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.

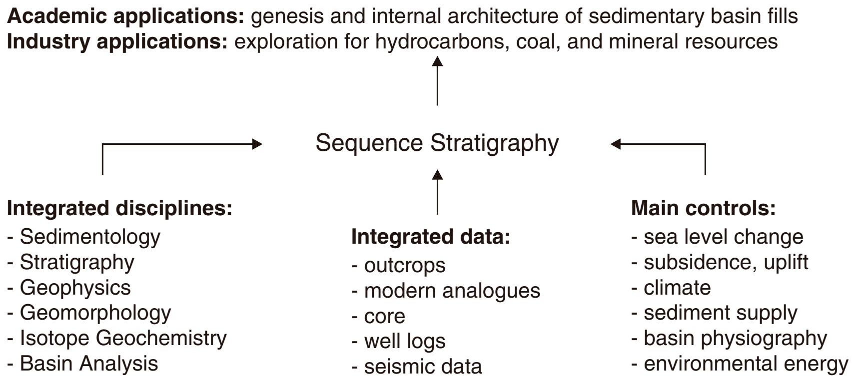
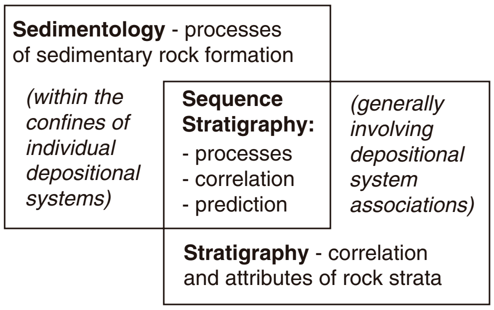


FIGURE 1.1 Sequence stratigraphy in the context of interdisciplinary research—main controls, integrated data sets and subject areas, and applications.



Sedimentology: the scientific study of sedimentary rocks and of the processes by which they form.

Stratigraphy: the science of rock strata - all characters and attributes of rocks as strata, and their interpretation in terms of mode of origin and geologic history.

FIGURE 1.2 Sequence stratigraphy and its overlap with the conventional disciplines of sedimentology and stratigraphy (definitions modified from Bates and Jackson, 1987). When applied to a specific depositional system, sequence stratigraphy helps to understand processes of facies formation, facies relationships, and facies cyclicity in response to base-level changes. At larger scales, the lateral correlation of coeval depositional systems becomes a more significant issue, which also brings in a component of facies predictability based on the principle of common causality related to the basin-wide nature of the allogenic controls on sedimentation.

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).

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

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

FIGURE 1.3 Types of stratigraphy, defined on the basis of the property they analyze. The interplay of sedimentation and shifting base level at the shoreline generates changes in depositional trends in the rock record, and it is the analysis and/or correlation of these changes that defines the primary objectives of sequence stratigraphy.

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.

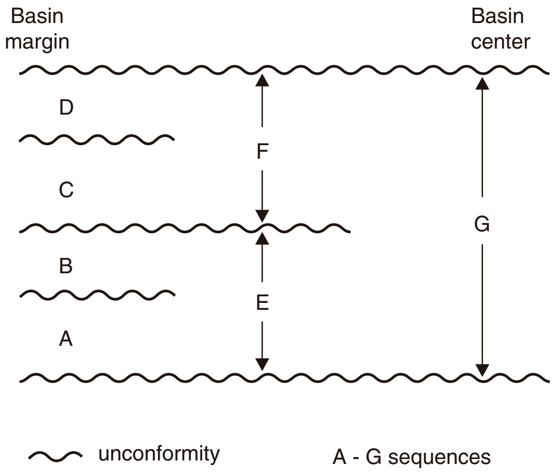


FIGURE 1.4 The concept of unconformity-bounded sequence of Sloss *et al.* (1949). As many unconformities are potentially restricted to the basin margins, the number of sequences mapped in the basin centre is often lower than the number of sequences present in an age-equivalent succession along the rim of the basin.

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

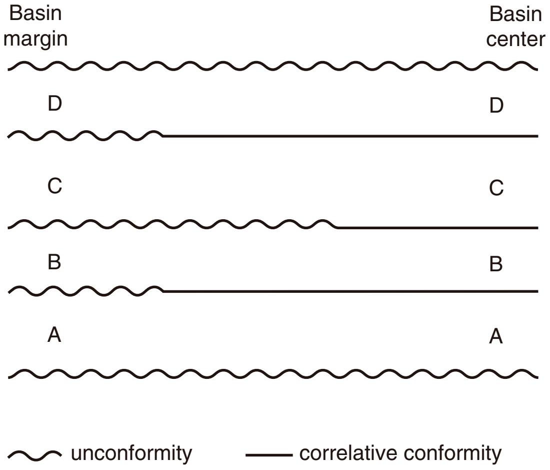


FIGURE 1.5 The concept of sequence as defined in seismic and sequence stratigraphy. The correlative conformities allow tracing sequences across an entire sedimentary basin. A–G—sequences.

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) shift 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).

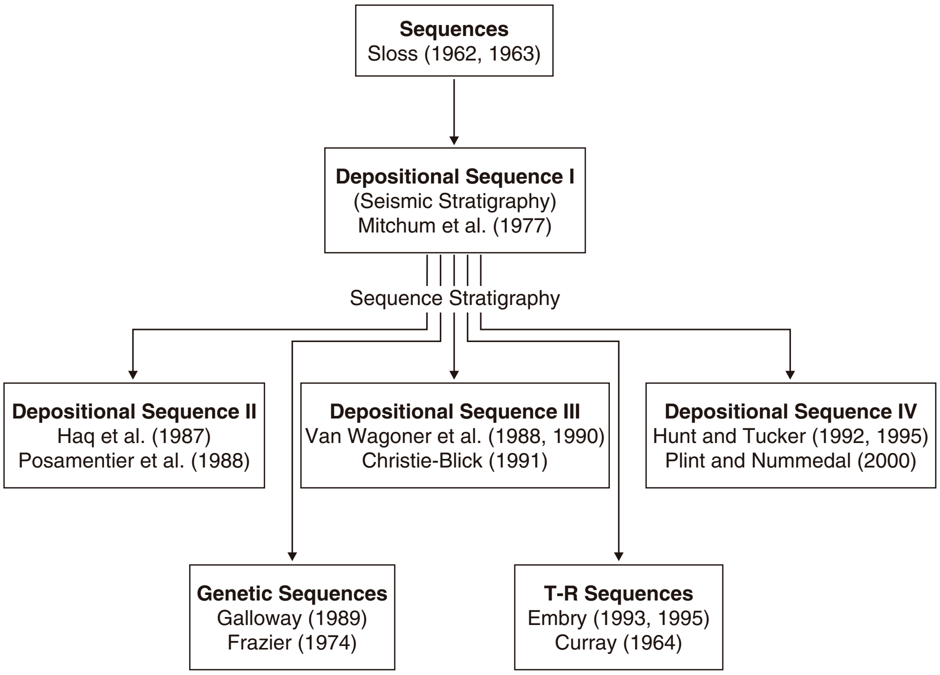
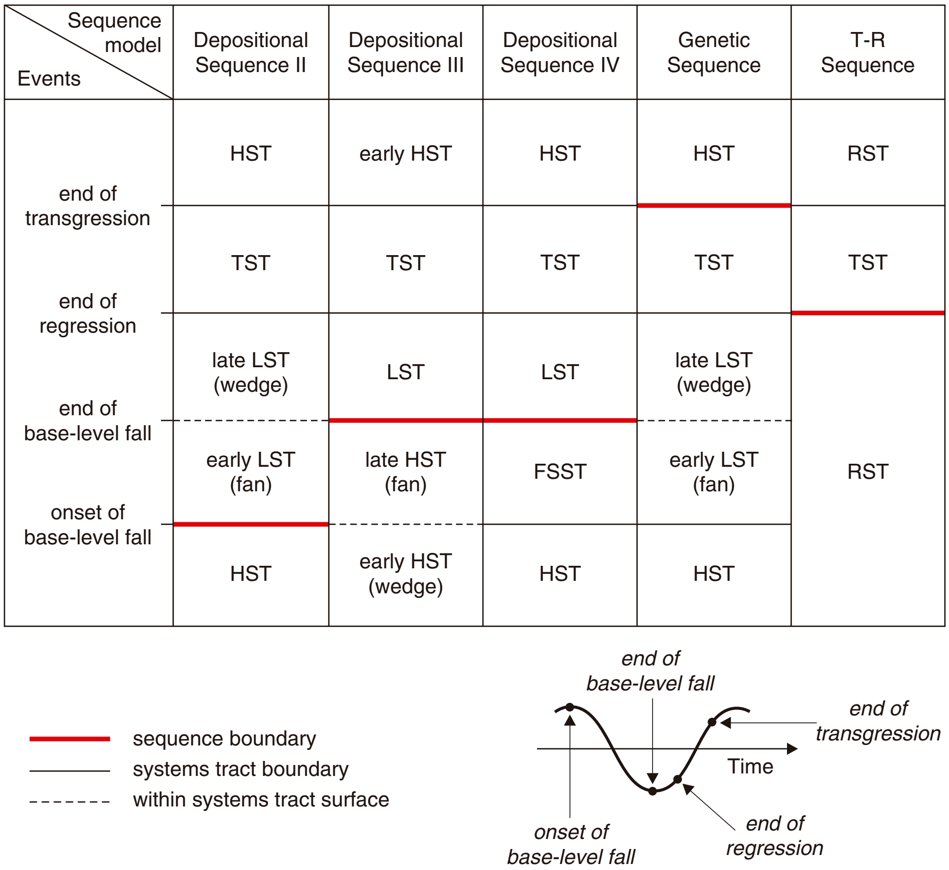


FIGURE 1.6 Family tree of sequence stratigraphy (modified from Donovan, 2001). The various sequence stratigraphic models mainly differ in the style of conceptual packaging of strata into sequences, i.e., with respect to where the sequence boundaries are picked in the rock record.



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

FIGURE 1.7 Timing of system tracts and sequence boundaries for the sequence models currently in use (modified from Catuneanu, 2002). The conformable portion of the sequence boundary of the depositional sequence II was originally considered to form *during early* sea-level fall (Posamentier *et al.*, 1988), which was later revised to the *onset* of sea-level fall (Posamentier *et al.*, 1992b), as represented in this table. In addition to these classic models, other hybrid models are also in use, as for example the approach that recognizes the four systems tracts of the depositional sequence IV, but with a sequence boundary that conforms to the depositional sequence II (Coe, 2003). Abbreviations: LST—lowstand systems tract; TST—transgressive systems tract; HST—highstand systems tract; FSST—falling-stage systems tract; RST—regressive systems tract; T–R—transgressive-regressive.

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 Wagoner *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 stratal 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.

Sequence stratigraphy (Posamentier et al., 1988; Van Wagoner, 1995): the study of rock relationships within a time-stratigraphic framework of repetitive, genetically related strata bounded by surfaces of erosion or nondeposition, or their correlative conformities.

Sequence stratigraphy (Galloway, 1989): the analysis of repetitive genetically related depositional units bounded in part by surfaces of nondeposition or erosion.

Sequence stratigraphy (Posamentier and Allen, 1999): the analysis of cyclic sedimentation patterns that are present in stratigraphic successions, as they develop in response to variations in sediment supply and space available for sediment to accumulate.

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

Note that sedimentation is separated from base-level changes. Also note important keywords:

- *"cyclicity": a sequence is a cyclothem, i.e. it corresponds to a stratigraphic cycle;*
- *"time framework": age-equivalent depositional systems are correlated across a basin. This provides the foundation for the definition of systems tracts. In the early days of sequence stratigraphy, bounding surfaces were taken as time lines, in the view of the global-eustasy model. Today, independent time control is required for large-scale correlations;*
- *"genetically related strata": no major hiatuses are assumed within a sequence.*

FIGURE 1.8 Definitions of sequence stratigraphy. In the simplest sense, sequence stratigraphy deals with the sedimentary response to base-level changes, which can be analyzed from the scale of individual depositional systems to the scale of entire basins.

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

Depositional systems (Galloway, 1989): three-dimensional assemblages of process-related facies that record major paleo-geomorphic elements.

Depositional systems (Fisher and McGowan, 1967, in Van Wagoner, 1995): three-dimensional assemblages of lithofacies, genetically linked by active (modern) processes or inferred (ancient) processes and environments.

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

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

> *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.*

The concepts of sequence, systems tracts, and stratigraphic surfaces are independent of scale, i.e. time for formation, thickness, or lateral extent. Same sequence stratigraphic terminology can be applied to different orders of cyclicity, via the concept of hierarchy. Well-log signatures are not part of the definition of sequence stratigraphic concepts, although general trends may be inferred from the predictable stacking patterns of systems tracts. The magnitude of the log deflections will vary with the magnitude/importance of the mapped surfaces and stratal units.

FIGURE 1.9 Main building blocks of the sedimentary record from a sequence stratigraphic prospective. With an increasing scale of observation, these units refer to depositional systems, systems tracts, and sequences.

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 using a consistent terminology regardless of scale is that jargon is kept to a minimum, which makes sequence stratigraphy more user-friendly and easier to understand across a broad spectrum of readership. These issues are tackled in more detail in Chapter 8, which deals with the hierarchy of sequences and sequence boundaries.

Among the key concepts shown in Fig. 1.9, the term *depositional system* is a general (conventional) notion defined on the basis of depositional setting and environment. The terms *systems tract* and *sequence* are specific sequence stratigraphic terms, defined in relationship to the base-level and the transgressive–regressive curves. A systems tract includes a sum of laterally correlative depositional systems (hence, the use of plural: *systems*). A sequence includes two or more systems tracts, depending on the model of choice (Fig. 1.7). The actual scale for sequence stratigraphic work is highly variable, depending on the problem in hand, ranging from depositional system scale (also highly variable) to the entire fill of the basin, and beyond. When applied to the analysis of a depositional system, e.g., an ancient delta (Fig. 1.10), sequence stratigraphy is mainly used to resolve the nature of contacts and the details of facies relationships. Such studies are often performed to describe the degree of reservoir compartmentalization in the various stages of oil field exploration and production. When applied to the scale of depositional system associations, the issue of stratigraphic correlation becomes a primary objective, and provides the framework for the larger scale distribution of facies.

The principles outlined above provide a general idea about the range of potential outcomes and objectives of sequence stratigraphy as a function of scope and scale of analysis. There is a common misconception that sequence stratigraphy is always related to regional, continental, or even global scales of observation (sub-basins, basins, and global cycles)—this does not need to be the case, as sequence stratigraphy can be applied virtually to any scale. A good example of this is the study of the 'East Coulee Delta' (Posamentier *et al.*, 1992a), where an entire range of sequence stratigraphic elements (including 'classic' systems tracts) have been documented at a centimeter to meter scale (Fig. 1.11). In recent years there have been numerous flume-based studies where sequences have been created under controlled laboratory conditions (e.g., Wood *et al.*, 1993; Koss *et al.*, 1994; Paola, 2000; Paola *et al.*, 2001). Such studies have provided valuable insight as to variations on the general sequence model.

Sequence Stratigraphy *vs.* Lithostratigraphy and Allostratigraphy

Almost any type of study of a sedimentary basin fill requires the construction of cross sections. The lines we draw on these two-dimensional representations are of

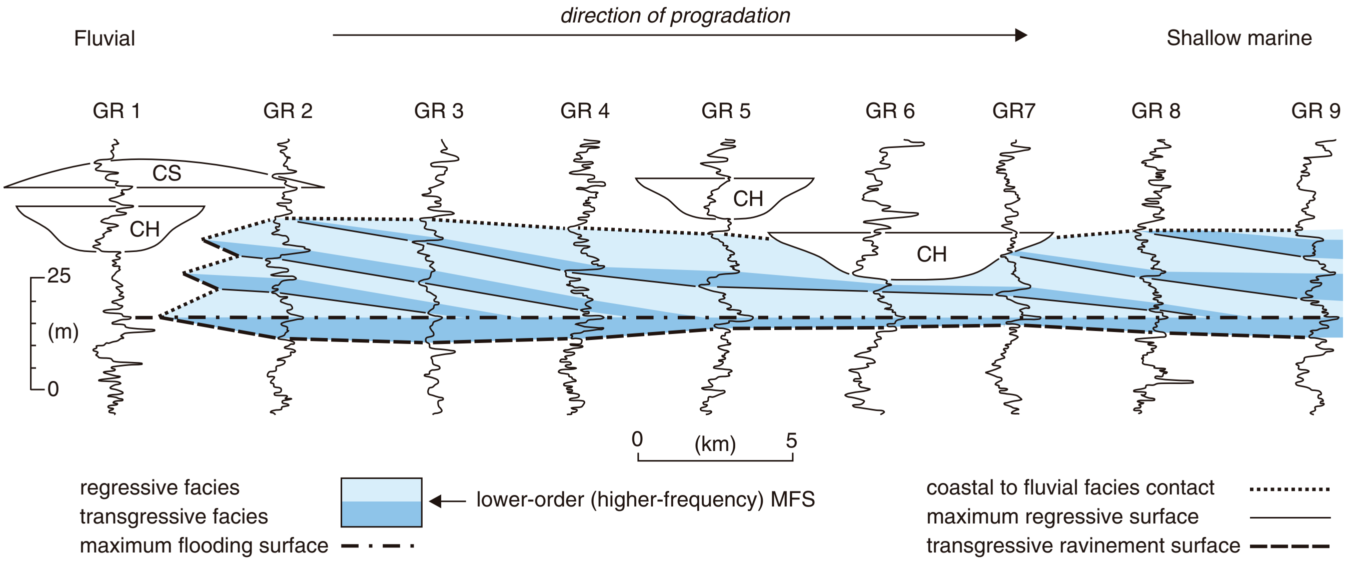


FIGURE 1.10 Example of sequence stratigraphy applied to understand the reservoir compartmentalization of a deltaic depositional system (case study illustrating the regression of the Late Cretaceous Bearpaw seaway, central Alberta). Abbreviations: GR—gamma ray logs; CH—fluvial channel fill; CS—crevasse splay; MFS—maximum flooding surface. Note that maximum flooding surfaces are associated with the finest-grained sediments, and their position reveals the overall progradation and geometry of the delta. The reservoir includes at least five separate hydrodynamic units, each corresponding to a stage of delta front progradation.

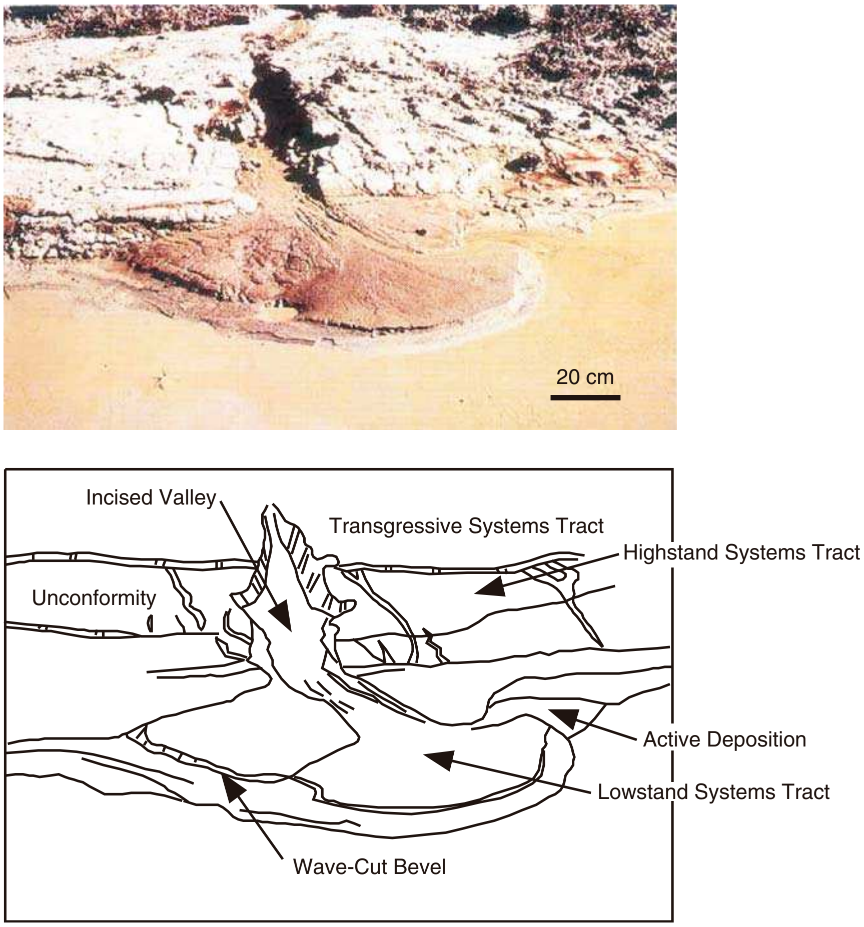


FIGURE 1.11 East Coulee Delta (approximately 1 m wide; modified from Posamentier *et al*., 1992a; image courtesy of H.W. Posamentier), demonstrating the applicability of sequence stratigraphic concepts at virtually any scale. In this example, the highstand systems tract was left behind, and it was subsequently incised as a result of the fall in the local (pond) base level during the progradation of the lower elevation lowstand delta. See Posamentier *et al*. (1992a) for a more detailed interpretation.

two main types: (1) lines that build the chronostratigraphic or time framework of the studied interval, and (2) lines that illustrate lateral changes of facies or lithology. The chronostratigraphic framework is constructed by the correlation of surfaces of sequence stratigraphic significance, or true time markers such as bentonites or magnetic polarity boundaries. This is where some confusion can arise. Strictly speaking, sequence stratigraphic surfaces commonly are not true time lines but in fact are to some degree time transgressive, or diachronous. However, because true time lines are not commonly observed, the geoscientist is relegated to using these surfaces as proxies for time lines, being pragmatic and accepting the notion that in most instances, within the confines of most study areas they are at least very close to being time lines and therefore, are fundamentally useful. The degree of diachroneity of sequence stratigraphic surfaces, as well as of other types of stratigraphic surfaces, is discussed in more detail in Chapter 7.

Sequence stratigraphic surfaces are not necessarily easier to observe than the more diachronous contacts that mark lateral and vertical changes of facies. Consequently the practitioner can be faced with the dilemma of where to begin a stratigraphic interpretation; in other words, what lines should go first on a cross-section. The sequence stratigraphic approach yields a genetic interpretation of basin fill, which clarifies by time increment how a basin has filled with sediment. To accomplish this, a chronostratigraphic framework is first established, and sequence stratigraphic surfaces are interpreted. Subsequently, the sections between sequence stratigraphic surfaces are interpreted by recognizing facies contacts. These two types of surfaces (i.e., ‘time lines’ and ‘facies contacts’) define sequence stratigraphy and lithostratigraphy, respectively (Fig. 1.12).

The inherent difference between lithostratigraphy and sequence stratigraphy is important to emphasize, as both analyze the same sedimentary succession but with the focus on different stratigraphic aspects or rock properties. Lithostratigraphy deals with the lithology of strata and with their organization into units based on lithological character (Hedberg, 1976).

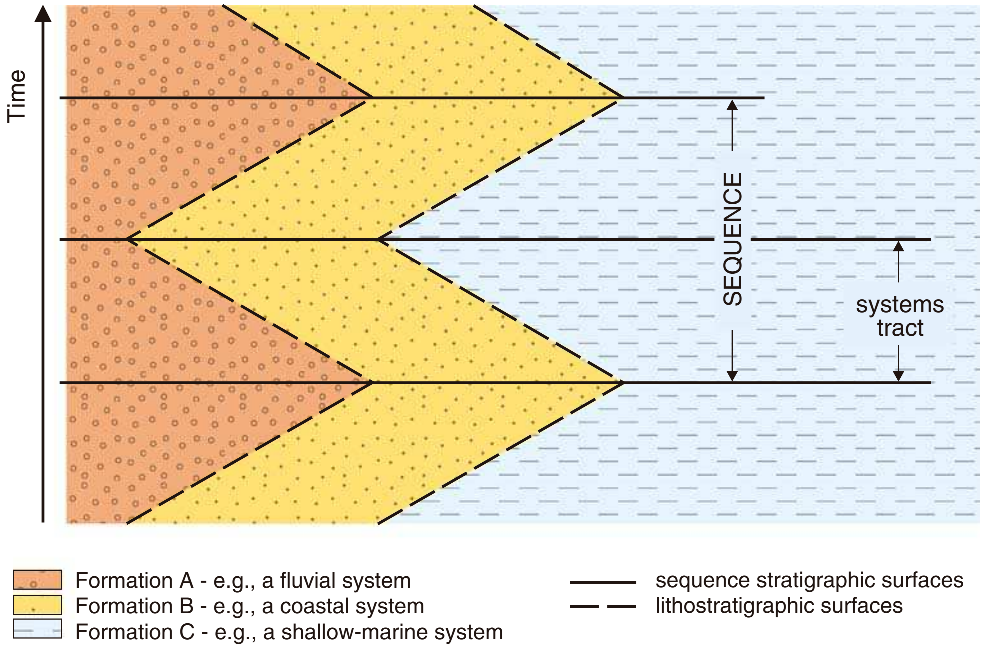


FIGURE 1.12 Conceptual contrast between lithostratigraphy and sequence stratigraphy. Sequence stratigraphic surfaces are event-significant, and mark changes in depositional trends. In this case, their timing is controlled by the turnaround points between transgressions and regressions. Lithostratigraphic surfaces are highly diachronous facies contacts. Note that the system tract and sequence boundaries cross the formation boundaries. Each systems tract is composed of three depositional systems in this example, and is defined by a particular depositional trend, i.e., progradational or retrogradational. A sequence corresponds to a full cycle of changes in depositional trends. This example implies continuous aggradation, hence no breaks in the rock record, with the cyclicity controlled by a shifting balance between the rates of base-level rise and the sedimentation rates.

The boundaries between lithostratigraphic units are often highly diachronous facies contacts, in which case they develop *within* the sedimentary packages bounded by sequence stratigraphic surfaces. Sequence stratigraphy deals with the correlation of coeval stratal units, irrespective of the lateral changes of facies that commonly occur across a basin, and which are bounded by low diachroneity (i.e., nearly synchronous) surfaces (Fig. 1.12). It is also important to note that facies analyses leading to the interpretation of paleoenvironments are much more critical for sequence stratigraphy than for lithostratigraphy, as illustrated in Figs. 1.13 and 1.14. These figures show that even along 1D vertical profiles, sequence stratigraphic units are often offset relative to the lithostratigraphic units due to their emphasis on different rock attributes. Understanding what constitutes a reasonable vertical and lateral relationship between facies within a time framework assists in correlating the same time lines through varying lithologies.

An example of a sequence stratigraphic—as contrasted with a lithostratigraphic—interpretation based on the same data set is illustrated in Fig. 1.15. The interpretation of sequence stratigraphic surfaces is based on two fundamental observations: the type of stratigraphic contact, conformable or unconformable; and the nature of facies (depositional systems) which are in contact across each particular surface. The reconstruction of paleodepositional environments is therefore a critical pre-requisite for a successful sequence stratigraphic interpretation. In contrast, the lithostratigraphic cross-section does not require knowledge of paleoenvironments, but only mapping of lithological contacts. Some of these contacts may coincide with sequence stratigraphic surfaces, others may only reflect diachronous lateral changes of facies. As a result, the lithostratigraphic units (e.g., formations A, B, and C in Fig. 1.15) provide only descriptive information of lithologic distribution, which in some instances could combine the products of sedimentation of various depositional environments. Thus a simple map of lithologic distribution may give little insight as to the general paleogeography, and as a result be of little use in predicting lithologies away from known data points.

Allostratigraphy is a stratigraphic discipline that is intermediate in scope between lithostratigraphy

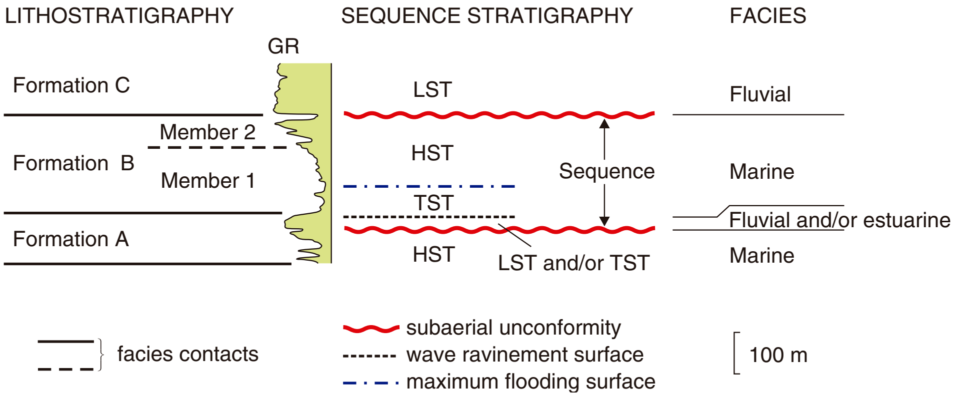


FIGURE 1.13 Lithostratigraphic and sequence stratigraphic interpretations of a gamma ray (GR) log (modified from Posamentier and Allen, 1999). Lithostratigraphy defines rock units on the basis of lithology, often irrespective of the depositional environment. Sequence stratigraphy defines rock units based on the event-significance of their bounding surfaces. Abbreviations: LST—lowstand systems tract; TST—transgressive systems tract; HST—highstand systems tract.

and sequence stratigraphy. The North American Commission on Stratigraphic Nomenclature (NACSN) introduced formal allostratigraphic units in the 1983 North American Stratigraphic Code to name discontinuity-bounded units. As currently amended, 'an allostratigraphic unit is a mappable body of rock that is defined and identified on the basis of its bounding discontinuities' (Article 58). Allostratigraphic units, in order of decreasing rank, are allogroup, alloformation, and allomember—a terminology that originates and is modified from lithostratigraphy. The fundamental unit is the alloformation (NACSN, 1983, Art. 58). The bounding discontinuities which define the allostratigraphic approach are represented by any mappable lithological contact, with or without a stratigraphic hiatus associated with it. Basically, any type of stratigraphic contact illustrated in Fig. 1.16 may qualify as an allostratigraphic boundary. In this approach, all lithostratigraphic *and* sequence stratigraphic surfaces that are associated with a lithological contrast may be used for allostratigraphic studies (e.g., Bhattacharya and Walker, 1991; Plint, 2000).

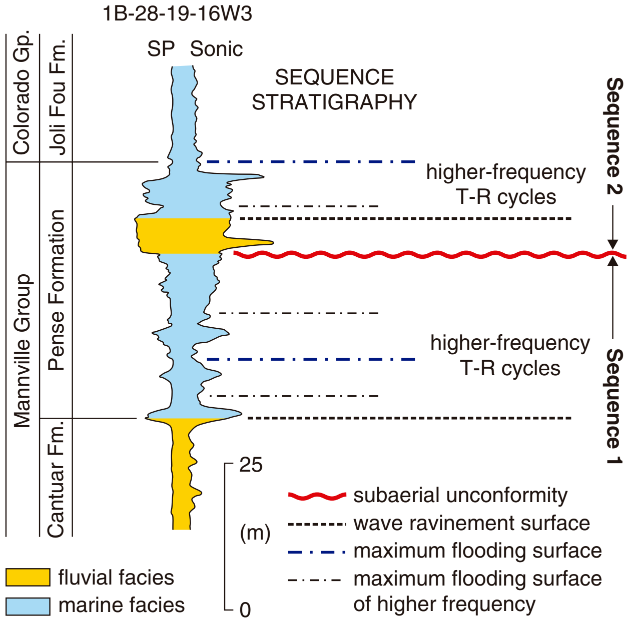
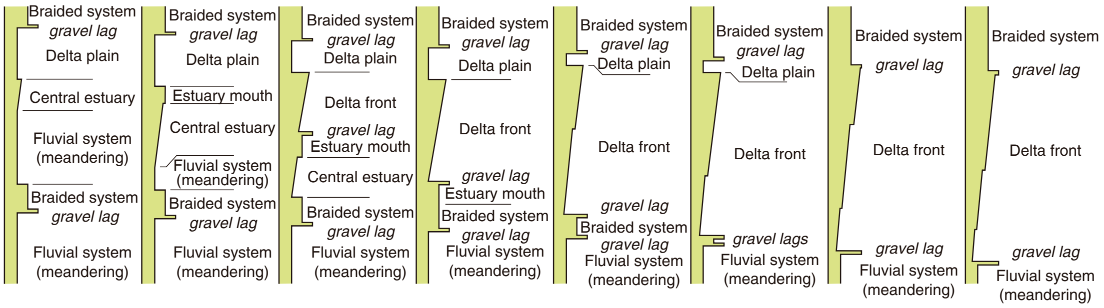


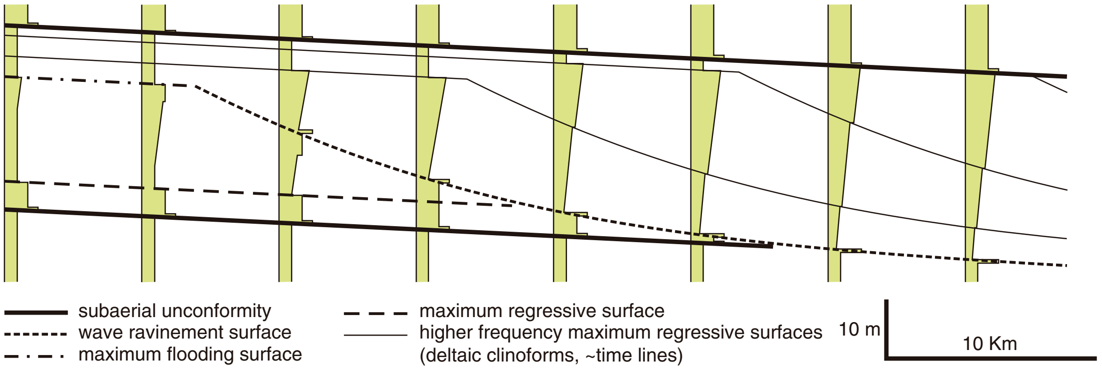
FIGURE 1.14 Relationship between depositional environments, lithostratigraphy, and sequence stratigraphy (wireline logs from the Western Canada Sedimentary Basin). Note that facies analysis (interpretation of paleodepositional environments) is more critical to sequence stratigraphy than to lithostratigraphy. Several higher frequency transgressive–regressive cycles can be noted within each sequence. The most prominent maximum flooding surface of each sequence, corresponding to the peak of finest sediment, belongs to the same hierarchical order as the sequence itself. *These* maximum flooding surfaces separate the transgressive and highstand systems tracts of sequences 1 and 2. Abbreviations: SP—spontaneous potential; T–R—transgressive–regressive.

Whereas allostratigraphy provides the means to take lithostratigraphy to a higher level of genetic interpretation of paleodepositional histories, because of the use of time-significant surfaces, its pitfall rests with the vague definition of 'discontinuities.' NACSN deliberately left the definition of 'discontinuity' to the practicing geologist who wishes to define or use allostratigraphic units, so the actual meaning of such units is largely equivocal. Because a stratigraphic unit is as well or poorly defined as its bounding surfaces, the formalization of allostratigraphic units in the North American Stratigraphic Code remains a half realized achievement until discontinuity surfaces are also defined and formalized. Between the European and the North American commissions on stratigraphic nomenclature, efforts are being made to clarify both the degree of overlap and the outstanding differences between the 'unconformity-bounded units' of the 1994 International Stratigraphic Guide (i.e., the pre-sequence stratigraphy 'sequences' of Sloss *et al.*, 1949) and the 'discontinuity-bounded units' of the 1983 NACSN (i.e., allostratigraphic units). Because the

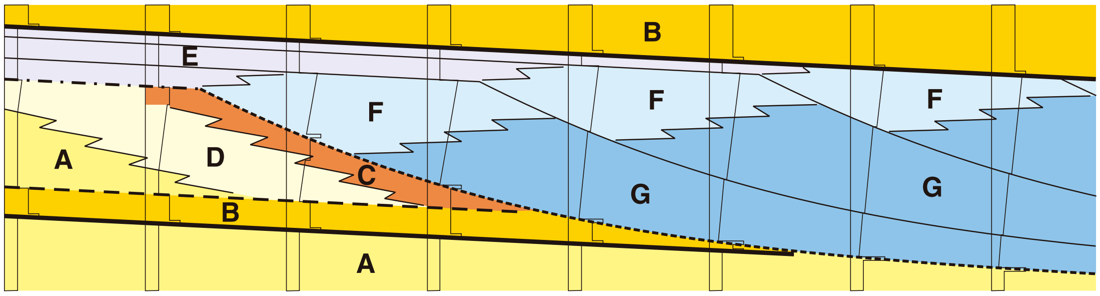
1. Data: vertical profiles and paleo-environments



2. Sequence stratigraphic framework



3. Sequence stratigraphic framework, facies contacts, and paleo-depositional environments



4. Cross-section emphasizing lithostratigraphic units

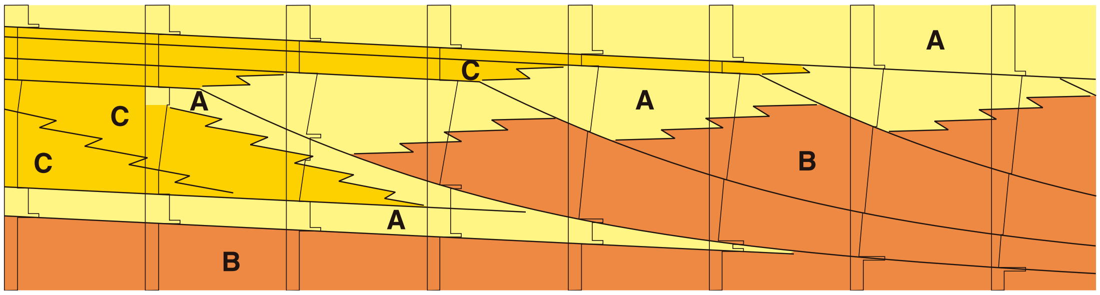


FIGURE 1.15 Sequence stratigraphic *vs.* lithostratigraphic frameworks, starting from the same set of facies data. 1. The reconstruction of paleodepositional environments *via* facies analysis is an important pre-requisite for sequence stratigraphic interpretations. The nature of stratigraphic contacts (scoured, conformable) also needs to be assessed *via* sedimentological analysis. 2. The sequence stratigraphic framework is constructed by correlating the key sequence stratigraphic surfaces. All sequence stratigraphic surfaces shown on the cross section are good chronostratigraphic markers (low diachroneity), with the exception of the transgressive wave-ravinement surface which is highly diachronous. 3. Sequence stratigraphic cross section, showing key surfaces, within-trend facies contacts, and paleodepositional environments. Within-trend facies contacts, marking lateral changes of facies, are placed on the cross-section *after* the sequence stratigraphic framework is constructed. Facies codes: A—meandering system; B—braided system; C—estuary-mouth complex; D—central estuary; E—delta plain; F—upper delta front; G—lower delta front—prodelta. 4. Lithostratigraphic cross-section. Three main lithostratigraphic units (e.g., formations) may be defined: A—a sandstone-dominated unit; B and C – mudstone-dominated units, with silty and sandy interbeds. Formations B and C are separated by Formation A. Additional lithostratigraphic units (e.g., members—subdivisions of units A, B, C) may be defined as a function of variations in lithology and color.

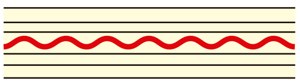
STRATIGRAPHIC CONTACTS

A. **Unconformity** = significant hiatus ± erosion (usually with erosion)

A substantial break or gap in the geological record … It normally implies uplift and erosion with loss of the previously formed record. … Relationship between rock strata in contact, characterized by a lack of continuity in deposition, and corresponding to a period of nondeposition, weathering, or esp. erosion (either subaerial or subaqueous) prior to the deposition of the younger beds.

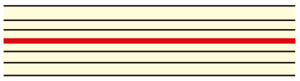
1. **Disconformity** = hiatus + erosion

An unconformity in which the bedding planes above and below the break are essentially parallel, indicating a significant interruption in the orderly sequence of sedimentary rocks, generally by a considerable interval of erosion ..., and usually marked by a visible and irregular or uneven erosion surface of appreciable relief.



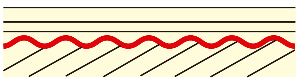
2. **Paraconformity** = hiatus ± erosion (no discernable erosion)

An obscure or uncertain unconformity in which no erosion surface is discernable ..., and in which the beds above and below the break are parallel.



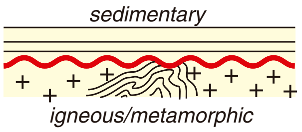
3. **Angular unconformity** = hiatus, erosion, and tilt

An unconformity between two groups of rocks whose bedding planes are not parallel or in which the older, underlying rocks dip at a different angle (usually steeper) than the younger, overlying strata.



4. **Nonconformity** = top of basement rocks

An unconformity developed between sedimentary rocks and older igneous or metamorphic rocks that had been exposed to erosion before the overlying sediments covered them.



B. **Diastem** = short hiatus ± erosion (a minor paraconformity)

A relatively short interruption in sedimentation, involving only a brief interval of time, with little or no erosion before deposition is resumed; a depositional break of lesser magnitude than a paraconformity, or a paraconformity of very small time value.

C. **Conformity** = no hiatus

Undisturbed relationship between adjacent sedimentary strata that have been deposited in orderly sequence... True stratigraphic continuity in the sequence of beds.

FIGURE 1.16 Types of stratigraphic contacts (definitions from Bates and Jackson, 1987). Note that any of these stratigraphic contacts may qualify as an allostratigraphic unit boundary, i.e., a 'discontinuity,' as long as it is associated with a lithological contrast.

(lithological) 'discontinuity' is a much less specific term, including both unconformities and conformities (Fig. 1.16), 'unconformity-bounded units' remain only a special case of allostratigraphic units. In this context, the currently informal concepts of sequence stratigraphy may ultimately provide the framework that will allow previously defined types of stratigraphic units and surfaces to obtain a clear status in relation to each other and within the bigger picture of genetic stratigraphy. Formalizing sequence stratigraphic concepts is thus an important next task for all international commissions on stratigraphy.