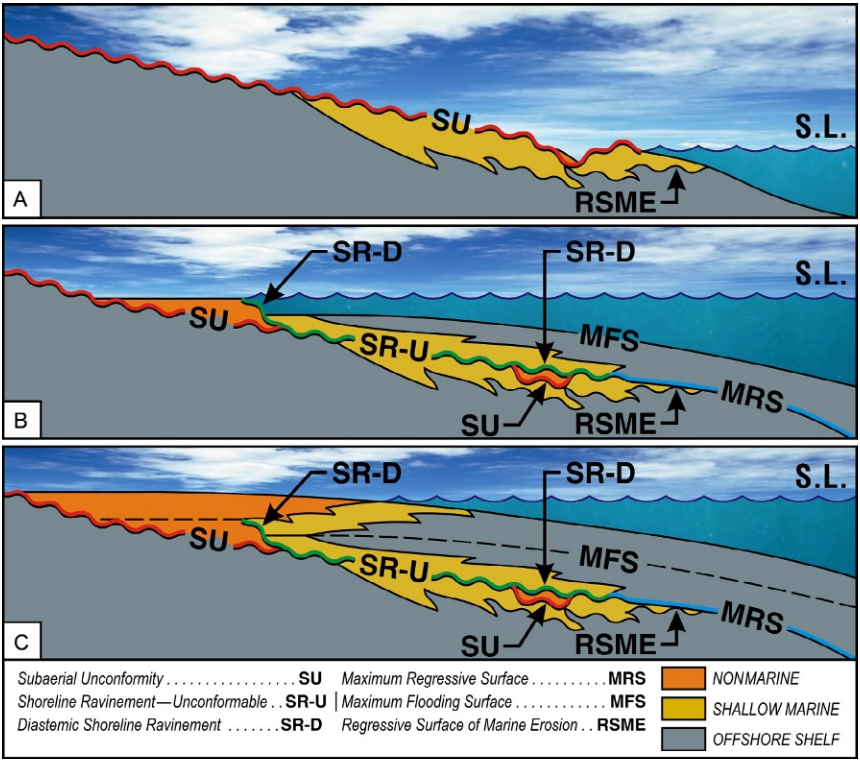

Fig. 3 Schematic evolution of the inductive sequence stratigraphic surfaces in a ramp setting. (A) By the end of base-level fall, the subaerial unconformity (SU) reaches its maximum extent and a regressive surface of marine erosion (RSME), a highly diachronous surface at the base of shoreface deposits, has migrated basinward. (B) An unconformable shoreline ravinement (SR-U) begins to migrate landward as base level starts to rise, eroding portions of the SU. Finer sediment is deposited at any given marine locality and a maximum regressive surface (MRS) is generated in deeper water. A maximum flooding surface (MFS) develops near the time of maximum transgression. (C) In the late phase of base-level rise a progradational, coarsening-upward succession begins to accumulate on the shelf. *Modified from Figure 4, Embry, A.F., 2010. Correlating siliciclastic successions with sequence stratigraphy. In: Ratcliffe, K., Zaitlin, B. (Eds.), Application of Modern Stratigraphic Techniques: Theory and Case Histories, SEPM Special Publication 94. pp. 35–53.*

sequences across an entire basin. This greatly expanded the utility of sequences for basin analysis.

Two types of sequences were defined in the late 1980s. Exxon scientists (Van Wagoner et al., 1988) defined a depositional sequence as a unit bound by SUs or their correlative conformities. Contemporaneously, Galloway (1989) proposed a sequence bounded by MFSs which he termed a genetic

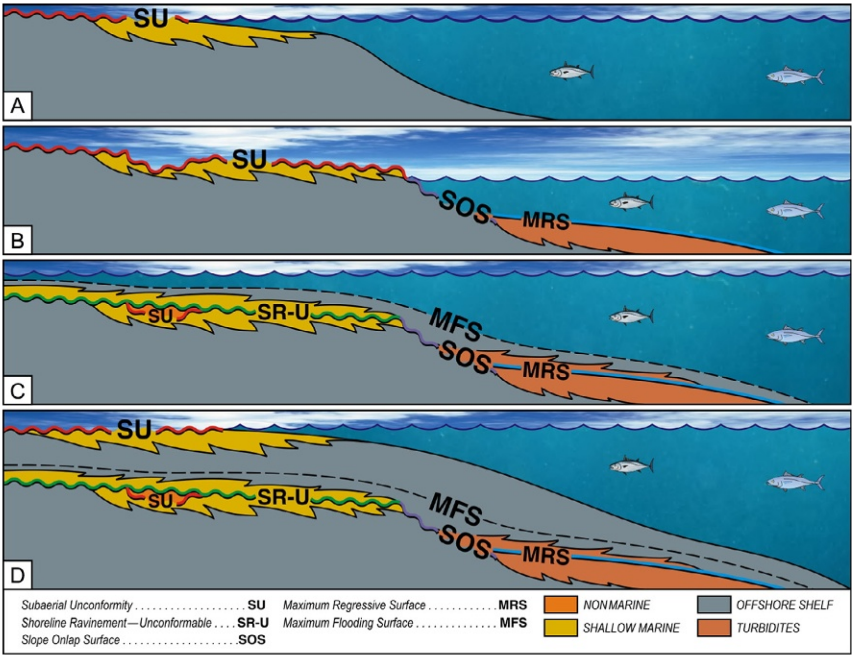

Fig. 4 Schematic evolution of inductive sequence stratigraphic surfaces associated with a shelf/slope/basin setting. (A) Falling base level is accompanied by the basinward migration of the subaerial unconformity (SU). (B) The late stage of falling base level, when much of the shelf is exposed, is marked by the generation of a slope onlap surface (SOS) and deposition of turbidites in the basin. The initiation of rising base level is defined by a maximum regressive surface (MRS) within the basinal turbidite deposits. (C) During transgression, an unconformable shoreline ravinement (SR-U) removes most of the SU. Finer-grained sediment accumulates in the basin as base level rises. The stratigraphic position of the finest sediment defines the maximum flooding surface (MFS). (D) The reversal of rising base level results in the accumulation of coarser-grained sediment only to be eroded as the SU progrades basinward. *Modified from Figure 7.4, Embry, A.F., 2009. Practical Sequence Stratigraphy. Canadian Society of Petroleum Geologists, Calgary, 76 pp.*

stratigraphic sequence. The genetic stratigraphic sequence is considered to be compatible with the general definition of a sequence because a portion of the MFS may be unconformable due mainly to sediment starvation and/or minor scouring. However, the MFS is clearly much different from the depositional sequence boundary of Van Wagoner et al. (1988). Finally, a T-R sequence was defined (Embry, 1993; Embry and Johannessen, 1993) as a sequence bounded by an SU and/or an SR-U on the basin margins and an MRS farther basinward. Because a T-R sequence fits the definition of the earlier defined, depositional sequence, we apply the name depositional T-R sequence to emphasize this equivalence. Notably, this is the only type of depositional sequence so far defined in the literature bounded solely by inductive surfaces.

Given various types of sequences have been defined, a suitable, generic definition of a sequence is required. Accordingly, Embry (2009) defined a sequence as "a stratigraphic unit bounded by a specific type of unconformity or its correlative surfaces." A correlative surface is a sequence stratigraphic surface that passes laterally into a sequence-bounding unconformity, thereby forming a continuous sequence boundary. Consistent with this definition, a specific type of sequence can be defined and named on the basis of different types of bounding unconformities and/or their correlative surfaces. For example, the defining unconformity for a depositional sequence is an SU and that for a genetic stratigraphic sequence is the unconformable portion of the MFS.

The inductive, sequence stratigraphic approach requires that all bounding surfaces of any type of sequence must be material-based surfaces. The fact that the MFS is a relatively easily recognized, inductive surface makes the genetic stratigraphic sequence an acceptable inductive sequence. Indeed, there are many published examples of the use of genetic stratigraphic sequences in basin analysis (e.g., Combellas-Bigott and Galloway, 2006; Partington et al., 1993; Xue and Galloway, 1993).

The defining SU of a depositional T-R sequence is material-based as are its correlative surfaces. Fig. 5 illustrates inductive depositional T-R sequences and their bounding surfaces in both ramp (Fig. 5A) and shelf–slope–basin (Fig. 5B) settings. The relationships of the surfaces to each other are based on our stratigraphic studies over the past 40 years (Embry, 1993, 2010, 2011; Embry and Johannessen, 1993; Hadler-Jacobsen et al., 2005; Johannessen and Embry, 1989; Johannessen and Steel, 2005; Johannessen et al., 1995, 2011; Mjos et al., 1998) and on a published (Embry, 2009, 2010), base-level/sedimentation interaction model for surface generation (Figs. 3 and 4). A depositional T-R sequence in a ramp setting is bounded by an SU and an SR-U on the flanks of a basin. The boundary passes laterally basinward into an MRS which joins with the seaward termination of the shoreline ravinement. A depositional T-R sequence boundary in a shelf–slope-basin setting (Fig. 5B) is bounded by a combination of SU and unconformable shoreline ravinement (SU/SR-U) over part, or all, of the shelf. Where the SU/SR-U does not come close to the edge of the shelf (Fig. 5B, lower boundary), the boundary is most often extended from the

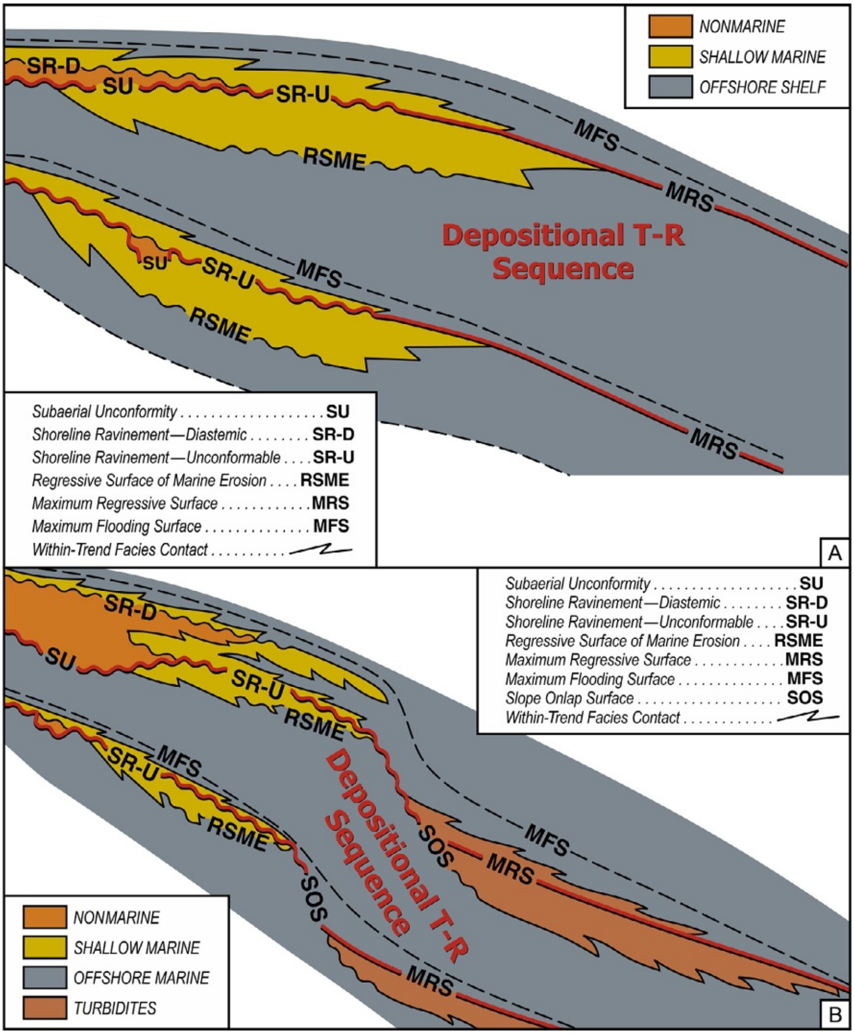

Fig. 5 Depositional T-R sequences. (A) Boundaries of a depositional T-R sequence in a ramp setting are shown in *red*. The unconformable shoreline ravinement (SR-U) truncates the basinward portion of the subaerial unconformity (SU) and is a correlative surface of the SU. The SR-U passes basinward into the maximum regressive surface (MRS). Thus, a continuous depositional T-R sequence boundary in this setting consists of an SU, SR-U, and MRS. (B) Boundaries of a depositional T-R sequence in a shelf/slope/basin setting are shown in *red*. The correlative surfaces of the SU include SR-U, the slope onlap surface (SOS), and the MRS. *Modified from Figure 2, Embry, A.F., 2010. Correlating siliciclastic successions with sequence stratigraphy. In: Ratcliffe, K., Zaitlin, B. (Eds.), Application of Modern Stratigraphic Techniques: Theory and Case Histories, SEPM Special Publication 94. pp. 35–53.*

outer shelf, slope, and basin along the MRS. In the situations where the SU/SR-U can be traced to the shelf edge, the depositional sequence boundary can be traced basinward along an SOS, an unconformable, often channeled, surface onlapped by the MRS in deeper regions of the basin (Fig. 5B). Given that the correlative surfaces of an SU are an SR-U and an MRS (Fig. 5), a unit bounded on top and bottom by an SR-U and/or an MRS without a presence of an SU would also be classified as a depositional T-R sequence. It is noteworthy that many published examples of material-based, depositional T-R sequences in siliciclastic and carbonate successions can be found in the literature (e.g., Beauchamp and Henderson, 1994; Brigaud et al., 2014; Embry, 1993; Hampson, 2016; Lash and Engelder, 2011; Sansom, 2010; Sonnenfeld and Cross, 1993; Wendte and Uyeno, 2005; Zimmermann et al., 2015).

Catuneanu et al. (2009, 2011) have noted that, from a theoretical perspective (e.g., Jervey, 1988), the shoreline ravinement (SR) may not intersect and erode part or all of the SU. Consequently, an SR-U would not be generated and only a highly diachronous, SR-D would be present. In such a case, the MRS would not be continuous with the SU (by way of an intervening SR-U) forming a through-going boundary (Fig. 6). Our review of the literature has revealed a few, well-documented cases of this relationship and all occur in siliciclastic strata characterized by very high rates of deposition (e.g., Pellegrini et al., 2017). In such cases, the inductive, depositional T-R sequence boundary cannot be extended beyond the basinward termination of the SU (Fig. 6). However, such an occurrence seems to be rare. For example, all sequence boundaries in the 13-km-thick, Carboniferous–Cretaceous succession of the Sverdrup Basin of Arctic Canada include an SR-U as part of the unconformable portion of the boundary (Embry and Beauchamp, 2008). However, in the absence of an SR-U, the only option for extending the sequence boundary basinward of the distal termination of the SU is to use the deductive approach as is discussed in a subsequent section.

2.3.2 Systems Tracts

A sequence can be subdivided into component units on the basis of sequence stratigraphic surfaces within a sequence, thereby enhancing the resolution of the sequence stratigraphic framework. The component unit of the sequence is the systems tract (Posamentier and Vail, 1988; Van Wagoner et al., 1988), a unit originally defined by Brown and Fisher (1977), as "a linkage of contemporaneous depositional systems." This definition is not adequate because

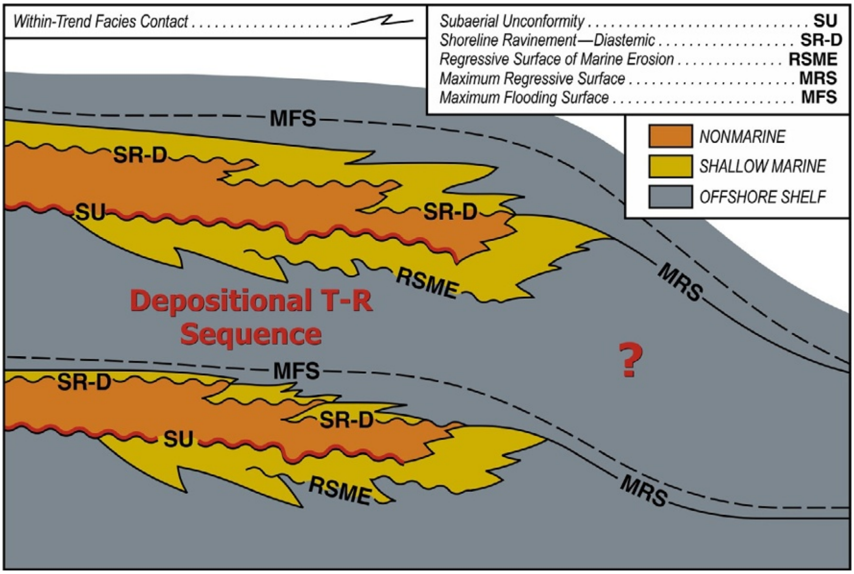

Fig. 6 Depositional T-R sequence with sequence boundaries highlighted in *red*. An unconformable shoreline ravinement (SR-U) has not formed in this model (only a diastemic shoreline ravinement (SR-D)). Sequence boundaries consist only of subaerial unconformities (SU) restricted to the basin flanks. There are no inductive, correlative surfaces, which would allow the sequence boundaries to be extended into the basin. As discussed in the text, such stratigraphic relationships are very rare but have been documented in a few cases. *Modified from Figure 9.7, Embry, A.F., 2009. Practical Sequence Stratigraphy. Canadian Society of Petroleum Geologists, Calgary, 76 pp.*

it does not identify the bounding surfaces of the systems tract. A simpler and more straightforward definition, and one which matches the application of systems tracts, is a component unit of a sequence which is bound by sequence stratigraphic surfaces.

In the inductive approach, the depositional T-R and genetic stratigraphic sequences can be subdivided into systems tracts using inductive, sequence stratigraphic surfaces. A system tract is defined by its bounding stratigraphic surfaces rather than by the strata that comprise it. Still, the characteristics of the strata (e.g., grain size trends) aid in the recognition of various bounding surfaces and, thus, indirectly contribute to the delineation of a given systems tract.

The only inductive, low diachroneity, sequence stratigraphic surface within depositional T-R sequences of ramp and shelf–slope–basin settings is the MFS (Fig. 5A and B). On this basis, Embry (1993) and Embry and Johannessen (1993) proposed that a depositional T-R sequence be subdivided into two systems tracts, a lower transgressive systems tract (TST) and an overlying regressive systems tract (RST) (Fig. 7A and B). A TST, adhering to the definition of Van Wagoner et al. (1988), is a sequence stratigraphic unit bounded at its base by an MRS and its correlative surfaces and

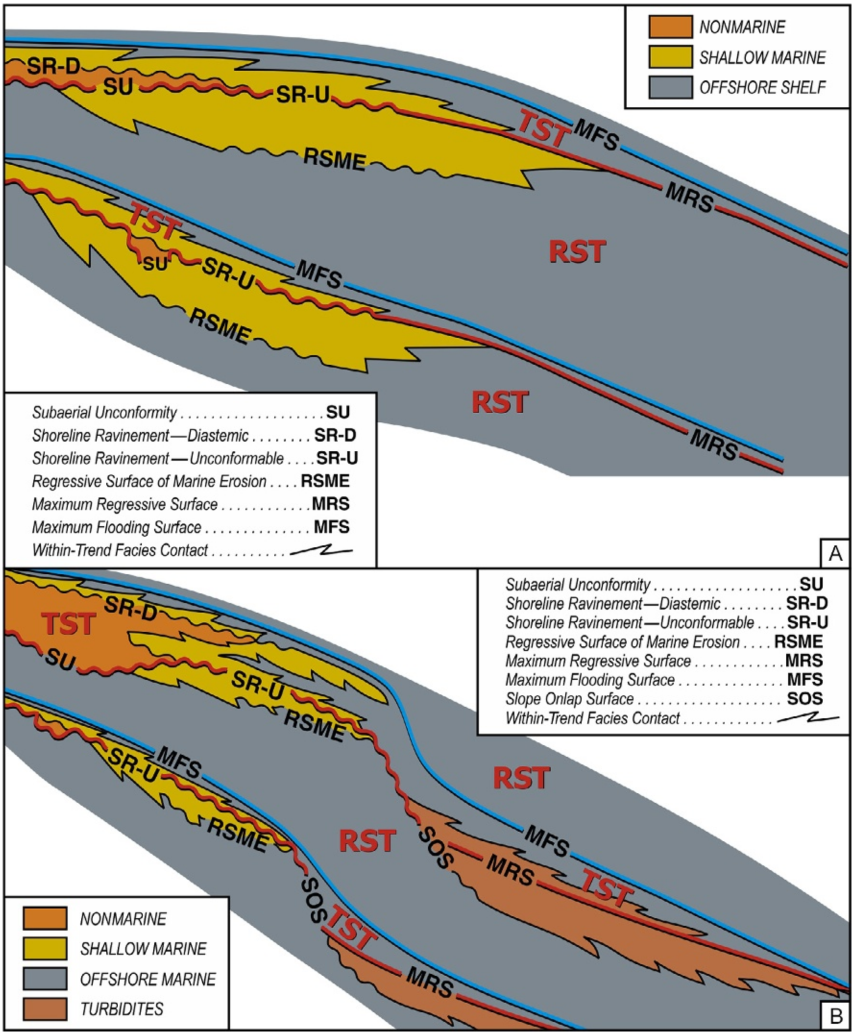

Fig. 7 Inductive systems tracts. (A) The boundaries of a depositional T-R sequence (SU, SR-U, MRS) in a ramp setting are shown in *red*. The occurrence of the maximum flooding surface (MFS) allows the sequence to be subdivided into two systems tracts—a transgressive systems tract (TST) and a regressive systems tract (RST). (B) The boundaries of depositional T-R sequence (SU, SR-U, SOS, MRS) in a shelf/slope/basin setting are shown in *red*. The internal, MFS allows a sequence to be subdivided into a TST and an RST.

an MFS above. The RST is bounded by an MFS below and by an MRS and its correlative surfaces above.

The genetic stratigraphic sequence has MFSs as its bounding surfaces as discussed previously. Like the depositional T-R sequence, it can also be subdivided into a TST and an RST by using the internal, composite boundary of an SU/SR-U/MRS/SOS as the shared boundary for both systems tracts.

The RST, as defined above, includes both the lowstand systems tract (LST) and highstand systems tract (HST) of Van Wagoner et al. (1988). The boundary used by Van Wagoner et al. (1988) to separate our RST into lowstand (LST) and highstand (HST) systems tracts is a highly diachronous, facies change surface in the basin area (e.g., base prograding turbidites). Such a surface is not a valid systems tract boundary, and thus, recognition of the HST and LST by the inductive approach is not possible. As will be subsequently discussed, the HST and LST are part of the deductive approach to sequence stratigraphy.

2.3.3 Parasequence

A parasequence was originally defined by Van Wagoner et al. (1988) as "a relatively conformable succession of beds or bedsets bound by marine-flooding surfaces." A marine-flooding surface or flooding surface (FS) 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." Given that all stratigraphic surfaces separate younger from older strata, this leaves "an abrupt increase in water depth," a highly interpretive criterion, as the only means of recognition. Van Wagoner et al. (1990) provided much more information and insight into what they meant by the terms flooding surface and parasequence. It is clear from their diagrams that Van Wagoner et al. (1988, 1990) envisioned a flooding surface as a contact between a marine sandstone and an overlying deeper water, marine shale/siltstone (Fig. 8). Such a contact is a diachronous lithofacies boundary which, in most cases, lies between an MRS below and an MFS above (Fig. 9). Thus, the parasequence as defined by Van Wagoner et al. (1988, 1990) is a lithostratigraphic rather than a sequence stratigraphic unit. This is not meant to diminish the utility of the parasequence to stratigraphic analysis; rather, it is simply not a unit of sequence stratigraphy.

2.4 Sequence Hierarchy in the Inductive Approach

As discussed in detail by Embry (1993, 1995, 2009), it is necessary to assign recognized sequence boundaries and other associated sequence surfaces of a

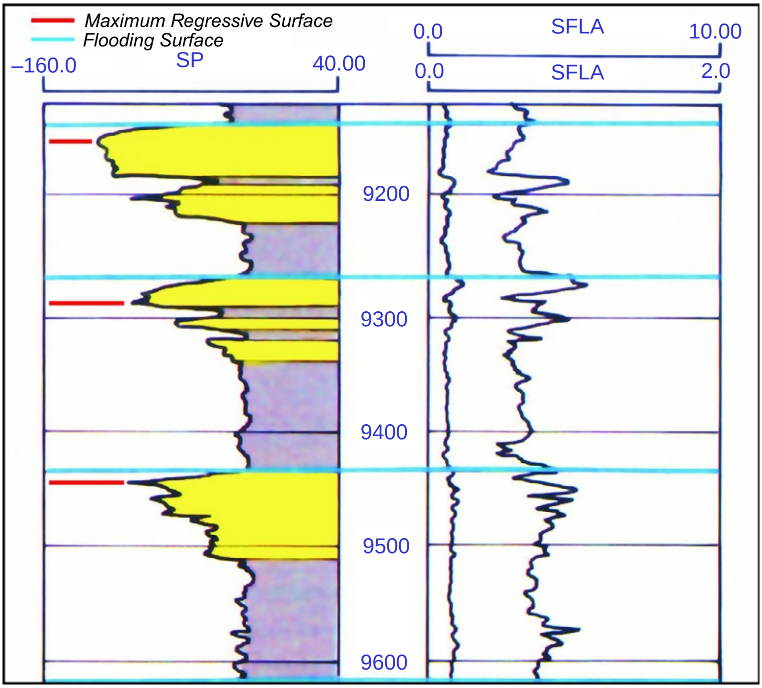

Fig. 8 A portion of Figure 7 of Van Wagoner et al. (1990) showing the parasequence boundaries (FSs in *blue*) as well as MRSs in *red*. Flooding surfaces represent a facies change from sandstone below to shale/siltstone above. *Modified from a portion of Figure 7, Van Wagoner, J.C., Mitchum, R.M., Campion, K.M., Rahmanian, V.D., 1990. Siliciclastic sequence stratigraphy in well logs, cores and outcrops. AAPG Methods in Exploration, No. 7. AAPG, Tulsa, 55 pp.*

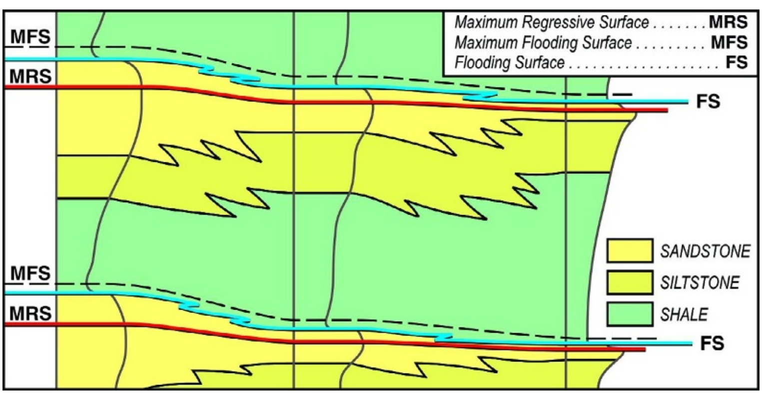

Fig. 9 A schematic cross-section illustrating the correlation of three transgressive–regressive successions using maximum regressive surfaces, maximum flooding surfaces, and flooding surfaces as defined by Van Wagoner et al. (1988, 1990). The diachronous, flooding surfaces (FS in *blue*), which are lithostratigraphic surfaces, bound each parasequence, making them lithostratigraphic units. The depositional T-R sequence is bounded by MRSs, whereas the MFSs bound genetic stratigraphic sequences.

basin to a hierarchy to allow the delineation of various orders of sequences. In the absence of such a hierarchy, any two sequence boundaries, regardless of their magnitude (e.g., any two MRSs in the case of a depositional T-R sequence), could, in theory, be used to form the boundaries of a sequence. This would result in a very large number of sequences and the only way to escape such a chaotic, unmanageable situation is to establish a hierarchy of surfaces.

The hierarchy of boundaries within a given basin is established based on observable criteria and an assessment of the relative magnitudes of the recognized sequence boundaries. Such criteria reflect the relative magnitudes of the base-level changes that generated the boundaries. The criteria include:

1. the degree to which the boundary reflects a changing tectonic regime;
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, especially those localities proximal to the basin edge;
4. the estimated amount of deepening associated with an MFS that overlies an erosional sequence boundary;
5. the distance that the SU and associated shoreline facies extend into the basin.

The largest magnitude sequence boundaries within a basin are referred to as first order and some basinal successions contain as many as six orders of sequence boundaries (Fig. 10). The reader is referred to Embry (1993, 1995, 2009, 2011) for in-depth discussion of the application of an inductive hierarchy and examples of its use. Catuneanu (2006) and Catuneanu et al. (2011) also favor the use of the inductive approach to determining a sequence hierarchy and recommend the use of similar observable features of the boundaries as discussed above.

3. DEDUCTIVE APPROACH TO SEQUENCE STRATIGRAPHY

3.1 Sequence Stratigraphy as a Deductive Stratigraphic Discipline

A second sequence stratigraphic methodology and classification entails a deductive, conceptual approach. This approach includes surfaces and units documented by the inductive approach, as well as several surfaces and units unique to the deductive approach. The deductive approach is based primarily on a mathematical, stratigraphic model which was developed by Mac Jervey of Exxon in 1979 (Jervey, 1988) to provide a theoretical basis for

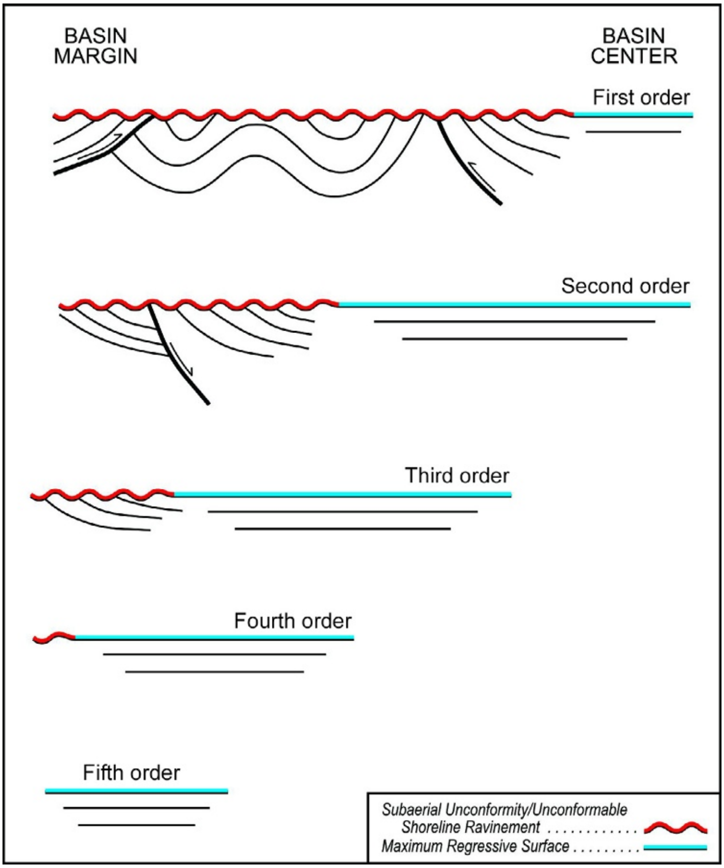

Fig. 10 Schematic depiction of five orders of sequence boundaries of the inductive sequence hierarchy. Each order is determined by observable criteria including degree of tectonic regime change and penetration of the unconformity into the basin. The criteria needed to build such a hierarchy reflect the amount of base-level change that resulted in the formation of the sequence stratigraphic surfaces. *Modified from Figure 7, Embry, A.F., 1995. Sequence boundaries and sequence hierarchies: problems and proposals. In: Steel, R.J., Felt, F.L., Johannessen, E.P., Mathieu, C. (Eds.), Sequence Stratigraphy on the Northwest European Margin. NPF Special Publication 5, pp. 1–11.*

seismic-based, sequence stratigraphic concepts presented by Exxon scientists in 1977 (Payton, 1977). The model used sinusoidal sea-level rise and fall, hinged subsidence that increased basinward, and a constant sediment supply as a priori input parameters. Notably, it predicted the occurrence of stacked, basin flank unconformities and downlap surfaces in central regimes of the basin, the principal surfaces interpreted from seismic sections. As noted earlier, this model provides a reasonable explanation for the inductive surfaces of sequence stratigraphy which had been empirically recognized long before the model was formulated. Exxon researchers (Posamentier and Vail, 1988; Posamentier et al., 1988; Van Wagoner et al., 1988) adopted the Jervey Model to provide the theoretical underpinning of sequence stratigraphy, including the terminology of sequence stratigraphy and sequence stratigraphic models (Posamentier et al., 1988). The reader is referred to Nystuen (1998), Embry (2002, 2009), and Catuneanu (2006) for comprehensive descriptions and discussions of the Exxon sequence stratigraphic methods and terminology.

3.2 Deductive Sequence Stratigraphic Surfaces

The deductive sequence stratigraphic approach recognizes seven surfaces, including SU, SR, RSME, MRS, MFS, basal surface of forced regression (BSFR), and correlative conformity (CC) (Catuneanu, 2006). The first five surfaces are recognized in the inductive approach, although they are defined somewhat differently by the inductive approach. As expressed by Catuneanu (2006), sequence stratigraphic surfaces in the deductive approach "are defined relative to the four main events of the base-level cycle" (Fig. 11). Consistent with the deductive methodology, "the maximum regressive surface is defined relative to the transgression-regressive curve, marking the change from shoreline regression to subsequent transgression" (Catuneanu, 2006, p. 135). Despite the more theoretical

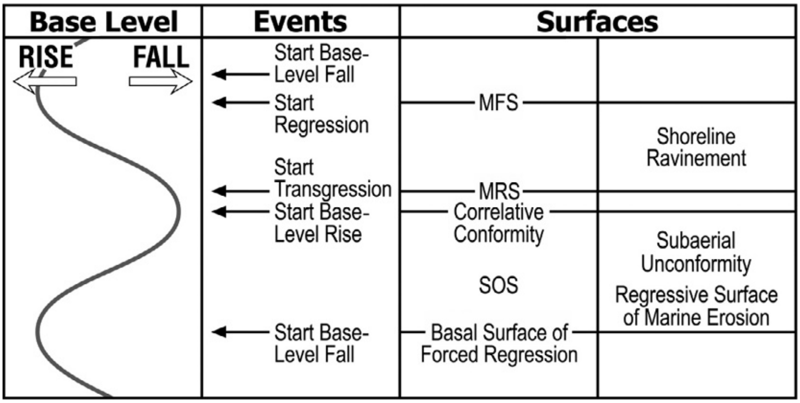

Fig. 11 The seven sequence surfaces of the deductive approach relative to events on base-level curve. As discussed in the text, the basal surface of forced regression (seafloor at start base-level fall) and the correlative conformity (seafloor at start base-level rise) are chronostratigraphic surfaces that display no diagnostic physical attributes.

approach to defining sequence surfaces inherent to the deductive approach, surfaces common to both approaches (SU, SR, MRS, MFS, RSME) are delineated based on objective, physical criteria, as they are in the inductive approach (Catuneanu, 2006; Embry, 2002, 2009, 2010). It is noteworthy that these surfaces are reliably and consistently delineated in studies using either sequence stratigraphic approach.

The two deductive surfaces not recognized in the inductive approach are the BSFR and the CC and both are integral to the deductive approach. They were originally defined by Hunt and Tucker (1992) who had recognized a few, critical inconsistencies in Posamentier et al.'s (1988) application of the Jervey Model. Specifically, Hunt and Tucker (1992) demonstrated that the stratigraphic position of the sequence boundary advocated by Posamentier et al. (1988) placed strata deposited during falling base level below the sequence boundary on the basin flanks and above it in more basinward localities. To rectify the inconsistency, Hunt and Tucker (1992) introduced the BSFR and CC. The BSFR equates to the depositional surface (time surface) at the start of base-level fall, whereas the CC represents the depositional surface at the start of base-level rise (Fig. 11). Recognition of these two chronostratigraphic surfaces is discussed in a subsequent section.

3.3 Deductive Sequence Stratigraphic Units

The deductive and inductive approaches to sequence stratigraphy share common units—sequence and system tract.

3.3.1 Sequence

The deductive approach defines a sequence in terms of the theoretical model of the generation of sequence stratigraphic surfaces as "a succession of strata deposited during a full cycle of change in accommodation or sediment supply" (Catuneanu et al., 2009, 2011). The model-based definition anticipates four main types of sequences: (1) depositional sequence type 1 bounded by a small portion of the SU and the BSFR (Fig. 12A), (2) depositional sequence type 2 bounded by the entire SU and the CC (Fig. 12B), (3) genetic stratigraphic sequence bound by MFSs, and (4) T-R sequence bounded by MRSs.

The genetic stratigraphic sequence is the same in both approaches. The T-R sequence is similar to the depositional T-R sequence of the inductive approach except that it does not include an SR-U as part of the boundary and the MRS onlaps the SU (compare Figs. 6 and 12).

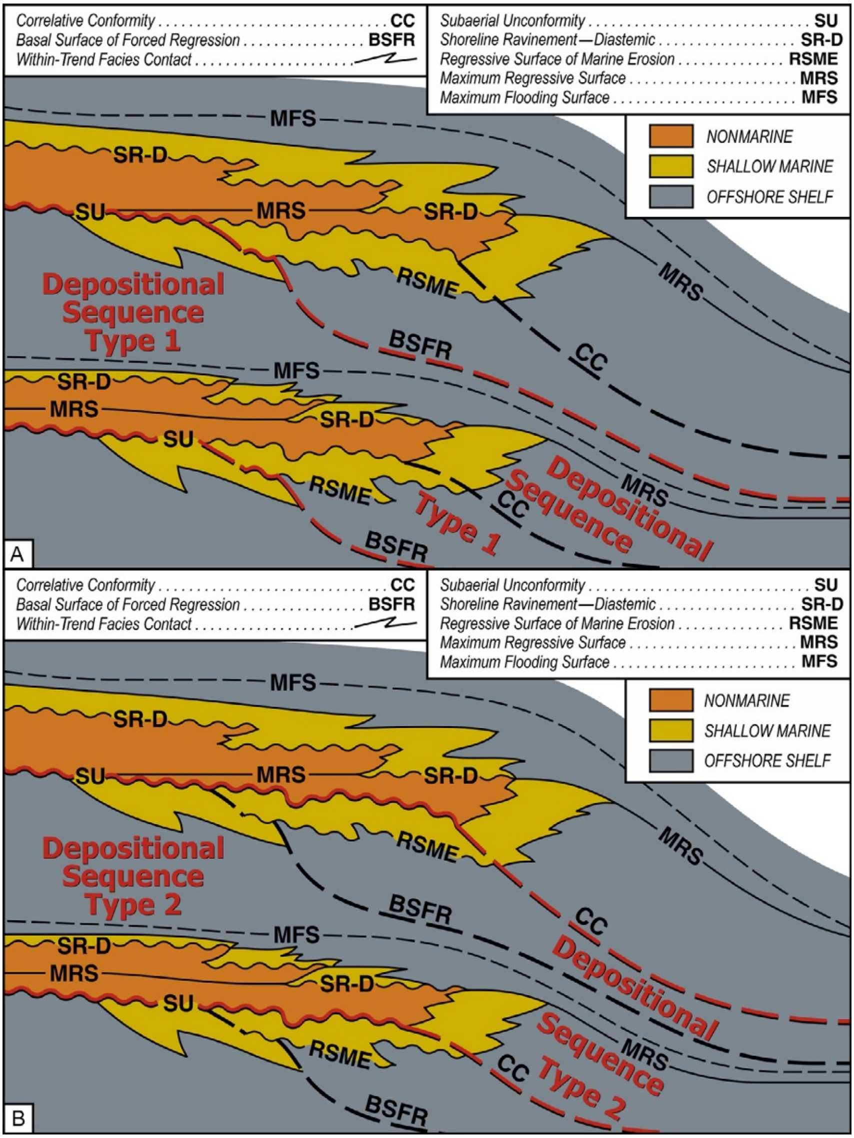

Fig. 12 Deductive depositional sequences. (A) Boundaries of a deductive depositional sequence type 1 in a ramp setting displayed in *red*. The basal surface of forced regression (BSFR) is used as the primary correlative surface of the SU. (B) Boundaries of a deductive depositional sequence type 2 in a ramp setting displayed in *red*. The correlative conformity (CC) is used as the primary correlative surface of the SU.

3.3.2 Systems Tracts

Any of the four deductive sequence types contain as many as three sequence surfaces. The depositional sequence type 2, equivalent to the depositional sequence of Hunt and Tucker (1992), is bounded by the SU on the basin margin and the CC farther basinward (Fig. 13). This sequence type includes an MRS, an MFS, and a BSFR. Hunt and Tucker (1992) defined four systems tracts on the basis of these three internal surfaces. Subsequently, Catuneanu et al. (2009, 2011) attributed the four systems tracts to the deductive approach. Thus, a depositional sequence type 2 comprises, from base to top, the LST, TST, HST, and falling-stage systems tract (FSST) (Fig. 13).

The LST is bounded by the SU/CC below and the MRS above. In the context of the deductive approach, deposits of this system tract accumulated between the onset of base-level rise (CC) and the start of transgression (MRS). The TST is bounded by the MRS below and the MFS (time of maximum transgression) above (Van Wagoner et al., 1988). Strata that comprise the HST were deposited between the time of maximum

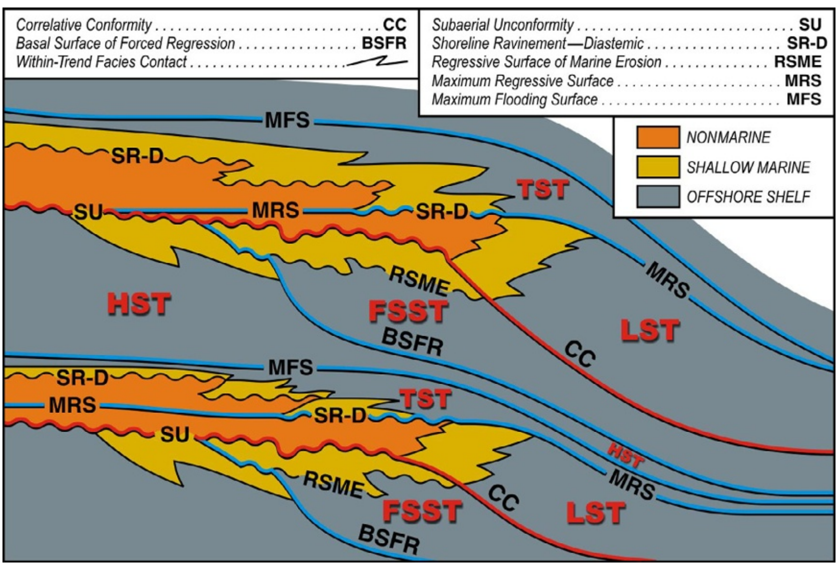

Fig. 13 Boundaries of a deductive depositional sequence type 2 in a ramp setting (SU, CC) are shown in *red*. The sequence contains three sequence stratigraphic surfaces—maximum regressive surface (MRS), maximum flooding surface (MFS), and basal surface of forced regression (BSFR). The sequence comprises four systems tracts: lowstand (LST), transgressive (TST), highstand (HST), and falling-stage (FSST).

transgression (MFS) and the start of base-level fall, defined by the BSFR. The uppermost systems tract, the FSST, is bounded at its base by the BSFR and its top by the CC, both model-derived, chronostratigraphic surfaces. Accordingly, the FSST encompasses all strata deposited during falling base level.

The above discussion demonstrates that the deductive approach to sequence stratigraphy subdivides a given type of sequence into four systems tracts, whereas the inductive approach recognizes only two systems tracts. The TST is the same for both approaches, whereas the RST of the inductive approach encompasses the LST, HST, and FSST of the deductive approach (Fig. 14). However, recognition of the three systems tracts of the regressive portion of a sequence relies upon the scientifically rigorous delineation of the BSFR and CC, chronostratigraphic surfaces. This critical point is addressed below.

Neal et al. (2016) have offered a modest variation of the deductive classification scheme as it relates to the depositional sequence type 2 of Catuneanu et al. (2011). Specifically, although they adopt SU and CC surfaces as sequence boundaries, they do not recognize the BSFR as a valid surface of sequence stratigraphy. Consequently, Neal et al. (2016) divide depositional sequences into three systems tracts rather than four. They

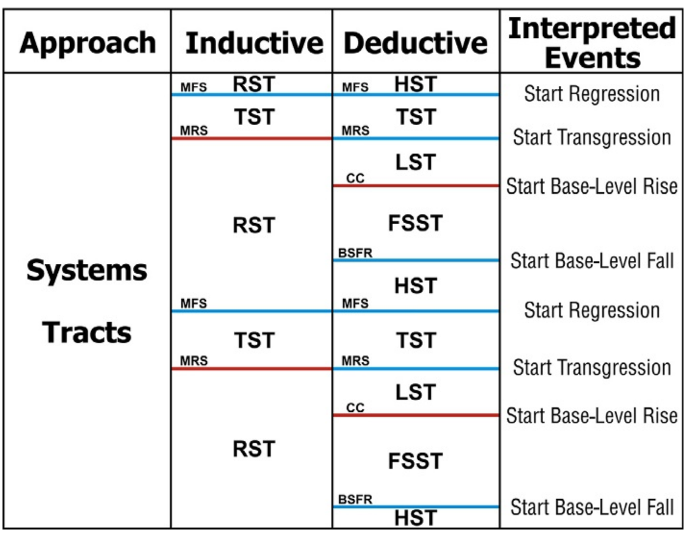

Fig. 14 Comparison of the systems tracts of an inductive, depositional T-R sequence and a deductive, depositional sequence type 2. The sequence boundaries are shown in *red* and systems tract boundaries in *blue*.

combine the HST and FSST, separated by the BSFR (Catuneanu et al., 2011), into a single unit, the HST.

3.3.3 Parasequence

The deductive approach adopts Van Wagoner et al.'s (1988) definition of a parasequence. As discussed previously, the parasequence is a lithostratigraphic unit rather than a sequence stratigraphic one.

3.4 Sequence Hierarchy in the Deductive Approach

The deductive approach to determine the hierarchy of sequence boundaries has been described by Vail et al. (1977), Mitchum and Van Wagoner (1991), Vail et al. (1991), and Posamentier and Allen (1999). This model-driven methodology assumes that sequence stratigraphic surfaces are generated by eustasy-driven, sinusoidal, base-level changes and that the amplitude of such eustatic cycles increase as frequency diminishes. Sequence boundaries associated with very large amplitude base-level changes (tectono-eustasy) are assigned to either a first- or second-order category. High-order boundaries (fourth, fifth, and sixth order) are related to climate-driven, high-frequency, eustatic changes in the 20,000–400,000 year band.

In the deductive approach, a sequence is assigned to a given order based on the amount of time which lapsed between the development of each of its bounding surfaces. Vail et al. (1991) defined six orders of boundaries consistent with the deductive approach to sequence stratigraphy. These were first order: 50 MA; second order: 3–50 MA; third order: 0.5–0.3 MA; fourth order: 0.08–0.5 MA; fifth order: 0.03–0.08 MA; and sixth order: 0.01–0.03 MA.

The deductive approach to establishing a hierarchy of sequences is basically unworkable and prone to circular reasoning. Any desired frequency of boundary occurrence can be determined simply by selecting only the boundaries that fit the desired result (Embry, 1995). As emphasized by Embry (2009), "If one wants to determine the frequency of 2nd order sequence boundaries, one must be able to empirically recognize 2nd 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. Duration is not an observable characteristic of a sequence." Catuneanu et al. (2011) also pointed out major flaws in the deductive approach to sequence hierarchy.

3.5 Recognizing Sequence Stratigraphic Surfaces in the Deductive Approach

The inductive approach employs five surfaces, two sequence types, and two systems tracts, whereas the deductive approach relies upon seven surfaces, four sequence types, and four systems tracts (Fig. 14). The deductive approach does not recognize the SOS, a useful empirical surface of the inductive approach (Embry, 2009). In contrast, the inductive approach does not utilize the two conceptual chronostratigraphic surfaces of the deductive approach—the BSFR and the CC.

The additional surfaces and units of the deductive approach potentially offer enhanced resolution, assuming that these surfaces can be recognized with a high level of certainty. The BSFR and the CC have been defined as chronostratigraphic surfaces tied to the base-level curve of the Jervey Model (Fig. 11). The chronostratigraphic nature of the BSFR was underscored by Catuneanu (2006, p. 123) who declared that the surface "approximates the paleo-seafloor at the onset of base level fall at the shoreline." The CC of Hunt and Tucker (1992) was envisioned to be a chronostratigraphic surface described by Catuneanu (2006) as the "end-of-fall paleo-seafloor."

Recognition and delineation of chronostratigraphic surfaces is a highly interpretive exercise because such conceptual surfaces are abstract and have few, if any, physical attributes. The BSFR displays no obvious sedimentological variation or grain size change that would permit its ready recognition in outcrop or well logs. Indeed, Posamentier and Allen (1999, p. 90) pointed out that, as the BSFR "exists only as a chronohorizon, precise identification … can be limited." Plint and Nummedal (2000, p. 5) wrote that the BSFR is "difficult or impossible to recognize in outcrops or well logs." Catuneanu (2006, p. 129) echoed this view declaring that "the basal surface of forced regression … has no physical expression in a conformable succession of shallow water deposits."

Similar problems attend recognition of the CC. Catuneanu (2006) noted that, "The main problem relates to the difficulty of recognizing it in most outcrop sections, core or wireline logs." The CC he continued "develops within a conformable prograding package (coarsening-upward trends below and above); lacking any lithofacies and grading contrasts." Catuneanu's (2006) points were underscored by Plint and Nummedal (2000, p. 5) who succinctly stated that "From a practical point of view, this marine surface will be difficult to impossible to identify."

Geologists using the deductive approach to sequence stratigraphy are faced with the prospect of recognizing these chronostratigraphic horizons. Indeed, failure to objectively and reliably delineate these surfaces negates the value of the deductive approach. Notably, erroneous interpretations can result if these surfaces are identified on a speculative basis or if inappropriate proxy surfaces (e.g., a facies contact for the BSFR) are used.

Catuneanu et al. (2009, 2011), referring to the Jervey Model, suggested that the BSFR and CC mark changes in parasequence stacking pattern. Specifically, the BSFR defines a change from a normal regressive stacking pattern to a forced regressive pattern. The CC marks the opposite trend, from a forced regressive stacking pattern to a normal regressive one. This approach, however, suffers from a lack of reasonably objective criteria that can be used to delineate these stacking pattern changes in outcrop or on well logs.

Catuneanu (2006) interpreted the BSFR to be the clinoform (paleoseafloor) at the start of offlap along a given transect perpendicular to the shoreline. Unfortunately, it is difficult at best to recognize the first clinoform associated with offlap, especially based on outcrop studies. Seismic data seem to offer the best hope for identifying a BSFR in this manner and, in theory, it is approximated by (or contained within) the reflector that intersects the SU at the start of a basinward trajectory. However, such an intersection point can rarely, if ever, be determined with objectivity as it is lost to erosion during falling base level (Catuneanu, 2006).

The viability of the CC as a meaningful chronostratigraphic surface depends on its ease of identification in the rock record. Unfortunately, the CC is not readily delineated on a regional basis by a change in stacking pattern from forced regression to normal regression, principally because physical attributes of such a change remain unknown in the rock record. As with the BSFR, seismic data hold the best potential for approximating the stratigraphic position of a CC, the surface being contained within a reflector that merges with that reflector defining the marginal unconformity (SU/SR-U). Notably, such a reflector would also most likely encompass the MRS, which generally forms simultaneously with, or shortly after, the CC (Figs. 1 and 6).

Catuneanu (2006, Fig. 6.2) and Catuneanu et al. (2011, Fig. 7) referenced a seismic section on which they have identified both a BSFR and a CC (Fig. 15A). However, we interpret their BSFR as an MFS, given the apparent downlap and condensation onto the reflector (Fig. 15B). The surface labeled as the CC on Fig. 15A can be interpreted as an MRS, given the overlying transgressive strata and initiation of a new sequence (Fig. 15B).

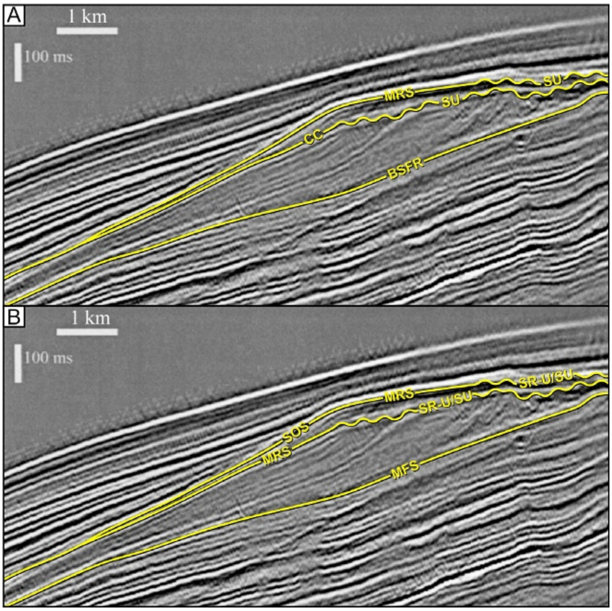

Fig. 15 Deductive interpretation vs inductive interpretation of a seismic section. (A) Deductive sequence stratigraphic interpretation of a seismic section of Pleistocene-Recent sediments in the Gulf of Mexico by Posamentier (2003) and Catuneanu (2006). (B) Inductive interpretation of the same seismic section. Refer to text for discussion. *BSFR*, basal surface of forced regression; *CC*, correlative conformity; *MFS*, maximum flooding surface; *MRS*, maximum regressive surface; *SOS*, slope onlap surface, *SU*, subaerial unconformity; *SR-U*, unconformable shoreline ravinement.

The reflector interpreted to be an MRS by Catuneanu (2006) (Fig. 15A) appears to merge with the SU/SR-U (clear downcutting) and an SOS (clear onlap) (Fig. 15B). The lesson to be learned from this example is that seismic data can be equivocal when used to identify sequence surfaces. The identification of the BSFR and CC requires unequivocal, physical criteria that can be applied in a consistent manner on a regional basis using a variety of databases. Such criteria have yet to be described and documented and, until they are, the widespread application of the deductive approach of sequence stratigraphy will not be reasonable or reliable.

4. COMPARISON OF THE TWO APPROACHES

It is essential for practitioners to be cognizant that two different approaches to sequence stratigraphic methodology exist and that a choice must be made as to which one will be used in any given situation. The inductive approach involves the delineation of five surfaces (SU, SR-U, SOS, MRS, MFS), all of which can be empirically recognized on the basis of physical characteristics and geometric relationships. These surfaces are used for correlation and as bounding surfaces of depositional T-R and genetic stratigraphic sequences, each of which can be subdivided into TST and RST. The great advantage of this approach is that all of these surfaces can be reliably and consistently identified using sedimentological and stratigraphic data from outcrop, well log, and/or seismic sections in undeformed to highly deformed sedimentary successions. Further, the inductive approach is more readily applied in regional work, because only objectively defined surfaces are correlated. The main disadvantage of this approach is that it does not provide the level of stratigraphic resolution and consequent interpretive insight as provided by the deductive approach. An additional, but minor, drawback is that in rare cases, a regional depositional T-R sequence boundary cannot be delineated because the SU does not adjoin the SR-U.

The deductive approach may provide more stratigraphic resolution and hence improved understanding of the depositional history of a sedimentary succession by virtue of its recognition of the BSFR and CC. As noted above, these chronostratigraphic surfaces potentially enhance the time stratigraphic framework of basin fills. The surfaces recognized by the deductive approach, including surfaces embodied in the inductive approach, allow four different types of sequences to be recognized, each of these divided into four systems tracts linked to the base-level and shoreline movement history. Thus, the fact that the deductive approach is potentially more comprehensive than the inductive approach would seem to make the former the preferred approach, all things being equal.

The major weakness of the deductive approach is the great difficulty in delineating the BSFR and CC in a reliable, consistent, and scientifically acceptable manner. Currently, there are no published examples of these surfaces being objectively recognized with rock-based data in a regional context. This stands in stark contrast to the regionally consistent recognition of the inductive surfaces of sequence stratigraphy described in numerous publications (e.g., Brigaud et al., 2014; Hampson, 2016; Ichaso et al., 2016; Lash and Engelder, 2011; Sansom, 2010; Zimmermann et al., 2015). It is noteworthy that every publication we examined purporting to delineate a BSFR and CC using rock-based data was, in fact, describing inductive, material-based stratigraphic surfaces (facies contacts, inductive sequence surfaces). Such misidentification of undoubtedly diachronous surfaces (e.g., lithofacies contacts) as chronostratigraphic surfaces leads to erroneous interpretations of sedimentology and depositional history.

In summary, the choice of whether to use the inductive approach or the deductive approach comes down to the question, "Are my data sufficient to reliably delineate and correlate BSFRs and CCs throughout my study area?" If so, then use of the deductive approach would be best so as to gain maximum resolution and greater insight into basin history. If not, then the practitioner would want to use the inductive approach to avoid nonactualistic and misleading interpretations of facies relationships and depositional history based on the misidentification of BSFRs and CCs.

5. SUMMARY

There are currently two distinctly different approaches to sequence stratigraphic classification and methodology. The inductive approach defines sequence surfaces on the basis of observable characteristics. The deductive approach, on the other hand, defines sequence surfaces that reflect the interaction of base-level change and sedimentation. It is important for any practitioner to be aware of these two different approaches to sequence stratigraphy so that the level of interpretation is justified by the data at hand and to escape the problem of force-fitting data to an inappropriate classification system.

The inductive approach recognizes seven surfaces of sequence stratigraphy in terms of observable characteristics. Five of these surfaces, SU, SR-U, SOS, MRS, and MFS, are used for correlation and as bounding surfaces of various sequence stratigraphic units.

A sequence is defined as a unit bounded by an unconformity or its correlative surfaces. Two types of inductive sequences are recognized: the depositional T-R sequence which is bounded by SUs and/or correlative surfaces (SR-U, MRS, SOS), and the genetic stratigraphic sequence which is bounded by MFSs. Each sequence type can be divided into two systems tracts: a TST and an RST. A parasequence, as originally defined and as currently employed in stratigraphic analysis, is a lithostratigraphic unit rather than a sequence stratigraphic one.

Sequence stratigraphic surfaces of the deductive approach include five surfaces recognized in the inductive approach (SU, SR, MRS, MFS, RSME). However, the deductive approach recognizes two additional chronostratigraphic surfaces: the BSFR which marks on the onset of falling base level, and the CC which represents the seafloor at the start of rising base level. Unlike the surfaces common to both sequence stratigraphic approaches, the BSFR and CC display no diagnostic physical characteristics. Rather, it is suggested that these surfaces can be identified based on interpreted changes in parasequence stacking patterns.

The deductive sequence stratigraphic approach recognizes four types of sequences, each one comprised of four systems tracts: lowstand, transgressive, highstand, and falling stage (LST, TST, HST, and FSST). Thus, the deductive approach is potentially superior to the inductive approach in that it yields greater resolution and interpretive insight. However, the deductive approach suffers from a general inability to reliably recognize the BSFR and the CC. The practitioner must choose between the inductive approach and its readily recognized surfaces, but lower resolution, and the nebulous surfaces but higher resolution of the deductive approach. Ultimately the choice usually comes down to answering the question, "Are my data sufficient to reliably identify and correlate the BSFR and CC throughout my study area?"

ACKNOWLEDGMENTS

First, we would like to acknowledge the fundamental contributions of Hollis Hedberg, the father of modern stratigraphic practice. From the late 1930s to the late 1970s he established the guiding principles for stratigraphic classification and nomenclature. His concepts and advice remain very relevant today. We would like to thank Michael Montenari for inviting our contribution and shepherding it through the publication process. The critical reviewers, especially Gary Lash, provided many helpful suggestions for improvement. We have discussed sequence stratigraphic concepts and practice with many colleagues over the past 40 years and we are grateful for all the insights and guidance they provided. Finally, we would like to thank our former employers, the Geological Survey of Canada (A.F.E.), and Statoil (E.P.J.) for fostering our stratigraphic studies.

REFERENCES

Barrell, J., 1917. Rhythms and the measurements of geologic time. Bull. Geol. Soc. Am. 28, 745–904.

Beauchamp, B., Henderson, C., 1994. The Lower Permian Raanes, Great Bear Cape and Trappers Cove formations. Bull. Can. Petrol. Geol. 42, 562–597.

Brigaud, B., Vincent, B., Carpentier, C., Robin, C., Guillocheau, F., Yven, B., Huret, E., 2014. Growth and demise of the Jurassic carbonate platform in the intracratonic Paris Basin (France): interplay of climate change, eustasy and tectonics. Mar. Pet. Geol. 53, 3–29.

Brown, L., Fisher, W., 1977. Seismic-stratigraphic interpretation of depositional systems: examples from the Brazilian rift and pull-apart basins. In: Payton, C. (Ed.), Seismic Stratigraphy: Application to Hydrocarbon Exploration, pp. 213–248. AAPG Memoir 26.

Burgess, P., Prince, G., 2015. Non-unique stratal geometries: implications for sequence stratigraphic interpretations. Basin Res. 27, 351–365.

Catuneanu, O., 2006. Principles of Sequence Stratigraphy. Elsevier, New York. 386 pp.

Catuneanu, O., Abreu, V., Bhattacharya, J.P., Blum, M.D., Dalrymple, R.W., Eriksson, P.G., Fielding, C.R., Fisher, W.L., Galloway, W.E., Gibling, M.R., Giles, K.A., Holbrook, J.M., Jordan, R., Kendall, C.G.S.C., Macurda, B., Martinsen, O.J., Miall, A.D., Neal, J.E., Nummedal, D., Pomar, L., Posamentier, H.W., Pratt, B.R., Sarg, J.F., Shanley, K.W., Steel, R.J., Strasser, A., Tucker, M.E., Winker, C., 2009. Towards the standardization of sequence stratigraphy. Earth Sci. Rev. 92, 1–33.

Catuneanu, O., Galloway, W.E., Kendall, C.G.S.C., Miall, A.D., Posamentier, H.W., Strasser, A., Tucker, M.E., 2011. Sequence stratigraphy: methodology and nomenclature. Newsl. Stratigr. 44, 173–245.

Combellas-Bigott, R., Galloway, W., 2006. Depositional and structural evolution of the middle Miocene depositional episode, east-central Gulf of Mexico. AAPG Bull. 90, 335–362.

Embry, A.F., 1993. Transgressive-regressive (T-R) sequence analysis of the Jurassic succession of the Sverdrup Basin, Canadian Arctic Archipelago. Can. J. Earth Sci. 30, 301–320.

Embry, A.F., 1995. Sequence boundaries and sequence hierarchies: problems and proposals. In: Steel, R.J., Felt, F.L., Johannessen, E.P., Mathieu, C. (Eds.), Sequence Stratigraphy on the Northwest European Margin, pp. 1–11. NPF Special Publication 5.

Embry, A., 2002. Transgressive-regressive (T-R) sequence stratigraphy. In: Armentrout, J., Rosen, N. (Eds.), Sequence Stratigraphic Models for Exploration and Production. Gulf Coast SEPM Conference Proceedings, Houston, pp. 151–172.

Embry, A.F., 2009. Practical Sequence Stratigraphy. Canadian Society of Petroleum Geologists, Calgary. 76 pp.

Embry, A.F., 2010. Correlating siliciclastic successions with sequence stratigraphy. In: Ratcliffe, K., Zaitlin, B. (Eds.), Application of Modern Stratigraphic Techniques: Theory and Case Histories, pp. 35–53. SEPM Special Publication 94.

Embry, A.F., 2011. Petroleum prospectivity of the Triassic-Jurassic succession of Sverdrup Basin, Canadian Arctic Archipelago. In: Spencer, A.M., Embry, A.F., Gautier, D.L., Stoupakova, A.V., Sørensen, K. (Eds.), Arctic Petroleum Geology. Geological Society, London, pp. 545–558. Memoirs 5.

Embry, A., Beauchamp, B., 2008. Sverdrup Basin. In: Miall, A. (Ed.), Sedimentary Basins of the World. In: The Sedimentary Basins of the United States and Canada, vol. 5. Elsevier, Amsterdam, pp. 451–472.

Embry, A.F., Johannessen, E.P., 1993. T-R sequence stratigraphy, facies analysis and reservoir distribution in the uppermost Triassic-Lower Jurassic succession, western Sverdrup Basin, Arctic Canada. In: Vorren, T., Bergsager, E., Dahl-Stamnes, O.A., Holter, E., Johansen, B., Lie, E., Lund, T.B. (Eds.), Arctic Geology and Petroleum Potential, pp. 121–146. NPF Special Publication 2.

Galloway, W., 1989. Genetic stratigraphic sequences in basin analysis I: architecture and genesis of flooding surface bounded depositional units. AAPG Bull. 73, 125–142.

Hadler-Jacobsen, F., Johannessen, E.P., Ashton, N., Henriksen, S., Johnson, S., Kristensen, J., 2005. Submarine fan morphology and lithology distribution: a predictable function of sediment delivery, gross shelf to basin relief, slope gradient and basin topography. In: Dore, A., Vining, B. (Eds.), Petroleum Geology: Northwest Europe and Global Perspectives. Geological Society, London, pp. 1121–1145.

Hampson, G.J., 2016. Towards a sequence stratigraphic solution set for autogenic processes and allogenic controls: Upper Cretaceous strata, Book Cliffs, Utah, USA. J. Geol. Soc. London 173, 817–836.

Hedberg, H.D., 1958. Stratigraphic classification and terminology. AAPG Bull. 42, 1881–1896.

Hedberg, H.D., 1959. Towards a harmony in stratigraphic classification. Am. J. Sci. 257, 674–683.

Helland-Hansen, W., 2009. Towards the standardization of sequence stratigraphy: discussion. Earth Sci. Rev. 94, 95–97.

Helland-Hansen, W., Gjelberg, J., 1994. Conceptual basis and variability in sequence stratigraphy: a different perspective. Sediment. Geol. 92, 1–52.

Hunt, D., Tucker, M., 1992. Stranded parasequences and the forced regressive wedge systems tract: deposition during base level fall. Sediment. Geol. 81, 1–9.

Ichaso, A.A., Dalrymple, R.W., Martinius, A.W., 2016. Basin analysis and sequence stratigraphy of the syn-rift Tilje Formation (Early Jurassic), Halten Terrace giant oil and gas fields, offshore mid-Norway. AAPG Bull. 100, 1329–1375.

Jervey, M., 1988. Quantitative geological modeling of siliciclastic rock sequences and their seismic expression. In: Wilgus, C., Hastings, B.S., Kendall, C.G., Posamentier, H.W., Ross, C.A., Van Wagoner, J.C. (Eds.), Sea Level Changes: An Integrated Approach, pp. 47–69. SEPM Special Publication 42.

Jervey, M., 1993. Siliciclastic sequence development in foreland basins, with examples from the Western Canada Foreland Basin. In: Macqueen, R.W., Leckie, D.A. (Eds.), Foreland Basins and Fold Belts, pp. 47–80. Am. Assoc. Pet. Geol. Mem. 55.

Johannessen, E.P., Embry, A.F., 1989. Sequence correlation: Upper Triassic to Lower Jurassic succession, Canadian and Norwegian Arctic. In: Collinson, J.D. (Ed.), Correlation in Hydrocarbon Exploration. Norwegian Petroleum Society/Graham and Trotman, London, pp. 155–170.

Johannessen, E.P., Steel, R.J., 2005. Shelf-margin clinoforms and prediction of deep water sands. Basin Res. 17, 521–550.

Johannessen, E.P., Mjos, R., Renshaw, D., Dalland, A., Jacobsen, T., 1995. Northern limit of the Brent delta at the Tampen Spur—a sequence stratigraphic approach for sandstone prediction. In: Steel, R., Felt, V., Johannessen, E., Mathieu, C. (Eds.), Sequence Stratigraphy of the Northwest European Margin, pp. 213–256. Norwegian Petroleum Society Special Publication 5.

Johannessen, E.P., Henningsen, T., Bakke, N.E., Johansen, T.A., Ruud, B.O., Riste, P., Elvebakk, H., Jochmann, M., Elvebakk, G., Woldengen, M.S., 2011. Palaeogene clinoform succession on Svalbard expressed in outcrops, seismic data, logs and cores. First Break 29, 35–44.

Lash, G.G., Engelder, T., 2011. Thickness trends and sequence stratigraphy of the Middle Devonian Marcellus Formation, Appalachian Basin: implications for Acadian foreland basin evolution. AAPG Bull. 95, 61–103.

Madof, A., Harris, A., Connell, S., 2016. Nearshore along-strike variability: is the concept of the systems tracts unhinged? Geology 44, 319–322.

Miall, A.D., 2004. Empiricism and model building in stratigraphy: the historical roots of present-day practices. Stratigraphy 1, 3–25.

Miall, A.D., Miall, C.E., 2004. Empiricism and model-building in stratigraphy: around the hermeneutic circle in the pursuit of stratigraphic correlation. Stratigraphy 1, 27–46.

Mitchum, R., Van Wagoner, J., 1991. High frequency sequences and their stacking patterns: sequence stratigraphic evidence for high frequency eustatic cycles. Sediment. Geol. 70, 131–160.

Mitchum, R., Vail, P., Thompson, S., 1977. Seismic stratigraphy and global changes in sea level, part 2: the depositional sequence as the basic unit for stratigraphic analysis. In: Payton, C. (Ed.), Seismic Stratigraphy: Application to Hydrocarbon Exploration, pp. 53–62. AAPG Memoir 26.

Mjos, R., Hadler-Jacobsen, F., Johannessen, E., 1998. The distal sandstone pinchout of the Mesa Verde Group, San Juan basin and its relevance for sandstone prediction of the Brent Group, northern North Sea. In: Gradstein, F., Sandvik, K., Milton, N. (Eds.), Predictive High Resolution Sequence Stratigraphy, pp. 263–297. Norwegian Petroleum Society Special Publication 8.

Neal, J.E., Abreu, V., Bohacs, K.M., Feldman, H.R., Pederson, K.H., 2016. Accommodation succession (δA/δS) sequence stratigraphy: observational method, utility and insights into sequence boundary formation. J. Geol. Soc. London 173, 803–816.
Nystuen, J.P., 1998. History and development of sequence stratigraphy. In: Gradstein, F., Sandvik, K., Milton, N. (Eds.), Predictive High Resolution Sequence Stratigraphy, pp. 31–116. Norwegian Petroleum Society Special Publication 8.
Partington, M., Mitchener, B., Milton, N., Fraser, A., 1993. Genetic sequence stratigraphy for the North Sea Late Jurassic and Early Cretaceous: distribution and prediction of Kimmeridgian–Late Ryazanian reservoirs in the North Sea and adjacent areas. In: Parker, J. (Ed.), Petroleum Geology of Northwest Europe, pp. 327–370. 4.
Payton, C. (Ed.), 1977. Seismic Stratigraphy: Applications to Hydrocarbon Exploration. AAPG, Tulsa. AAPG Memoir 26. 516 pp.
Pellegrini, C., Maselli, V., Gamberi, F., Asioli, A., Bohacs, K., Drexler, T., Trincardi, F., 2017. How to make a 350-m-thick lowstand systems tract in 17,000 years: the Late Pleistocene Po River (Italy) lowstand wedge. Geology 45, 327–330.
Plint, A., Nummedal, D., 2000. The falling stage systems tract: recognition and importance in sequence stratigraphic analysis. In: Hunt, D., Gawthorpe, R. (Eds.), Sedimentary Responses to Forced Regressions, pp. 1–17. Geological Society of London, Special Publication 172.
Posamentier, H.W., 2003. A linked shelf-edge delta and slope-channel turbidite system: 3D seismic case study from the eastern Gulf of Mexico. In: Roberts, H.H., Rosen, N.C., Fillon, R.H., Anderson, J.B. (Eds.), Shelf-Margin Deltas and Linked Downslope Petroleum Systems: Global Significance and Future Exploration Strategy. Proceedings, 23rd GCSSEPM Foundation Bob. F. Perkins Research Conference, pp. 115–134.
Posamentier, H., Allen, G., 1999. Siliciclastic Sequence Stratigraphy—Concepts and Applications. SEPM Concepts in Sedimentology and Paleontology 7, Tulsa, SEPM. 210 pp.
Posamentier, H., Vail, P., 1988. Eustatic controls on clastic deposition II—sequence and systems tract models. In: Wilgus, C., Hastings, B.S., Kendall, C.G., Posamentier, H.W., Ross, C.A., Van Wagoner, J.C. (Eds.), Sea Level Changes: An Integrated Approach, pp. 125–154. SEPM Special Publication 42.
Posamentier, H., Jervey, M., Vail, P., 1988. Eustatic controls on clastic deposition I—conceptual framework. In: Wilgus, C., Hastings, B.S., Kendall, C.G., Posamentier, H.W., Ross, C.A., Van Wagoner, J.C. (Eds.), Sea Level Changes: An Integrated Approach, pp. 109–124. SEPM Special Publication 42.
Sansom, P.J., 2010. Reappraisal of the sequence stratigraphy of the Humber Group of the UK Central Graben. In: Vining, B., Pickering, S. (Eds.), Petroleum Geology. Mature Basins to New Frontiers: Proceedings of the 7th Petroleum Geology Conference. Geological Society, London, pp. 177–211.
Sloss, L., 1963. Sequences in the cratonic interior of North America. GSA Bull. 74, 93–113.
Sloss, L., Krumbein, W., Dapples, E., 1949. Integrated facies analysis. In: Longwell, C. (Ed.), Sedimentary Facies in Geologic History. Geological Society America, pp. 91–124. Memoir 39.
Sonnenfeld, M., Cross, T., 1993. Volumetric portioning and facies differentiation within the Permian Upper San Andreas Formation of last Chance canyon, Guadaloupe Mountains, New Mexico. In: Loucks, R., Sarg, F. (Eds.), Carbonate Sequence Stratigraphy, pp. 435–474. AAPG Memoir 57.
Vail, P., Mitchum, R., Thompson, S., 1977. Seismic stratigraphy and global changes in sea level. In: Payton, C. (Ed.), Seismic Stratigraphy: Applications to Hydrocarbon Exploration, pp. 49–212. AAPG Memoir 26.
Vail, P., Audemard, F., Bowman, S., Eisner, P., Perez-Cruz, C., 1991. The stratigraphic signatures of tectonics, eustasy and sedimentology—an overview. In: Einsele, G., Ricken, W., Seilacher, A. (Eds.), Cycles and Events in Stratigraphy. Springer-Verlag, New York, pp. 617–659.

Van Wagoner, J.C., Posamentier, H.W., Mitchum, R.M., Vail, P.R., Sarg, J.F., Loutit, T.S., Hardenbol, J., 1988. An overview of the fundamentals of sequence stratigraphy and key definitions. In: Wilgus, C., Hastings, B.S., Kendall, C.G., Posamentier, H.W., Ross, C.A., Van Wagoner, J.C. (Eds.), Sea Level Changes: An Integrated Approach, pp. 39–46. SEPM Special Publication 42.

Van Wagoner, J.C., Mitchum, R.M., Campion, K.M., Rahmanian, V.D., 1990. Siliciclastic sequence stratigraphy in well logs, cores and outcrops. AAPG Methods in Exploration, No. 7, AAPG, Tulsa. 55 pp.

Wendte, J., Uyeno, T., 2005. Sequence stratigraphy and evolution of Middle to Upper Devonian Beaverhill Lake strata south-central Alberta. Bull. Can. Petrol. Geol. 53, 250–354.

Wheeler, H.E., 1958. Time stratigraphy. AAPG Bull. 42, 1208–1218.

Wheeler, H.E., 1959. Stratigraphic units in time and space. Am. J. Sci. 257, 692–706.

Wheeler, H.E., 1964. Base level, lithosphere surface and time stratigraphy. Geol. Soc. Am. Bull. 75, 599–610.

Xue, L., Galloway, W., 1993. Sequence stratigraphic and depositional framework of the Paleocene Lower Wilcox strata, northwestern Gulf of Mexico. GCAGS Trans. 43, 453–462.

Zimmermann, J., Franz, M., Heunisch, C., Luppold, F., Monnig, E., Wolfgramm, M., 2015. Sequence stratigraphic framework of the Lower and Middle Jurassic in the North German Basin: epicontinental sequences controlled by Boreal cycles. Palaeogeogr. Palaeoclimatol. Palaeoecol. 440, 395–416.

FURTHER READING

Nummedal, D., Riley, G., Templet, P., 1993. High resolution sequence architecture: a chronostratigraphic model based on equilibrium profile studies. In: Posamentier, H., Summerhayes, C., Haq, B., Allen, G. (Eds.), Sequence Stratigraphy and Facies Association, pp. 55–68. International Association of Sedimentologists, Special Publication 18.