PRINCIPLES OF SEQUENCE STRATIGRAPHY

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Sequence stratigraphy analyzes the sedimentary response to changes in base level, and the depositional trends that emerge from the interplay of accommodation (space available for sediments to fill) and sedimentation. Sequence stratigraphy has tremendous potential to decipher the Earth’s geological record of local to global changes, and to improve the predictive aspect of economic exploration and production. For these reasons, sequence stratigraphy is currently one of the most active areas of research in both academic and industrial environments.

‘Principles’ of sequence stratigraphy are to a large extent independent of the type of depositional environments established within a sedimentary basin (e.g., siliciclastic vs. carbonate), and clastic systems are generally used by default to explain and exemplify the concepts. However, the difference in stratigraphic responses to changes in base level between clastic and carbonate systems is discussed in the book, and the departure of the carbonate sequence stratigraphic model from the ‘standard’ model developed for clastic rocks is examined. The principles of sequence stratigraphy are also independent of scale. The resolution of the sequence stratigraphic work can be adjusted as a function of the scope of observation, from sub-depositional system scales to the scale of entire sedimentary basin fills. Between these end members, processes that operate over different spatial and temporal scales are interrelated. The sequence stratigraphic framework of facies relationships provides a template that allows one to see how smaller-scale processes and depositional elements fit into the bigger picture. As such, sequence stratigraphy is an approach to understanding the 4D development of sedimentary systems, integrating cross-sectional information (stratigraphy) with plan-view data (geomorphology) and insights into the evolution of sedimentation regimes through time (process sedimentology). Any of these ‘conventional’ disciplines may show a more pronounced affinity to sequence stratigraphy, depending on case study, scale, and scope of observation. The application of the sequence stratigraphic method also relies on the integration of multiple data sets that may be derived from outcrops, core, well logs, and seismic volumes.

Even though widely popular among all groups interested in the analysis of sedimentary systems, sequence stratigraphy is yet a difficult undertaking due to the proliferation of informal jargon and the persistence of conflicting approaches as to how the sequence stratigraphic method should be applied to the rock record. This book examines the relationship between such conflicting approaches from the perspective of a unifying platform, demonstrating that sufficient common ground exists to eliminate terminology barriers and to facilitate communication between all practitioners of sequence stratigraphy. The book is addressed to anyone interested in the analysis of sedimentary systems, from students to geologists, geophysicists, and reservoir engineers.

The available sequence stratigraphic literature has focussed mainly on (1) promoting particular models; (2) criticizing particular models or assumptions; and (3) providing comprehensive syntheses of previous work and ideas. This book builds on the existing literature and, avoiding duplication with other volumes on the same topic, shifts the focus towards making sequence stratigraphy a more user-friendly and flexible method of analysis of the sedimentary rock record. This book is not meant to be critical of some models in favor of others. Instead, it is intended to explain how models relate to each other and how their applicability may vary with the case study. There is, no question, value in all existing models, and one has to bear in mind that their proponents draw their experience from sedimentary basins placed in different tectonic settings. This explains in part the variety of opinions and conflicting ideas. The refinement of the sequence stratigraphic model to account for the variability of
tectonic and sedimentary regimes across the entire spectrum of basin types is probably the next major step in the evolution of sequence stratigraphy.

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I dedicate this book to Ana, Andrei, Gabriela, and my supportive parents.

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CHAPTER 1

Introduction

SEQUENCE STRATIGRAPHY—AN OVERVIEW

Sequence Stratigraphy in the Context of Interdisciplinary Research

Sequence stratigraphy is the most recent revolutionary paradigm in the field of sedimentary geology. The concepts embodied by this discipline have resulted in a fundamental change in geological thinking and in particular, the methods of facies and stratigraphic analyses. Over the past fifteen years, this approach has been embraced by geoscientists as the preferred style of stratigraphic analysis, which has served to tie together observations from many disciplines. In fact, a key aspect of the sequence stratigraphic approach is to encourage the integration of data sets and research methods. Blending insights from a range of disciplines invariably leads to more robust interpretations and, consequently, scientific progress. Thus, the sequence stratigraphic approach has led to improved understanding of how stratigraphic units, facies tracts, and depositional elements relate to each other in time and space within sedimentary basins (Fig. 1.1). The applications of sequence stratigraphy range widely, from predictive exploration for petroleum, coal, and placer deposits, to improved understanding of Earth’s geological record of local to global changes.

The conventional disciplines of process sedimentology and classical stratigraphy are particularly relevant to sequence stratigraphy (Fig. 1.2). Sequence stratigraphy is commonly regarded as only one other type of stratigraphy, which focuses on changes in depositional trends and their correlation across a basin (Fig. 1.3). While this is in part true, one should not neglect the strong sedimentological component that emphasizes on the facies-forming processes within the confines of individual depositional systems, particularly in response to changes in base level. At this scale, sequence stratigraphy is generally used to resolve and explain issues of facies cyclicity, facies associations and relationships, and reservoir compartmentalization, without necessarily applying this information for larger-scale correlations.

Integrated disciplines:
- Sedimentology
- Stratigraphy
- Geophysics
- Geomorphology
- Isotope Geochemistry
- Basin Analysis

Integrated data:
- outcrops
- modern analogues
- core
- well logs
- seismic data

Main controls:
- sea level change
- subsidence, uplift
- climate
- sediment supply
- basin physiography
- environmental energy

Academic applications: genesis and internal architecture of sedimentary basin fills
Industry applications: exploration for hydrocarbons, coal, and mineral resources

FIGURE 1.1 Sequence stratigraphy in the context of interdisciplinary research—main controls, integrated data sets and subject areas, and applications.
Owing to the ‘genetic’ nature of the sequence stratigraphic approach, process sedimentology is an important prerequisite that cannot be separated from, and forms an integral part of sequence stratigraphy. The importance of process sedimentology in sequence stratigraphic analysis becomes evident when attempting to identify sequence stratigraphic surfaces in the rock record. As discussed in detail throughout the book, most criteria involved in the interpretation of stratigraphic surfaces revolve around the genetic nature of facies that are in contact across the surface under analysis, which in turn requires a good understanding of depositional processes and environments. The importance of process sedimentology is also evident when it comes to understanding the origin and distribution of the various types of unconformities that may form in nonmarine, coastal, or fully marine environments, as well as the facies characteristics and variability that may be encountered within the different portions of systems tracts. The stratigraphic component of sequence stratigraphy consists of its applicability to correlations in a time framework, usually beyond the scale of individual depositional systems, in spite of the lateral changes of facies that are common in any sedimentary basin. In addition to its sedimentological and stratigraphic affinities, sequence stratigraphy also brings a new component of facies predictability which is particularly appealing to industry-oriented research (Fig. 1.2).

The conventional types of stratigraphy, such as biostratigraphy, lithostratigraphy, chemostratigraphy, or magnetostratigraphy, involve both data collection and interpretation based on the data, just as does sequence stratigraphy, but no sophisticated interpretation is required in order to do conventional stratigraphic correlations. In contrast, sequence stratigraphic correlations depend on interpretation to develop the correlation model. Therefore, sequence stratigraphy has an important built-in interpretation component which addresses issues such as the reconstruction of the allogenic controls at the time of sedimentation, and predictions of facies architecture in yet unexplored areas. The former issue sparked an intense debate, still ongoing, between the supporters of eustatic vs. tectonic controls on sedimentation, which is highly important to the understanding of Earth history and fundamental Earth processes. Beyond sea-level change and tectonism, the spectrum of controls on stratigraphic patterns is actually much wider, including additional subsidence mechanisms (e.g., thermal subsidence, sediment compaction, isostatic, and flexural crustal loading), orbital forcing of climate changes, sediment supply, basin physiography, and environmental energy (Fig. 1.1). The second issue, on the economic
aspect of facies predictability, provides the industry community with a powerful new analytical and correlation tool of exploration for natural resources.

In spite of its inherent genetic aspect, one should not regard sequence stratigraphy as the triumph of interpretation over data, or as a method developed in isolation from other geological disciplines. In fact, sequence stratigraphy builds on many existing data sources, it requires a good knowledge of sedimentology and facies analysis, and it integrates the broad field of sedimentary geology with geophysics, geomorphology, absolute and relative age-dating techniques, and basin analysis. As with any modeling efforts, the reliability of the sequence stratigraphic model depends on the quality and variety of input data, and so integration of as many data sets as possible is recommended. The most common data sources for a sequence stratigraphic analysis include outcrops, modern analogues, core, well logs, and seismic data (Fig. 1.1).

In addition to the facies analysis of the strata themselves, which is the main focus of conventional sedimentology, sequence stratigraphy also places a strong emphasis on the contacts that separate packages of strata characterized by specific depositional trends. Such contacts represent event-significant bounding surfaces that mark changes in sedimentation regimes, and are important both for regional correlation, as well as for understanding the facies relationships within the confines of specific depositional systems. The study of stratigraphic contacts may not, however, be isolated from the facies analysis of the strata they separate, as the latter often provide the diagnostic criteria for the recognition of bounding surfaces.

Sequence Stratigraphy—A Revolution in Sedimentary Geology

Sequence stratigraphy is the third of a series of major revolutions in sedimentary geology (Miall, 1995). Each revolution resulted in quantum paradigm shift that changed the way geoscientists interpreted sedimentary strata. The first breakthrough was marked by the development of the flow regime concept and the associated process/response facies models in the late 1950s and early 1960s (Harms and Fahnestock, 1965; Simons et al., 1965). This first revolution provided a unified theory to explain, from a hydrodynamic perspective, the genesis of sedimentary structures and their predictable associations within the context of depositional systems. Beginning in the 1960s, the incorporation of plate tectonics and geodynamic concepts into the analysis of sedimentary processes at regional scales, marked the second revolution in sedimentary geology.

Ultimately, these first two conceptual breakthroughs or revolutions led to the development of Basin Analysis in the late 1970s, which provided the scientific framework for the study of the origins and depositional histories of sedimentary basins. Sequence stratigraphy marks the third and most recent revolution in sedimentary geology, starting in the late 1970s with the publication of AAPG Memoir 26 (Payton, 1977), although its roots can be traced much further back in time as explained below. Sequence stratigraphy developed as an interdisciplinary method that blended both autogenic (i.e., from within the system) and allogenic (i.e., from outside the system) processes into a unified model to explain the evolution and stratigraphic architecture of sedimentary basins (Miall, 1995).

The success and popularity of sequence stratigraphy stems from its widespread applicability in both mature and frontier hydrocarbon exploration basins, where data-driven and model-driven predictions of lateral and vertical facies changes can be formulated, respectively. These predictive models have proven to be particularly effective in reducing lithology-prediction risk for hydrocarbon exploration, although there is an increasing demand to employ the sequence stratigraphic method for coal and mineral resources exploration as well.

HISTORICAL DEVELOPMENT OF SEQUENCE STRATIGRAPHY

Early Developments

Sequence stratigraphy is generally regarded as stemming from the seismic stratigraphy of the 1970s. In fact, major studies investigating the relationship between sedimentation, unconformities, and changes in base level, which are directly relevant to sequence stratigraphy, were published prior to the birth of seismic stratigraphy (e.g., Grabau, 1913; Barrell, 1917; Sloss et al., 1949; Wheeler and Murray, 1957; Wheeler, 1958, 1959, 1964; Sloss, 1962, 1963; Curray, 1964; Frazier, 1974). As early as the eighteenth century, Hutton recognized the periodic repetition through time of processes of erosion, sediment transport, and deposition, setting up the foundation for what is known today as the concept of the ‘geological cycle.’ Hutton’s observations may be considered as the first account of stratigraphic cyclicity, where unconformities provide the basic subdivision of the rock record into repetitive successions. The link between unconformities and base-level changes was explicitly emphasized by Barrell (1917), who stated that ‘sedimentation controlled by base level will result in divisions of the stratigraphic series separated by breaks.’
The term ‘sequence’ was introduced by Sloss et al. (1949) to designate a stratigraphic unit bounded by subaerial unconformities. Sloss emphasized the importance of such sequence-bounding unconformities, and subsequently subdivided the entire Phanerozoic succession of the interior craton of North America into six major sequences (Sloss, 1963). Sloss also emphasized the importance of tectonism in the generation of sequences and bounding unconformities, an idea which is widely accepted today but was largely overlooked in the early days of seismic stratigraphy. It is noteworthy that the original ‘sequence’ of Sloss referred to ‘unconformity-bounded masses of strata of greater than group or supergroup rank’ (Krumbein and Sloss, 1951), which restricted the applicability of the ‘sequence’ concept only to regional-scale stratigraphic studies. The meaning of a stratigraphic ‘sequence’ has been subsequently expanded to include any ‘relatively conformable succession of genetically related strata’ (Mitchum, 1977), irrespective of temporal and spatial scales. In parallel with the development of the ‘sequence’ concept in a stratigraphic context, sedimentologists in the 1960s and 1970s have redefined the meaning of the term ‘sequence’ to include a vertical succession of facies that are ‘organized in a coherent and predictable way’ (Pettijohn, 1975), reflecting the natural evolution of a depositional environment. This idea was further perpetuated in landmark publications by Reading (1978) and Selley (1978a). Examples of facies sequences, in a sedimentological sense, would include coarsening-upward successions of deltaic facies (which many stratigraphers today would call ‘parasequences’), or the repetition of channel fill, lateral accretion and overbank architectural elements that is typical of meandering river systems (which may be part of particular systems tracts in a stratigraphic sense). The development of seismic and sequence stratigraphy in the late 1970s and 1980s revitalized the use of the term ‘sequence’ in a stratigraphic context, which remained the dominant approach to date. It is therefore important to distinguish between the ‘sequence’ of sequence stratigraphy and the ‘facies sequence’ of sedimentology (see van Loon, 2000, for a full discussion).

The unconformity-bounded sequences promoted by Sloss (1963) and Wheeler (1964) in the pre-sequence stratigraphy era provided the geological community with informal mappable units that could be used for stratigraphic correlation and the subdivision of the rock record into genetically-related packages of strata. The concept of ‘unconformity-bounded unit’ (i.e., Sloss’ ‘sequence’) was formalized by the European ‘International Stratigraphic Guide’ in 1994. The limitation of this method of stratigraphic analysis was imposed by the lateral extent of sequence-bounding unconformities, which are potentially restricted to the basin margins. Hence, the number of sequences mapped within a sedimentary basin may significantly decrease along dip, from the basin margins towards the basin centre (Fig. 1.4). This limitation required a refinement of the early ideas by finding a way to extend sequence boundaries across an entire sedimentary basin. The introduction of ‘correlative conformities,’ which are extensions towards the basin center of basin-margin unconformities, marked the birth of modern seismic and sequence stratigraphy (Fig. 1.5) (Mitchum, 1977). The advantage of the modern sequence, bounded by a composite surface that may include a conformable portion, lies in its basin-wide extent — hence, the number of sequences mapped at the basin margin equals the number of sequences that are found in the basin center. Due largely to disagreements regarding the timing of the correlative conformity relative to a reference curve of base-level changes, this new sequence bounded by unconformities or their correlative conformities remains and informal designation insofar as has not yet been ratified by either the European or the North American commissions on stratigraphic nomenclature. Nonetheless, this usage has seen widespread adoption in the scientific literature of the past two decades.

Sequence Stratigraphy Era—Eustatic vs. Tectonic Controls on Sedimentation

Seismic stratigraphy emerged in the 1970s with the work of Vail (1975) and Vail et al. (1977). This new
method for analyzing seismic-reflection data stimulated a revolution in stratigraphy, with an impact on the geological community as important as the introduction of the flow regime concept in the late 1950s—early 1960s and the plate tectonics theory in the 1960s (Miall, 1995). The concepts of seismic stratigraphy were published together with a global sea-level cycle chart (Vail et al., 1977), based on the underlying assumption that eustasy is the main driving force behind sequence formation at all levels of stratigraphic cyclicity. Seismic stratigraphy and the global cycle chart were thus introduced to the geological community as a seemingly inseparable package of new stratigraphic methodology. These ideas were then passed on to sequence stratigraphy in its early years, as seismic stratigraphy evolved into sequence stratigraphy with the incorporation of outcrop and well data (Posamentier et al., 1988; Posamentier and Vail, 1988; Van Wagoner et al., 1990). Subsequent publications (e.g., Hunt and Tucker, 1992; Posamentier and James, 1993; Posamentier and Allen, 1999) shifted the focus away from eustasy and towards a blend of eustasy and tectonics, termed ‘relative sea level.’ Nonetheless, the global-eustasy model as initially proposed (Vail et al., 1977) posed two challenges to the practitioners of ‘conventional’ stratigraphy: that sequence stratigraphy, as linked to the global cycle chart, constitutes a superior standard of geological time to that assembled from conventional chronostratigraphic evidence, and that stratigraphic processes are dominated by the effects of eustasy, to the exclusion of other allogenic mechanisms, including tectonism (Miall and Miall, 2001). Although the global cycle chart is now under intense scrutiny and criticism (e.g., Miall, 1992), the global-eustasy model is still used for sequence stratigraphic analysis in some recent publications (e.g., de Graciansky et al., 1998).

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

The switch in emphasis from sea-level changes to relative sea-level changes in the early 1990s (e.g., Hunt and Tucker, 1992; Christie-Blick and Driscoll, 1995) marked a major and positive turnaround in sequence stratigraphy. By doing so, no interpretation of specific eustatic or tectonic fluctuations was forced upon sequences, systems tracts, or stratigraphic surfaces. Instead, the key surfaces, and implicitly the stratal units between them, are inferred to have formed in relation to a more ‘neutral’ curve of relative sea-level (base-level) changes that can accommodate any balance between the allogenic controls on accommodation.
Sequence Models

The concept of sequence is as good, or accepted, as the boundaries that define it. As a matter of principle, it is useless to formalize a unit when the definition of its boundaries is left to the discretion of the individual practitioner. The sequence defined by Sloss et al. (1949) as an unconformity-bounded unit, was widely embraced (and formalized in the 1994 International Stratigraphic Guide) because the concept of unconformity was also straightforward and surrounded by little debate. The modification of the original concept of sequence by the introduction of correlative conformities as part of its bounding surfaces triggered both progress and debates at the onset of the seismic and sequence stratigraphy era. The main source of contention relates to the nature, timing, and mappability of these correlative conformities, and as a result a number of different approaches to sequence definition and hence sequence models are currently in use, each promoting a unique set of terms and bounding surfaces. This creates a proliferation of jargon and concomitant confusion, and represents a barrier to communication of ideas and results. In time, many of these barriers will fade as the discipline matures and the jargon is streamlined. Likewise, the varying approaches to sequence delineation, also a cause for confusion, will become less contentious, and perhaps less important, as geoscientists focus more on understanding the origin of strata and less on issues of nomenclature or style of conceptual packaging. Some of the reasons for the variety of approaches in present-day sequence stratigraphy include: the underlying assumptions regarding primary controls on stratigraphic cyclicity; the type of basin from which models were derived; and the gradual conceptual advances that allowed for alternative models to be developed. The fact that controversy persists can be viewed as a healthy aspect in the maturation of the discipline; it suggests that the science is continuing to evolve, just as it should do. Present-day sequence stratigraphy can thus be described as a still-developing field that is taking the science of sedimentary geology in an exciting new direction of conceptual and practical opportunities, even though the road may be punctuated by disagreements and controversy.

The early work on seismic and sequence stratigraphy published in AAPG Memoir 26 (Payton, 1977) and SEPM Special Publication 42 (Wilgus et al., 1988) resulted in the definition of the depositional sequence, as the primary unit of a sequence stratigraphic model. This stratigraphic unit is bounded by subaerial unconformities on the basin margin and their correlative conformities towards the basin center. The depositional sequence was subdivided into lowstand, transgressive, and highstand systems tracts on the basis of internal surfaces that correspond to changes in the direction of shoreline shift from regression to transgression and vice versa (Posamentier and Vail, 1988). Variations on the original depositional sequence theme resulted in the publication of several slightly modified versions of the depositional sequence model (Figs. 1.6 and 1.7).

FIGURE 1.6 Family tree of sequence stratigraphy (modified from Donovan, 2001). The various sequence stratigraphic models mainly differ in the style of conceptual packaging of strata into sequences, i.e., with respect to where the sequence boundaries are picked in the rock record.
Soon after the SEPM Special Publication 42, Galloway (1989), based on Frazier (1974), proposed that maximum flooding surfaces, rather than subaerial unconformities, be used as sequence boundaries. This unit was termed a genetic stratigraphic sequence, also referred to as a regressive–transgressive (R–T) sequence. Embry and Johannessen (1992) proposed a third type of stratigraphic unit, named a transgressive–regressive (T–R) sequence, corresponding to a full cycle of transgressive and regressive shoreline shifts (Figs. 1.6 and 1.7).

The various sequence models that are currently in use differ from each other mainly in the style of conceptual packaging of the stratigraphic record, using different timing for systems tract and sequence boundaries in relation to a reference cycle of base-level shifts (Figs. 1.6 and 1.7). Each sequence model may work best under particular circumstances, and no one model is universally preferable, or applicable to the entire range of case studies (Catuneanu, 2002). The dominant approaches, as reflected by the sequence stratigraphic literature, are those popularized by the Exxon school (Posamentier and Vail, 1988; Van Wagener et al., 1990; Posamentier and Allen, 1999) and to a somewhat lesser extent by Galloway (1989) and Embry and Johannessen (1992).

Nonetheless, the applicability and practical limitations of each approach are discussed in detail in this book.

**SEQUENCE STRATIGRAPHIC APPROACH**

**Terminology**

Figures 1.8 and 1.9 provide the most popular definitions for sequence stratigraphy and the main stratigraphic units used in a sequence stratigraphic analysis. In contrast with all other types of stratigraphy (including allostratigraphy), and in spite of having been widely accepted in the geologic literature, sequence stratigraphy has not yet been formally incorporated into the North American Code of Stratigraphic Nomenclature, nor into the International Stratigraphic Guide. The reason for this is the lack of consensus on some basic principles, including the definition of a sequence (i.e., which surfaces should constitute the sequence boundaries), and also the proliferation of a complex jargon that is difficult to standardize.
The fact that several different sequence models are currently in use does not make the task of finding a common ground easy, even for what a sequence should be. A key aspect of the problem lies in the fact that the position of the sequence boundary (in both space and time) varies from one model to another, to the extent that any of the sequence stratigraphic surfaces may become a sequence boundary or at least a part of it. Nevertheless, all versions of sequence boundaries regardless of which model is employed include both unconformable and conformable portions, which means that the original definition of sequence by Mitchum (1977) (Fig. 1.9), which incorporates the notion of a correlative conformity, still satisfies most of the current approaches.

Jargon is a potential distraction that can make sequence stratigraphy a difficult undertaking for those embarking on the application of this approach. All sequence models purport to describe the same rocks, though they often use different sets of terms. Beyond this terminology barrier and beyond the issue of which surfaces constitute the sequence boundaries, sequence stratigraphy is, in fact, a relatively easy method to use. A careful analysis of the different models reveals a lot of common ground between the various approaches with much of the terminology synonymous or nearly so. Again, the main differences between these approaches lie in the conceptual packaging of the same succession of strata. Once these differences are understood, the geoscientist has the flexibility of using whatever model works best for the particular circumstances of a specific case study. Having said that, it is also desirable to proceed towards a unified sequence stratigraphic approach, which is the only way that can lead to the formal standardization of sequence stratigraphic concepts. The differences highlighted in Fig. 1.7 show that (1) a significant part of the ‘disagreement’ is in fact a matter of semantics, hence it can be easily overcome; and (2) the position of the sequence boundary, especially its conformable portion, varies with the model. Beyond these issues, all models are bridged by the fact that the subdivisions of each type of sequence are linked to the same reference curve of base-level changes, and hence they are conceptual equivalents. It is therefore conceivable that a basic set of principles may ultimately be accepted as the formal backbone of the discipline by all practitioners of stratigraphic analysis. Such acceptance would not preclude divergence of analytical styles as a function of case study and/or the data available for analysis.

This book attempts to demonstrate that, irrespective of the model of choice, and its associated timing of sequence boundaries, the ‘heartbeat’ of sequence stratigraphy is fundamentally represented by shoreline shifts, whose nature and timing control the formation of all systems tracts and bounding surfaces. Beyond nomenclatural preferences, each stage of shoreline shift (normal regression, forced regression, transgression) corresponds to the formation of a
systems tract with unique stratal stacking patterns. Surfaces that can serve, at least in part, as systems tract boundaries constitute surfaces of sequence stratigraphic significance. These fundamental principles are common to all models, and ultimately provide the basis for a unified sequence stratigraphic approach.

**Concept of Scale**

It is important to note that the application and definition of sequence stratigraphic concepts is independent of scale (Figs. 1.8 and 1.9). This means that the same terminology can and should be applied for sequences, systems tracts, and surfaces that have developed at different temporal and spatial scales. The general sequence stratigraphic approach thus applies to features as small as those produced in an experimental flume, formed in a matter of hours (e.g., Wood et al., 1993; Koss et al., 1994; Paola, 2000; Paola et al., 2001), as well as to those that are continent wide and formed over a period of millions of years. Nonetheless a distinction must be made between larger- and the smaller-scale sequences, systems tracts, and stratigraphic surfaces. This is addressed through a hierarchy based on the use of modifiers such as first-order, second-order, third-order, etc., commonly in a relative rather than an absolute sense. Although this terminology is often associated with specific time ranges (Vail et al., 1977, 1991; Krapez, 1996), this has not always been common practice in the scientific literature (see discussions in Embry, 1995; Posamentier and Allen, 1999; Catuneanu et al., 2004, 2005). One reason for this is that we often do not know the scale (especially duration, but also lateral extent or thickness changes across a basin) of the stratal units we deal with within a given study area, so the use of specific names for specific scales may become quite subjective. Another advantage of

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

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

A systems tract includes all strata accumulated across the basin during a particular stage of shoreline shifts.

Systems tracts are interpreted based on stratal stacking patterns, position within the sequence, and types of bounding surfaces. The timing of systems tracts is inferred relative to a curve that describes the base-level fluctuations at the shoreline.

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

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

Sequences correspond to full stratigraphic cycles of changing depositional trends. The conformable or unconformable character of the bounding surfaces is not an issue in the process of sequence delineation, nor the degree of preservation of the sequence.