Abstract

Sequence stratigraphy studies the change in depositional trends in response to the interplay of accommodation and sediment supply, from the scale of individual depositional systems to entire sedimentary basin-fills. As accommodation is controlled by allogenic mechanisms that operate at basinal to global scales, the change in depositional trends is commonly synchronized among all environments established within a basin, thus providing the basis for the definition of systems tracts and the development of models of facies predictability. All classical sequence stratigraphic models assume the presence of an interior seaway within the basin under analysis and are centered around the direction and types of shoreline shifts, which control the timing of all systems tracts and sequence stratigraphic surfaces. In overfilled basins, dominated by nonmarine sedimentation, the definition of systems tracts is based on changes in fluvial accommodation, as inferred from the shifting balance between the various fluvial architectural elements.

The method of sequence stratigraphy requires the application of the same set of core principles irrespective of the age of strata under analysis, from Precambrian to Phanerozoic. The study of Precambrian basins is often hampered by poorer stratal preservation and by a general lack of time control. However, where sedimentary facies are well preserved, the lack of time control may be partially compensated by a good knowledge of facies architecture and relationships, as well as by paleocurrent data. The latter are particularly important to understand the stratigraphic record of tectonically active basins, where abrupt shifts in paleoflow directions allow one to infer tectonic events and map the corresponding sequence-bounding unconformities.

Arguably the most important contribution of Precambrian research to sequence stratigraphy is the better understanding of the mechanisms controlling stratigraphic cyclicity in the rock record, and hence of the criteria that should be employed in a system of sequence stratigraphic hierarchy. There is increasing evidence that the tectonic regimes which controlled the formation and evolution of sedimentary basins in the more distant geological past were much more erratic in terms of origin and rates than formerly inferred solely from the study of the Phanerozoic record. In this context, time is largely irrelevant as a parameter in the classification of stratigraphic sequences, and it is rather the stratigraphic record of changes in the tectonic setting that provides the key criteria for the basic subdivision of the rock record into basin-fill successions separated by first-order sequence boundaries. These first-order basin-fill successions are in turn subdivided into second- and lower-order sequences that result from shifts in the balance between accommodation and sedimentation at various scales of observation, irrespective of the time...
span between two same-order consecutive events. Sequences identified in any particular basin are not expected to correlate to other first- and lower-order sequences of other basins that may be similar in age but may have different timing and duration.
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1. Introduction

1.1. Overview

Sequence stratigraphy is a modern interdisciplinary approach in the broad field of sedimentary geology that revamps geological thinking and the methods of facies and stratigraphic analyses. Modern research trends show that staying within the boundaries of conventional disciplines brings little opportunity for significant progress—it is rather the integration of various approaches, data sets, and subject areas that generates potential for breakthrough advances in science. This is exactly the main theme of sequence stratigraphy, which integrates the methods of several disciplines with the purpose of providing improved and reliable models on how sedimentary facies form and relate to each other within sedimentary basins (Fig. 1).

As opposed to other, more conventional types of stratigraphy, such as biostratigraphy, lithostratigraphy, chemostratigraphy or magnetostratigraphy, sequence stratigraphy has an important built-in interpretation component that addresses issues such as (1) the reconstruction of the allogenic controls at the time of sedimentation, and (2) predictions of facies architecture in yet unexplored areas. The former issue sparked an intense debate, still ongoing, regarding the relative importance of eustasy and tectonism 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). The second issue, on the economic aspect of facies predictability, provides the industry community with a new and powerful analytical and correlation tool for exploration of natural resources.

As with any modeling efforts, the reliability of the sequence stratigraphic model depends on the quality and variety of input data, and so integration and mutual calibration of as many data sets as possible are recommended. The most common data sources for a sequence stratigraphic analysis include outcrops, core, well logs, and seismic data (Fig. 1). In addition to the facies analysis of the strata themselves, sequence stratigraphy also places a strong emphasis on the geological contacts that separate packages of strata characterized by specific depositional trends. Such contacts may represent event-significant bounding...
surfaces that mark changes in sedimentation regimes, and may be important both for regional correlation, as well as for understanding the facies relationships within the confines of specific depositional systems.

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

1.2. Historical development of sequence stratigraphy

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; Sloss, 1962, 1963; Wheeler and Murray, 1957; Wheeler, 1958, 1959, 1964; Curray, 1964; Frazier, 1974). Even before the 20th century, the periodic repetition through time of processes of erosion, sediment transport and deposition was recognized by James Hutton (18th century), 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 Phanerzoic 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.

The unconformity-bounded sequences promoted by L. Sloss and H. Wheeler 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. One limitation on this method of stratigraphic analysis is the lateral extent of sequence-bounding unconformities, which in many instances are restricted to basin margins. Hence, the number of sequences mapped within a sedimentary basin may significantly decrease down dip, from the basin margins toward the basin center (Fig. 2). This limitation required a refinement of the early ideas by finding a way to extend sequence boundaries across an entire sedimentary basin. The definition of “correlative conformities”, which are extensions towards the basin center of basin-margin unconformities, marked the birth of modern seismic and sequence stratigraphy (Fig. 3). The advantage of modern model sequences, which are bounded by composite surfaces, consists in their 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 conceptual disputes regarding
the timing of the correlative conformity relative to the base-level cycle, this new concept of a sequence bounded by unconformities or their correlative conformities is yet to be ratified by either the European or the North American commissions on stratigraphic nomenclature. The concept of “unconformity-bounded unit” (i.e., Sloss’ “sequence”) was only formalized by the European “International Stratigraphic Guide” in 1994.

**1.3. Precambrian vs. Phanerozoic sequence stratigraphy**

The principles of sequence stratigraphy are independent of the age of strata under analysis. Similarly, the scope and the step-by-step routine of the sequence stratigraphic model development are the same irrespective of the age of the studied sedimentary basin. Both Precambrian and Phanerozoic case studies share the common goal of elucidating the history of sedimentation in response to base-level changes, but often with different ‘ammunition’ in terms of data available for analysis. The basic contrasts between Precambrian and Phanerozoic, in terms of aspects relevant to sequence stratigraphy, are summarized in Fig. 4.

The amount and quality of data tend to deteriorate with increasing stratigraphic age, due to factors such as post-depositional tectonics, diagenesis and metamorphism, which hamper Precambrian case studies relative to the Phanerozoic counterparts. Both the preservation potential and the available time control for facies correlations are superior in the case of younger sequences, and hence the resolution of sequence stratigraphic models that can be constructed for Phanerozoic successions is usually significantly better relative to what can be achieved for Precambrian deposits. For this reason, the method of sequence stratigraphy has been developed essentially based on the study of Phanerozoic successions, being subsequently expanded to the study of Precambrian sedimentary basins as well.

In spite of the limitations imposed by data availability and quality, the application of sequence stratigraphy to the Precambrian should not be regarded simply as the low-resolution equivalent of Phanerozoic sequence stratigraphy. The Precambrian

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<th>Precambrian</th>
<th>Phanerozoic</th>
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<td><strong>Time span</strong></td>
<td>c. 88% of Earth’s history</td>
<td>c. 12% of Earth’s history</td>
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<tr>
<td><strong>Facies preservation</strong></td>
<td>Relatively poor (due to post-depositional tectonics, diagenesis, metamorphism)</td>
<td>Relatively good</td>
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<tr>
<td><strong>Time control</strong></td>
<td>Relatively poor (based on marker beds and lower resolution radiochronology)</td>
<td>Relatively good (marker beds, biostratigraphy, magnetostratigraphy, radiochronology)</td>
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<td><strong>Basin-forming mechanisms</strong></td>
<td>Competing plume tectonics and plate tectonics, more erratic regime</td>
<td>Plate tectonics, more stable regime</td>
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Fig. 4. Main contrasts between Precambrian and Phanerozoic, in terms of aspects relevant to sequence stratigraphy.
offers not only challenges, but also unique opportunities, because its time window into the Earth’s geological history is vastly wider relative to the duration of the Phanerozoic (Fig. 4). This greater time span provides the opportunity for observing Earth’s processes at a broader scale, and thus gaining an improved understanding on issues such as the mechanisms governing stratigraphic cyclicity and the variability thereof. The study of the Precambrian therefore provides better insights into some key issues of sequence stratigraphy, for which the time span of the Phanerozoic is simply too short to allow for any meaningful generalizations.

The Precambrian record, which encompasses nearly 90% of Earth’s history, allows one to see that the tectonic regimes leading to the formation of sedimentary basins were, for the greater part of geological time, not as stable or uniform as one might infer from Phanerozoic case studies. This has profound implications on the selection of criteria that should be used to classify stratigraphic sequences, and helps to resolve existing debates generated from the study of the Phanerozoic record. This paper provides a set of core principles of sequence stratigraphy that are valid irrespective of stratigraphic age. It also explores the unique insights offered by the Precambrian record, especially in terms of allogenic controls on sedimentation and their relevance to the various aspects of sequence stratigraphy.

2. Basic principles of sequence stratigraphy

The principles of sequence stratigraphy have been summarized in several recent volumes, including Emery and Myers (1996), Miall (1997), Posamentier and Allen (1999) and Catuneanu (2003). The essential aspects of the sequence stratigraphic method are presented below.

2.1. Controls on sedimentation and stratigraphic architecture

Sedimentation is generally controlled by a combination of authigenic and allogenic processes, which determine the distribution of depositional elements within a depositional system, as well as the broader scale stacking patterns of depositional systems within a sedimentary basin. Authigenic processes (e.g., self-induced avulsion in fluvial and deep water environments) are particularly important at sub-depositional system scale, and are commonly studied using the methods of conventional sedimentology and facies analysis. Allogenic processes, on the other hand, are directly relevant to sequence stratigraphy, as they control the regional-scale architecture of the basin-fill.

Allogenic controls provide the common platform that connects and synchronizes the depositional trends recorded at any given time in all environments established within a sedimentary basin, thus allowing for sequence stratigraphic models to be developed at the basin scale. This in turn is the key for the facies predictability applications of sequence stratigraphy, which are so much praised by both academic and industry practitioners. The basic allogenic controls on sedimentation include the climate, tectonics and sea level changes; their relationships with sediment supply, accommodation and depositional trends are summarized in Fig. 5. Eustasy and tectonics both control directly the amount of space (accommodation) that is available for sediments to accumulate. Climate mainly affects accommodation via eustasy, as for example during glacio-eustatic falls and rises in sea level. The effect of climate is also reflected in the amount of sediment supply, by modifying the efficiency of weathering, erosion, and sediment transport processes. This is why eustasy, tectonics and climate are all invoked when discussing the controls on sedimentation, but only eustasy and tectonics are usually accounted for when dealing with the controls on accommodation (Fig. 5).

It is important to note that the allogenic controls are ‘external’ relative to the sedimentary basin, but not necessarily independent of each other (Fig. 5). Eustatic fluctuations of global sea level are controlled by both tectonic and climatic mechanisms, over various time scales. Climatic fluctuations are primarily controlled by orbital forcing (Milankovitch cycles), but at more local scales may also be triggered by tectonic processes such as the formation of thrust-fold belts that may act as barriers for atmospheric circulation. Tectonism is primarily driven by forces of internal Earth dynamics, which are expressed at the surface by plume- or plate-tectonic processes. Criteria to differentiate between the signatures of eustasy, tectonics and paleoclimate have been summarized in
numerous publications (e.g., Aspler and Chiarenzelli, 2002; Aspler et al., 2001; Eriksson et al., 2001a,b; Martins-Neto et al., 2001; Ojakangas et al., 2001a,b; Strand, 2002; Young et al., 2001; Catuneanu, 2003).

There is increasing evidence that the tectonic regimes which controlled the formation and evolution of sedimentary basins in the more distant geological past were much more erratic in terms of origin and rates than formerly inferred solely from the study of the Phanerozoic record (e.g., Catuneanu, 2001; Eriksson et al., 2004, this volume, a,b,c; Eriksson and Catuneanu, 2004b). The more recent basin-forming processes seem to be largely related to a rather stable plate-tectonic regime, whereas the formation of Precambrian basins reflects a combination of competing mechanisms, including magmatic-thermal processes (‘plume tectonics’) and a more erratic plate-tectonic regime (Fig. 4; Eriksson et al., this volume, a,b). These insights offered by the Precambrian record are critical for extracting the essence of how one should categorize the stratigraphic sequences that can be observed within a sedimentary succession at different scales. This issue is discussed in more detail in the section dealing with the sequence-stratigraphic hierarchy.

2.2. Sediment accommodation

The concept of ‘accommodation’ describes the amount of space that is available for sediments to fill, being measured by the distance between base level and the depositional surface (Jervey, 1988). As the base level itself is a conceptual and dynamic surface of equilibrium between deposition and erosion, largely dependent on fluctuations in environmental energy, the precise quantification of accommodation at any given time and in any given location is rather difficult. For this reason, proxies and approximations are generally required for workable visualizations of the available accommodation. At first approximation, sea level is a proxy for base level (Jervey, 1988; Schumm, 1993), and so the available accommodation in a marine environment may be measured as the distance between the sea level and the sea floor. Both the sea level and the sea floor may independently change their position with time relative to the center of Earth in response to various controls, and therefore the amount of available accommodation fluctuates accordingly. Sea level is one of the primary allogenic controls on sedimentation, and it is in turn controlled by climate and tectonism, as discussed in the previous section (Fig. 5). The upward and downward shifts in the position of the sea floor relative to the center of Earth depend on two main parameters, namely the magnitude of total subsidence or uplift, and sedimentation. The amount of available accommodation at any given time and in any given location therefore equals the balance between how much accommodation is created (or destroyed) by factors such as tectonism and sea level change, and how much of this space is consumed by sedimentation at the same time. The separation between these two members of the
accommodation equation (creation/destruction vs. consumption) is one of the key themes of sequence stratigraphy, which allows one to understand the fundamental mechanisms behind the formation of systems tracts and sequence stratigraphic surfaces.

Fig. 6 helps to define some of the basic concepts involved in the accommodation equation, such as eustasy (sea level relative to the center of Earth), relative sea level (sea level relative to a datum that is independent of sedimentation), and water depth (sea level relative to the sea floor). A change in relative sea level is a proxy for how much accommodation was created or lost during a period of time, independent of sedimentation, whereas water depth is a proxy for how much accommodation is still available after the effect of sedimentation is also taken into account. The datum in Fig. 6 monitors the total amount of subsidence or uplift (including the effects of sediment compaction) recorded at any location within the basin relative to the center of the Earth. This datum reference plane is placed as close to the sea floor as possible in order to capture the entire subsidence component related to sediment compaction, but its actual position is not as important as the change in the distance between itself and sea level. This is because we are more interested in the changes in relative sea level, which reflect how much accommodation is created or lost during a period of time, rather than the actual height of relative sea level at any given time.

The separation between relative sea level changes and sedimentation is a fundamental approach in sequence stratigraphy, which allows for the comparison between their rates as independent variables. The balance between these rates (creation/destruction of accommodation vs. consumption of accommodation) controls the direction and type of shoreline shifts, and implicitly the timing of all sequence stratigraphic surfaces and systems tracts. This approach is therefore key to a proper understanding of sequence stratigraphic principles. Failure to do so may result in confusions between relative sea level changes, water depth changes, and the directions of shoreline shift.

The above discussion on the controls on accommodation is based on the assumption that sea level is a proxy for base level. This is true at first approximation, but in reality base level is commonly below the sea level, due to the energy flux brought about by waves and currents. As noted by Schumm (1993), this is also supported by the fact that at their mouths, rivers erode slightly below the sea level. The actual distance between base level and sea level depends on environmental energy, as for example the base level is lowered during storms relative to its position during fair-weather. Such energy fluctuations usually take...
place at seasonal to sub-seasonal time scales, at a frequency that is higher than most highest-frequency cycles investigated by sequence stratigraphy. Longer-term shifts in base level, at scales relevant to sequence stratigraphy, are generally controlled by the interplay of eustasy and total subsidence. In other words, the proxies used in the above discussion (i.e., sea level for base level, and relative sea level changes for changes in accommodation) are acceptable in a sequence stratigraphic analysis. The most complete scenario that illustrates the interplay of the controls on accommodation and shoreline shifts in a marine environment is presented in Fig. 7.

The contrast between the rates of change in accommodation and the sedimentation rates in locations placed in the vicinity of the shoreline allows one to understand why the shoreline may shift either landward or seaward during times of relative sea level (base level) rise. Accommodation outpacing sedimentation generates transgression (i.e., accommodation is created faster than it is consumed by sedimentation), whereas an overwhelming sediment supply may result in shoreline regression (i.e., accommodation is consumed more rapidly than is being created). In either situation, the river mouth moves accordingly, landward or seaward, connecting the continuously adjusting fluvial profile to the shifting base level. In the case of a delta that progrades during a stage of base level rise, for example, the newly created space is not sufficient to accommodate the entire amount of sediment brought by the river, and as a result the river mouth shifts seaward. This shift triggers a change in depositional regimes from prodelta and delta front environments, where sedimentation is limited to the space between the sea floor and the base level, to delta plain and alluvial plain environments (landward relative to the shoreline), where depositional trends (aggradation, bypass, or erosion) are governed by the relative position between the fluvial graded profile and the actual fluvial profile.

The fluvial graded profile is the conceptual equivalent of the marine base level in the nonmarine realm, as it describes the imaginary and dynamic surface of equilibrium between deposition and erosion in the fluvial environment. This equilibrium profile is achieved when the river is able to transport its.

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**Fig. 7.** Controls on accommodation and shoreline shifts in a marine environment (modified from Catuneanu, 2003). This diagram also applies to lacustrine environments by substituting sea level with lake level. See Fig. 6 for the definition of the DATUM. The energy flux lowers the base level via the effects of waves, wave-generated currents, tidal currents, contour currents or gravity flows. Short-term climatic changes (seasonal to sub-seasonal time scales) are accounted for under energy flux, whereas the longer-term climatic changes (e.g., Milankovitch type) are built into eustasy.
sediment load without aggradation or degradation of the channels (Leopold and Bull, 1979). In this context, the amount of fluvial accommodation is defined as the space between the graded profile and the actual fluvial profile (Posamentier and Allen, 1999). If we compare this definition with the concept of marine accommodation, discussed above, the graded profile is the equivalent of the base level, and the actual fluvial profile is the counterpart of the sea floor in the marine environment. If we follow this comparison even further, we notice that the sea level, which is used as a proxy for base level, does not have an equivalent in the fluvial realm, which makes the visualization of fluvial accommodation rather difficult as there is no physical proxy for the fluvial graded profile. The only observable surface is the actual fluvial landscape, whose position relative to an independent datum changes in response to surface processes of aggradation or erosion (Fig. 6). In turn, these surface processes are triggered by an attempt of the river to reach its graded profile.

The graded profile is ‘anchored’ to the base level at the river mouth, and as the base level rises and falls this anchoring point moves either landward or seaward, or up or down, triggering an in-kind response of the graded profile (Posamentier and Allen, 1999). Therefore, base-level changes exert an important control on graded profiles, and implicitly on fluvial accommodation, especially in the distal reaches of the fluvial system (Shanley and McCabe, 1994; Fig. 8). The position of graded profiles also depends on fluctuations in energy flux, which are mainly attributed to the effects of climate on a river’s transport capacity (Blum and Valastro, 1989; Blum, 1990; Fig. 8). Such energy fluctuations may be recorded over different time scales, from seasonal climatic changes that may occur with a frequency higher than the highest-frequency cycles studied by sequence stratigraphy, to Milankovitch-scale orbital forcing.

The effect of base-level changes on fluvial processes (aggradation vs. erosion) is only ‘felt’ by rivers within a limited distance upstream relative to the river mouth, which is usually in a range of less than 200 km (Miall, 1997). Beyond the landward limit of base-level influences, rivers respond primarily to a combination of tectonic and climatic controls (Fig. 9). Tectonism dictates the overall geometry of fluvial sequences, as the creation of fluvial accommodation follows the patterns of regional subsidence. For example, the rates of subsidence induced by flexural loading in a foreland basin increase in a proximal direction, toward the center of loading, whereas the rates of thermal and mechanical subsidence in an extensional basin increase in a distal direction. These

![Fig. 8. Controls on fluvial accommodation in the distal reaches of a fluvial system. See Fig. 6 for the definition of the DATUM. The energy flux is mainly controlled by short- to longer-term climatic changes (especially the discharge component), but also by tectonic tilt.](image)

![Fig. 9. Controls on fluvial accommodation in the proximal reaches of a fluvial system. See Fig. 6 for the definition of the DATUM. The energy flux is mainly controlled by short- to longer-term climatic changes (especially the discharge component), but also by tectonic tilt.](image)
patterns are reflected by the geometry of fluvial sequences that may fill the basin. Superimposed on these general trends, the climatic control on runoff and discharge also affect the position of graded profiles, as discussed above (Fig. 9).

The role of climate as a control on accommodation is always difficult to quantify because it operates via other variables such as eustasy and environmental energy flux. In a marine environment, the short-term climatic changes (seasonal to sub-seasonal time scale) translate into fluctuations in energy flux, whereas the longer-term changes are accounted for under eustasy (Fig. 7). In the case of fluvial environments, both short- and longer-term climatic changes are reflected in the fluctuations in energy flux because there is no physical proxy for the graded profile that could be related to the longer-term climate shifts (Figs. 8 and 9). Climate is also relevant to the ‘sedimentation’ box in all cases (Figs. 7-9) because the amount of sediment supply transferred from source areas to the sedimentary basin depends on the efficiency of weathering and sediment transport processes, both of which are partly dependent on climate.

A significant debate still persists regarding the relationship between base level and the fluvial graded profile. One school of thought argues that the term ‘base level’ should apply to both concepts, as the same definition can describe them both (i.e., a dynamic surface of equilibrium between deposition and erosion; Barrell, 1917; Sloss, 1962; Cross, 1991; Cross and Lessenger, 1998). A second school of thought restricts the term ‘base level’ to the level of the body of water into which the river debouches (sea level, lake level, or even another river), as used in this paper (Powell, 1875; Davis, 1908; Bates and Jackson, 1987; Schumm, 1993; Posamentier and Allen, 1999; Catuneanu, 2003). Terminology is trivial to some extent, but we find value in keeping the concepts of graded fluvial profile and base level separate because they are in a process–response relationship—i.e., the position in space of the fluvial graded profile is in part a function of the elevation of the base level, and changes with time thereof.

2.3. Types of shoreline shifts

The interplay of base-level changes and sedimentation controls the available accommodation, as well as the transgressive and regressive shifts of the shoreline (Fig. 7). The types of shoreline shifts are critical in a sequence stratigraphic framework, as they determine the formation of packages of strata with specific stacking patterns, known as systems tracts. Three types of shoreline shifts may be recorded, as outlined below.

2.3.1. Transgressions

Transgressions take place when accommodation is created more rapidly than it is consumed by sedimentation, i.e., when the rates of base-level rise outpace the sedimentation rates at the shoreline. This results in a retrogradation (landward shift) of facies. The scour surface cut by waves during the shoreline transgression (wave ravinement surface) is onlapped by the aggrading and retrograding shoreface deposits (Fig. 10). The combination of wave scouring in the upper shoreface and deposition in the lower shoreface is required to preserve the concave-up shoreface profile that is in equilibrium with the wave energy during transgression (Bruun, 1962; Dominguez and Wanless, 1991). The onlapping deposits that accumulate in the lower shoreface ‘heal’ the bathymetric profile of the seafloor that is oversteepened as a result of the transgressive shoreline shift, which is why they are known as ‘healing phase’ deposits (Posamentier and Allen, 1993; Fig. 10).

The rise in base level at the shoreline promotes coastal aggradation in estuarine (river mouth) or beach (open shoreline) environments. However, the tendency of coastal aggradation is counteracted by the wave scouring in the upper shoreface, as the latter gradually shifts in a landward direction. The balance between these two opposing forces, of sedimentation vs. erosion, determines the overall type of transgressive coastline (Fig. 10). Coastlines dominated by aggradation lead to the preservation of estuarine or backstepping beach facies in the rock record. Coastlines dominated by erosion are associated with unconformities in the nonmarine part of the basin, whose stratigraphic hiatuses are age-equivalent with the transgressive marine facies. Regardless of the overall nature of coastal processes, the wave ravinement surface is onlapped by transgressive shallow marine (‘healing phase’) deposits, which provides a clue for understanding the transgressive nature of some subaerial unconformities.
2.3.2. Forced regressions

Forced regressions occur during stages of base-level fall, when the shoreline is forced to regress by the falling base level, irrespective of sediment supply. In wave-dominated coastal settings, such as open shorelines or wave-dominated deltas, the preservation of the concave-up sea floor profile that is in equilibrium with the wave energy requires coeval deposition and erosion in the upper and lower parts of the subtidal area, respectively (Bruun, 1962; Plint, 1988; Dominguez and Wanless, 1991; Fig. 11). As the shoreline shifts basinward, the upper subtidal forced regressive deposits downlap the scour generated in the lower subtidal zone (Fig. 11). At the same time, the subaerially exposed area is subject to sediment starvation, as well as fluvial and wind degradation. The amount of nonmarine downcutting is proportional to the magnitude of base-level fall (see Posamentier, 2001, for a discussion of incised vs. unincised fluvial bypass systems).

In the case of river-dominated deltas, the angle of repose of delta front clinoforms is generally steeper.

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Fig. 10. Shoreline trajectory in transgressive settings (from Catuneanu, 2003). Transgressions are driven by base level rise, where the rates of base level rise outpace the sedimentation rates in the shoreline area. The balance between the opposing trends of aggradation (in front of the shoreline) and wave scouring (behind the shoreline) determines the type of transgressive coastline. In addition to this, shallow-gradient coastal plains are prone to coastal aggradation, whereas steeper coastal plains are prone to coastal erosion. In both cases, the gradients may be shallower than the average shoreface profile (ca. 0.3°).

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In the case of river-dominated deltas, the angle of repose of delta front clinoforms is generally steeper.

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Fig. 11. Shoreline trajectory in forced regressive settings (modified from Catuneanu, 2003). Forced regressions are driven by base level fall, irrespective of sediment supply, and the rates of progradation are generally high. Wave-dominated subtidal settings are characterized by shallow gradients of the seafloor, which is subject to wave scouring in order to preserve a profile that is in equilibrium with the wave energy. River-dominated deltas generally have delta front clinoforms that are steeper than the wave equilibrium profile, and therefore no wave scouring takes place during forced regression. HST—highstand systems tract.
than the gradient required to balance the energy of the waves, so there is no reason for wave scouring in the lower delta front area (Fig. 11). Therefore, the marine scour surface that forms in shallow marine wave-dominated settings during forced regression is missing from the stratal architecture of forced regressive river-dominated deltas. In the former case, a vertical profile through the shallow marine forced regressive succession shows an abrupt shift of facies from offshore muds to subtidal sands, whereas this facies shift is gradational in the river-dominated deltas.

Stages of forced regression are generally characterized by a significant increase of sediment supply to the deep-water depositional systems. This is due to (1) a lack of accommodation in the fluvial to shallow marine environments, and therefore the terrigenous sediment tends to bypass these settings and be delivered to the deep-water environment; and (2) additional sediment may be supplied by erosion processes in the fluvial and lower shoreface environments. On continental shelves, forced regressions may result in the formation of incised valleys, which are filled during subsequent ‘lowstand’ normal regressions and transgressions with fluvial, estuarine, and even shallow marine deposits (Fig. 12).

2.3.3. Normal regressions

Normal regressions occur in the early and late stages of base-level rise, when the sedimentation rates outpace the low rates of base-level rise at the shoreline. In this case, sedimentation totally fills the newly created accommodation, sediment bypass accompanies aggradation (the surplus of sediment for which no accommodation is available), and facies prograde (Fig. 13).

The process of coastal aggradation, in response to rising base level, is an important diagnostic feature that separates normal regressive from forced regressive deposits (Figs. 11 and 13). As a result, a topset package of delta plain (in river mouth settings) or beach/strandplain (in open shoreline settings) sediments accumulates and progrades over the shallow marine delta front/shoreface facies. The preservation potential of this topset package is higher in the case of the early rise (‘lowstand’) normal regressive deposits because the late rise (‘highstand’) normal regressive strata are potentially truncated by subaerial unconformities (Fig. 11).

2.4. Sequence stratigraphic models

The concept of a ‘sequence’ is only as good, or acceptable, as the boundaries that define it. As a

![Diagram of normal regressions](image)

Fig. 13. Shoreline trajectory in normal regressive settings (from Catuneanu, 2003). Normal regressions are driven by sediment supply, where the rates of base level rise at the shoreline are outpaced by sedimentation rates. Normal regressions occur during early and late stages of base level rise, when the rates of base level rise are low. Progradation rates are generally lower relative to forced regressions. Aggradation occurs in coastal environments (delta plains in river mouth settings, or strandplains along open shorelines), which triggers fluvial aggradation on the adjacent alluvial plain.
matter of principle, it is useless to formalize a unit whose boundary definitions are 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. 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 and timing of these correlative conformities, and consequently a number of different models are now in use, each promoting a unique set of terms and bounding surfaces. This creates unnecessary jargon and confusion, and hampers communication of ideas and results. A few reasons for this variety of approaches in sequence stratigraphy include: (1) the underlying assumptions regarding the primary controls on stratigraphic cyclicity; (2) the type of basin from which models were derived; and (3) the gradual conceptual advances that allowed for alternative models to be developed. Present-day sequence stratigraphy can thus be described as a still developing field that takes the science of Sedimentary Geology in an exciting new direction of conceptual and practical opportunities, even though along a bumpy road punctuated by disagreements and controversy.

Early work on seismic and sequence stratigraphy published in the AAPG Memoir 26 (Payton, 1977) and the SEPM Special Publication 42 (Wilgus et al., 1988) resulted in ‘depositional sequence’ being defined 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 toward 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. Variations on the original depositional sequence theme resulted in the publication of several slightly modified versions of the depositional sequence model (Figs. 14 and 15).

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)

---

**Fig. 14.** 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. Finally, 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. 14 and 15).

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 a different timing for systems tract and sequence boundaries in relation to a cycle of base-level shifts (Figs. 14 and 15). Each sequence model may work best under particular circumstances, and no one model is universally applicable to the entire range of case studies (Catuneanu, 2002). The applicability and practical limitations of each approach are discussed in detail by Catuneanu (2003).

Irrespective of the model of choice, a common theme emerges in the sense that a full cycle of base-level changes records four main stratigraphic events that signify changes in the type of shoreline shifts; i.e., the onset of forced regression, the end of forced regression, the end of (normal) regression and the end of transgression (Fig. 16). These events separate systems tracts, and result in the formation of four sequence stratigraphic surfaces: the basal surface of forced regression (=correlative conformity sensu Posamentier et al., 1988), the correlative conformity (sensu Hunt and Tucker, 1992), the maximum regressive surface (=transgressive surface), and the maximum flooding surface respectively (Fig. 16). Three more sequence stratigraphic surfaces form during particular stages of shoreline shift, such as the subaerial unconformity during forced regression (fluvial scour in Fig. 11), the regressive surface of marine erosion during forced regression in wave-dominated settings (marine scour in Fig. 11), and the wave ravinement surface during transgression (wave scour in Fig. 10). The correct identification of these
Sequence stratigraphic surfaces is the key for a robust sequence stratigraphic interpretation, regardless of how we name the systems tracts between them, or where we choose to place the sequence boundary (Fig. 15). Criteria for identifying sequence stratigraphic surfaces are now firmly established, based on the nature of contacts, nature of facies that are in contact across the surface, and types of stratal terminations that are associated with each particular type of surface (Fig. 17). Catuneanu (2003) discusses these criteria in detail.

### 3. Sequence stratigraphic hierarchy

#### 3.1. Introduction

A sequence hierarchy assigns different orders to stratigraphic sequences and bounding surfaces based on their relative importance. Within a hierarchical system, the most important sequence is recognized as of ‘first-order’ and may be subdivided into two or more ‘second-order’ sequences. In turn, a second-order sequence may be subdivided into two or more

<table>
<thead>
<tr>
<th>Stratigraphic surface</th>
<th>Nature of contact</th>
<th>Strata below</th>
<th>Strata above</th>
<th>Stratal terminations</th>
<th>Temporal attributes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subaerial unconformity</td>
<td>Scoured or top of paleosol</td>
<td>Variable (where marine, c-u)</td>
<td>Nonmarine</td>
<td>Truncation, toplap, fluvial onlap, offlap</td>
<td>Variable hiatus</td>
</tr>
<tr>
<td>Correlative conformity</td>
<td>Conformable</td>
<td>Marine, c-u</td>
<td>Marine (c-u on shelf)</td>
<td>Downlap</td>
<td>Low diachroneity</td>
</tr>
<tr>
<td>Regressive surface of marine erosion</td>
<td>Scoured</td>
<td>Shelf, c-u</td>
<td>Shoreface, c-u</td>
<td>Truncation, downlap</td>
<td>High diachroneity</td>
</tr>
<tr>
<td>Basal surface of forced regression</td>
<td>Conformable or scoured</td>
<td>Marine, variable (c-u on shelf)</td>
<td>Marine, c-u</td>
<td>Downlap</td>
<td>Low diachroneity</td>
</tr>
<tr>
<td>Maximum regressive surface</td>
<td>Conformable</td>
<td>Variable (where marine, c-u)</td>
<td>Variable (where marine, f-u)</td>
<td>Downlap, marine onlap</td>
<td>Low diachroneity</td>
</tr>
<tr>
<td>Maximum flooding surface</td>
<td>Conformable or scoured</td>
<td>Variable (where marine, f-u)</td>
<td>Variable (where marine, c-u)</td>
<td>“Downlap surface”</td>
<td>Low diachroneity</td>
</tr>
<tr>
<td>Wave ravinement surface</td>
<td>Scoured</td>
<td>Variable (where marine, c-u)</td>
<td>Marine, f-u</td>
<td>Coastal onlap</td>
<td>High diachroneity</td>
</tr>
</tbody>
</table>

Fig. 17. Diagnostic features of sequence stratigraphic surfaces (modified from Embry and Catuneanu, 2002; Catuneanu, 2003). *Sensu Hunt and Tucker (1992); **correlative conformity sensu Posamentier et al. (1988). Abbreviations: c-u—coarsening-upward; f-u—fining-upward.
third-order sequences, and so on (Fig. 18). The more important sequences are designated as ‘high-order’ (at the top of the hierarchy pyramid), and generally have a low frequency in the stratigraphic record. The less important sequences are of ‘lower-order’ and are more common in the rock record (Fig. 18).

The critical element in developing a system of sequence hierarchy is the set of criteria that should be used to differentiate between the relative importance of sequences and bounding surfaces. Two different approaches are currently in use, based on the study of the Phanerozoic record: (1) a system based on boundary frequency (sequence duration), and (2) a system based on the magnitude of base-level changes which resulted in boundary formation (independent of sequence duration). The former system has historical priority, having being proposed at the dawn of seismic and sequence stratigraphy (Vail et al., 1977; Fig. 19). This time-based hierarchy emphasizes eustasy as the main driving force behind stratigraphic cyclicity, which in turn is controlled by a combination of plate tectonic and orbital mechanisms. As eustasy is global in nature, the philosophy behind this hierarchy system led to the construction of global cycle charts (Vail et al., 1977), whose validity is currently under intense scrutiny (Miall, 1992, 1997).

### 3.2. Hierarchy system based on boundary frequency

In addition to the controversy brought about by global cycle charts, the application of the hierarchy system based on sequence duration poses an important practical problem, which is the fact that good time control is required to ensure that a ‘third-order’ sequence falls indeed within the 1–10 My duration bracket (Fig. 19; Vail et al., 1977), and so on. Such time control is often difficult to acquire even for Phanerozoic successions, and it becomes more and more unrealistic with increasing stratigraphic age. In spite of this practical limitation, the hierarchy system based on sequence duration, which was originally developed based on Phanerozoic case studies (Vail et al., 1977), was eventually extrapolated to the Precambrian as well (Krapez, 1996, 1997). Krapez (1996) provides average durations for sequence orders as follows: fourth=90–400 ky, third=1–11 My, second=22–45 My, and first=approximately 364 My. Each of these orders of stratigraphic cyclicity is genetically related to particular tectonic (and to a much lesser extent climatic) controls whose periodicity is assumed to be more or less constant during geological time. For example, the 364 My duration of

<table>
<thead>
<tr>
<th>Hierarchical order</th>
<th>Duration (My)</th>
<th>Cause</th>
</tr>
</thead>
<tbody>
<tr>
<td>First order</td>
<td>200–400</td>
<td>Formation and breakup of supercontinents</td>
</tr>
<tr>
<td>Second order</td>
<td>10–100</td>
<td>Volume changes in mid-oceanic spreading centers</td>
</tr>
<tr>
<td>Third order</td>
<td>1–10</td>
<td>Regional plate kinematics</td>
</tr>
<tr>
<td>Fourth and fifth order</td>
<td>0.01–1</td>
<td>Orbital forcing</td>
</tr>
</tbody>
</table>

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Fig. 18. Diagrammatic representation of the concept of hierarchy. This pyramid approach assumes that the events leading to the formation of the most important sequences and bounding surfaces (first-order) occurred less frequently in the geological record relative to the events leading to the formation of lower order sequence boundaries.

Fig. 19. Tectonic and orbital controls on eustatic fluctuations (modified from Vail et al., 1977; Miall, 2000). These hierarchies are NOT proposed here for orders of stratigraphic sequences (see text for details). Local- or basin-scale tectonism is superimposed and independent of these global sea level cycles, often with higher rates and magnitudes, and with a range of time scales.
first-order cycles is calculated based on the assumption that nine equal-period global tectonic (Wilson) cycles of supercontinent assembly and breakup took place during the 3500–224 Ma interval (Krapez, 1993, 1996). The need for a hierarchy system based on sequence duration is based on the argument that “There are no physical criteria with which to judge the rank of a sequence boundary. Therefore, sequence rank is assessed from interpretations of the origin of the strata contained between the key surfaces, and of the period of the processes that formed these strata” (Krapez, 1997, p. 2).

More important than the current practical limitations related to the availability of time control, or the lack thereof, which may be resolved in the future as the resolution of dating techniques improves, is the fundamental question of whether or not the nature and periodicity of tectonic mechanisms controlling stratigraphic cyclicity were indeed constant throughout the Earth’s history, as assumed by the proponents of time-based hierarchy systems. The Phanerozoic time window into the geological past is simply too small to provide an unequivocal answer to this question, and therefore the study of the Precambrian most likely holds the key to this debate. The hierarchy systems based on sequence duration are fundamentally predicated on the assumption that the controls on cyclicity at specific hierarchical orders are predictable, repetitive, and unchanged during the evolution of Earth. This implies that the controls on stratigraphic cyclicity are governed by the law of uniformitarianism throughout the Earth’s history, allowing equal periodicity for stratigraphic cycles of the same hierarchical order, irrespective of age. This means that time is the last, or at least not the primary, variable that one should employ in designing a universally applicable hierarchy system. Instead, alternative criteria need to be identified for a more flexible conceptual framework that can be used irrespective of basin type and stratigraphic age.

3.3. Hierarchy system based on the magnitude of base-level changes

A hierarchy system based on the magnitude of base-level changes that resulted in boundary formation provides a classification in which the order of a sequence depends on the physical attributes of its bounding surfaces, and is independent of sequence duration (Embry, 1995; Fig. 20). Six attributes have been chosen to establish the boundary classification: the areal extent over which the sequence boundary can be recognized; the areal extent of the unconformable portion of the boundary; the degree of deformation that strata underlying the unconformable portion of the boundary underwent during the boundary generation; the magnitude of the deepening of the sea and the flooding of the basin margin as represented by the nature and extent of the transgressive strata overlying the boundary; the degree of change of the sedimentary regime across the boundary; and the degree of change of the tectonic setting of the basin and surrounding areas across the boundary. Five different orders of sequence boundaries have been defined on the basis of these characteristics (Embry, 1995; Fig. 20).

Two potential pitfalls with this classification scheme have been discussed by Miall (1997, pp. 330–331). One is that it implies tectonic control in sequence generation. Sequences generated by glacioeustasy, such as the Upper Paleozoic cyclothems of North America and those of Late Cenozoic age on modern continental margins, would be first-order sequences in this classification on the basis of their areal distribution, but lower-order on the basis of the nature of their bounding surfaces. The second problem is that this classification requires good preservation of the basin margin in order to properly assess the areal extent of the unconformable portion of the boundary or the degree of deformation across the boundary. Beyond its practical limitations, the hierarchy system based on the magnitude of base-level shifts has the advantage of employing physical criteria for boundary delineation, irrespective of the time span between sequence boundaries that show similar attributes. This represents a major advantage in the case of Precambrian case studies, where the lack of time control is generally the norm. This approach also bypasses the problem of the erratic nature and
periodicity of the controls on stratigraphic cyclicity manifest throughout Earth’s history, as discussed above.

3.4. Discussion

Because the sequence hierarchy systems that are currently in use present conceptual and/or practical limitations, the practitioner of sequence stratigraphy still faces the dilemma of how to deal with the variety of sequences that are more or less important relative to each other. As argued by Catuneanu (2003), the easiest solution to this problem is to deal with the issue of hierarchy on a case-by-case basis, assigning hierarchical orders to sequences and bounding surfaces based on their relative importance within each individual basin. This approach is an adaptation of Embry’s (1995) method of sequence delineation, and requires the partitioning of the stratigraphic record into successions that are the product of sedimentation in discrete sedimentary basins. In this context, the most important sequence boundaries in the stratigraphic record are genetically related to shifts in the tectonic setting that led to changes in the type of sedimentary basins.

This working methodology places the emphasis on the nature of the tectonic setting and changes thereof. As a result, the most fundamental events in the rock record that led to changes in tectonic setting and basin type are marked as first-order sequence boundaries, irrespective of the time span between two such consecutive events. In this context, first-order sequences correspond to entire sedimentary basin-fills, regardless of the origin and life span of each particular basin. Within this framework, second-order cycles provide the basic subdivision of a first-order sequence (basin-fill) into packages with unique character that reflect overall shifts in the balance between accommodation and sedimentation, and so on as we decrease the scale of observation. These sequences are not expected to correlate to other first- and lower-order sequences of other, separate basins, which most likely have different timing and duration. This method may prove to be more flexible and realistic given the fact that each basin is unique in terms of formation, evolution and history of base-level changes.

Our conclusions are supported by statistical surveys of the duration and thickness of stratigraphic sequences, which demonstrated that there is no evidence for a hierarchy in the rock record that can...
be linked to the periodicity of recurrence of the same-order bounding surfaces (Algeo and Wilkinson, 1988; Carter et al., 1991; Drummond and Wilkinson, 1996). As pointed out by Drummond and Wilkinson (1996), “discrimination of stratigraphic hierarchies and their designation as nth-order cycles [based on cycle duration] may constitute little more than the arbitrary subdivision of an uninterrupted stratigraphic continuum”. The link between hierarchical orders and temporal durations is artificial and meaningless to a large extent, as multiple sequence-generating mechanisms that do not readily fall into simple temporal classifications may interact and contribute to the architecture of sequences in the rock record (Miall, 1997). The combination of such independent controls often results in sequences whose durations and thicknesses have log-normal distributions that lack significant modes (Drummond and Wilkinson, 1996). Similar conclusions are reflected by the work of Algeo and Wilkinson (1988), as well as that of Peper and Cloetingh (1995), who demonstrated that calculated periodicities of stratigraphic cycles may have random distributions relative to any given sequence-forming mechanism.

An added bonus of this case-by-case basin approach is the simplification of terminology because modifiers such as first-order, second-order, etc., have straightforward meanings, reflecting relative importance independent of time connotations. In contrast, the time-based hierarchy systems are permeated by unnecessary and sometimes conflicting jargon. For example, the “supersequence” of Krapez (1996) is referred to as a “sequence” by Vail et al. (1977); the “sequence” of Krapez (1996) corresponds to the “mesothem” of Ramsbottom (1979), or to the “megacyclothem” of Heckel (1986); the “paracycle” of Krapez (1996) is equivalent to the “major cycle” of Heckel (1986), etc. Further, the term ‘paracycle’ (and its corresponding ‘parasequence’) is particularly confusing, because parasequences (as bounded by ‘flooding surfaces’) may not even technically be a type of sequence, depending on what the flooding surface actually is (see discussion in Catuneanu, 2003). Beyond the terminology issue, which may be trivial to some extent, the real danger consists of the fact that each of these terms (e.g., megasequence, supersequence, parasequence, etc.) is associated with a specific time connotation (sequence duration), which requires a time control that is unavailable in many Precambrian (and even Phanerozoic) case studies.

4. Case studies

An increasing number of case studies of Precambrian sequence stratigraphy have become available in recent years, allowing us to see the complexity of the controlling factors on sedimentation and stratigraphic cyclicity at a scale larger than originally made possible by the study of the Phanerozoic record. More meaningful generalizations can now be formulated as a result of this research. This section synthesizes the results of some of these case studies, from the ca. 3.0–2.0 Ga (Late Archean–Early Proterozoic) interval of the Kaapvaal craton of South Africa to the ca. 1.75–0.65 Ga (late Paleoproterozoic–late Neoproterozoic) interval of the São Francisco craton and Araçuaí fold belt of eastern Brazil. These case studies cover more than 2 Gy of Precambrian Earth’s evolution.

4.1. Kaapvaal craton of South Africa

The stratigraphy and tectonic evolution of the Kaapvaal craton of South Africa during the ca. 3.0–2.0 Ga (Late Archean–Early Proterozoic) interval are presented in detail by Eriksson et al. (this volume, b). Relevant to this paper is the fact that the ca. 1 Gy record of Kaapvaal evolution was marked by a combination of plate tectonic and plume tectonic regimes, whose relative importance determined the type of tectonic setting and sedimentary basin established at any given time. The shifting balance between these two allogenic controls on accommodation resulted in a succession of discrete basins, starting with the Witwatersrand (accommodation provided by subduction-related tectonic loading), followed by the Venterdsorp (accommodation generated by thermal uplift-induced extensional subsidence), and lastly by the Transvaal (accommodation created by extensional and subsequent thermal subsidence). The end of the Transvaal cycle was marked by a relatively short-lived plume tectonics event, which led to the emplacement of the Bushveld igneous complex. The sedimentary fill of these three
basins, each of which is genetically related to different tectonic settings, represents an unconformity-bounded first-order depositional sequence.

The temporal duration of the Kaapvaal first-order cycles varied greatly with the type of tectonic setting, from ca. 5 My in the case of the plume-related Ventersdorp thermal cycle, to >600 My in the case of the extensional Transvaal Basin. This first-order cyclicity was independent of the Wilson-type cycles of supercontinent assembly and breakup, being rather a reflection of the interplay between plate tectonics (e.g., extension or subduction-related tectonic loading) and plume tectonics. It is noteworthy that the first-order cycles controlled by plate tectonics lasted about two orders of magnitude longer (ca. 10^2 My) relative to the plume tectonics cycles (ca. 10^0 My). Each of the Kaapvaal first-order cycles is subdivided into second-order cycles, whose temporal duration also varies greatly, from ca. 1 My in the case of the Ventersdorp plume tectonics-controlled basin to ca. 100 My in the case of the plate tectonics-controlled basins.

The case study of the Kaapvaal craton suggests that time, and implicitly the frequency of occurrence of same-order sequence boundaries in the rock record, are irrelevant to the hierarchy of stratigraphic cycles. This is a consequence of the fact that processes controlling the formation and evolution of sedimentary basins in the geological past were far more erratic than originally inferred from the study of the Phanerozoic record. The extrapolation of principles developed from Phanerozoic case studies (e.g., Vail et al., 1977; Fig. 19) to the entire geological record based on the law of uniformitarianism is therefore inadequate for providing a unified approach to the concept of sequence hierarchy. This conclusion reinforces the idea that the classification of sequences and bounding surfaces should be approached on a case-by-case basis, starting from the premise that each sedimentary basin-fill corresponds to a first-order sequence.

4.2. São Francisco craton and Araçuaí fold belt of eastern Brazil

A record of the late Paleoproterozoic to late Neoproterozoic history of the São Francisco craton and Araçuaí fold belt of eastern Brazil (Fig. 21) is preserved by sedimentary successions in the Espinhaço, Macaúbas, and Bambuí basins (Martins-Neto et al., 2001). Each of these major sedimentary successions represents a first-order depositional sequence, which is the record of an unconformity-bounded, single basin-fill cycle (Martins-Neto et al., 2001). Collectively, these basins track major plate reorganizations that affected the São Francisco craton through a time interval greater than 1 Gy, which marks one episode of aborted lithospheric stretching, and a complete cycle of supercontinent breakup and assembly. The Espinhaço Basin records a stage (ca. 1.73–1.50 Ga) of aborted lithospheric stretching of the São Francisco–Congo continental mass that had amalgamated during the Transamazonian–Eburnian orogeny (ca. 2.2–2.0 Ga; Trompette, 1994; Alkmim and Marshak, 1998). The Macaúbas Basin (ca. 950–700 Ma) comprises rift-to-drift successions that were deposited during the breakup of the supercontinent Rodinia and the opening of the Brazilide–Adamastor ocean (Dalziel, 1997). The Bambuí Basin (ca. 800–650 Ma) formed as a consequence of thrust loading related to shortening in the Brasilia fold belt on the western flank of the São Francisco craton (Fig. 21) during the closing of the Brazilide ocean and the amalgamation of the Gondwana supercontinent. Because most deposits of the Espinhaço and Bambuí basins are well exposed in cratonic areas or in the weakly deformed external domains of the Araçuaí orogenic belt, sequence stratigraphy can be applied to their successions.

4.2.1. Espinhaço Basin

Sedimentologic, paleogeographic, stratigraphic, structural and tectonic studies in the Paleo/Mesoproterozoic metasedimentary Espinhaço first-order sequence in southeastern Brazil indicate deposition in a rift-sag basin (Martins-Neto, 2000). The basin displays a ‘steer’s-head’ geometry where four basin evolution stages are recognized (pre-rift, rift, transitional and flexural). These four stages form the basic subdivision of the first-order basin-fill sequence and therefore can be equated with unconformity-bounded second-order sequences. The unconformities are recognized in the field and are mapped on a regional scale. The pre-rift and rift second-order sequences of the Espinhaço Basin consist of nonmarine depositional systems that were deposited during continental lithosphere stretching. The recognition of 3rd order unconformities allowed the recognition and mapping
of three 3rd order synrift sequences within the rift 2nd order sequence. The first marine incursion within the Espinhaço Basin marks the change in the subsidence regime of the basin from extensional to thermally driven, and is due to thermal contraction of the lithosphere during cooling when the transitional and flexural stages evolved. The transitional stage was characterized by relatively low subsidence rates. Higher subsidence rates and a consequent base-level rise characterize the flexural stage of the Espinhaço Basin.

At increased detail, the ca. 900-m-thick second-order flexural (‘Conselheiro Mata’) succession of the Espinhaço Basin is subdivided into three third-order transgressive–regressive sequences (Fig. 22). These third-order sequences were first recognized by Dupont (1995), each with a transgressive base and a progradational top. The first sequence (250–400 m thick) contains transgressive barred nearshore deposits and progradational beach to shallow marine deposits. Its maximum flooding surface marks the greatest expansion of the Espinhaço sea (Martins-
The second sequence (250–350 m thick) comprises transgressive shelf deposits overlain by progradational alluvial plain to coastal successions. The third sequence (200–300 m thick) is defined by transgressive mixed siliciclastic-carbonate shelf deposits overlain by coastal to fluvial sediments. The top of the third sequence marks the final filling of the Espinhaço Basin and therefore corre-

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**Fig. 22.** Schematic stratigraphic cross-section showing the three third-order transgressive–regressive sequences of the Conselheiro Mata (second-order) succession of the Espinhaço Basin (modified after Dupont, 1995). The eastern section is about 900 m thick.

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**Fig. 23.** Stratigraphic chart of the Bambui first-order sequence (modified after Martins-Neto et al., 2001). The succession is about 3000 m thick. Note that the three, inverted thin black triangles show the three second-order sequences within the Bambui first-order sequence.
sponds to a first-order sequence boundary. Each of these third-order sequences has an estimated duration in the range of tens of million years and is considered to be the product of in-plane stress variations (Martins-Neto, 2000).

4.2.2. Bambuí basin

The carbonate to siliciclastic deposits of the Bambuí first-order sequence, which are up to 3000 m thick, overlie much of the São Francisco Craton. They are also exposed in the Brasiliano/Pan African fold belts surrounding the craton, mainly in the Brasília fold belt on its western flank (Fig. 21). Recent studies (e.g., Castro and Dardenne, 2000; Martins-Neto et al., 2001) indicate deposition in a foreland basin that was generated during thrusting and crustal loading in the Brasília fold belt along the western margin of the São Francisco Craton.

Fig. 24. Reflection seismic profile in the cratonic area of the São Francisco Basin, showing the seismic expression of first-order sequences and sequence boundaries. The Bambuí first-order sequence is composed of three prograding second-order sequences. Note that the older two second-order sequences of the Bambuí succession show siliciclastic deposits at their bases and carbonate deposits at their tops. The Paranóa/Canastra first-order sequence represents passive-margin deposits of the western flank of the São Francisco craton, whose closure generated the Brasília fold belt.
Craton, related to the ca. 800 to 650 Ma arc–continent to continent–continent collision (Pimentel et al., 2000). Three second-order transgressive–regressive sequences characterize the fill of the Bambuí Basin (Dardenne, 1981; Figs. 23 and 24). Each of these sequences represents the record of initial flooding of the basin (higher accommodation relative to sediment supply as a result of flexural loading and rapid subsidence) and the subsequent filling of accommodation by a prevailing sediment supply.

The organic-rich marine shales of the Sete Lagoas Formation (Fig. 23) were deposited in the central and western parts of the basin. Distal deposits near an inferred forebulge consist of a carbonate ramp succession of limestone (locally with stromatolites), dolostone and argillaceous limestone. The carbonate ramp prograded westward over the deeper-water pelites, and produced the first transgressive–regressive second-order sequence. Dolomitized supratidal deposits with microbial mats, dissolution structures, tepees and birds-eye structures as well as mud cracks, characterize the top of the unit, indicating subaerial exposure and marking the second-order sequence boundary.

The second transgressive–regressive second-order sequence begins with shale and argillaceous limestone of the Serra de Santa Helena Formation (Fig. 23), which shows an upward increase in the abundance of siltstone beds and storm-wave reworking. Limestone, calcarenite, oolitic limestone and siltstone, which were deposited in a storm-influenced ramp of the Lagoa do Jacaré Formation, prograded over the Serra de Santa Helena Formation. Higher frequency prograding deposits occupy the transitional interval between the deeper-water facies of the Serra de Santa Helena Formation and the shallower-water facies of the Lagoa do Jacaré Formation. Each sequence comprises storm-influenced shale-calcilutite rhythmite at the base, and coastal oolitic calcarenite at the top (Fig. 25).

The uppermost transgressive–regressive second-order sequence consists at its base of the marine shale and siltstone of the Serra da Saudade Formation, which are over lain by siltstone, sandstone, arkose and conglomerate of the Três Marias Formation that were deposited in a storm-dominated shallow marine system, and finally passing upward to sediments deposited in alluvial environments (Fig. 23).

5. Discussion and conclusions

The principles of sequence stratigraphy may be applied at different spatial scales, from individual depositional systems to entire sedimentary basin-fills. The common theme, irrespective of scale, is the study of the sedimentary response to changes in accommodation. Within the boundaries of individual depositional systems, changes in accommodation result in predictable shifts with time in the types of depositional elements and lithofacies that accumulate in each particular environment. As changes in accommodation are in turn controlled by allogenic mechanisms that operate at basin scales, such shifts in depositional trends are synchronized across the basin, allowing the grouping of depositional systems into systems tracts characterized by specific stacking patterns and facies relationships.

Sequence-stratigraphic surfaces and systems tracts may be identified at particular locations within the
basin, such as boreholes (using core and/or well log data) or outcrops, or at broader scales involving mapping and correlations of outcrop and/or surface (well log, core, seismic) data. The criteria identified in Fig. 17 for the recognition of sequence stratigraphic surfaces (and especially the nature of contacts and juxtaposed facies associated with each contact) may be applied in any given location, without requiring time control. The identification of stratal terminations usually requires a broader scale of observation, and is best performed on seismic lines and in large outcrops. Time control is generally desired for correlation, but the lack thereof, which is a common theme in Precambrian case studies, may be compensated for by a good knowledge of facies architecture and relationships within the study area.

In tectonically active basins, the most important breaks in the rock record (e.g., second-order sequence boundaries that provide the basic subdivision of the first-order basin-fill) are commonly associated with stages of tectonic reorganization within the basin, which usually lead to changes in tilt directions across the major unconformities. In such cases, paleocurrent data provide the key to infer tectonic events during the basin’s evolution and to map event-significant sequence boundaries across the basin. This is the case with the Early Proterozoic Athabasca Basin in Canada, where each second-order sequence is characterized by unique fluvial drainage systems, with abrupt shifts in paleocurrent patterns across the second-order sequence boundaries (Ramaekers and Catuneanu, 2004). In this basin, paleocurrent data provide the best evidence to constrain regional correlations and to compensate for the general lack of time control in a succession that is relatively homogeneous from a lithofacies point of view.

Sequence stratigraphy uses the same set of core principles irrespective of the age of strata under analysis. In that respect its application to Precambrian deposits is no different from the methods applied to Phanerozoic successions. Where sedimentary basins are transgressed by interior seaways, the shifts in shoreline position, which are in turn controlled by the interplay of accommodation and sediment supply, represent the fundamental element that constrains the timing of all systems tracts and sequence stratigraphic surfaces. All classic sequence-stratigraphic models (Fig. 15) account for the presence of a shoreline within the basin under analysis, thus justifying a systems-tract nomenclature that makes specific reference to transgressions and regressions. In overfilled basins, however, the depositional environment may be entirely nonmarine, and so the application of sequence stratigraphy must be adapted accordingly. In such cases, the systems-tract nomenclature makes direct reference to the amount of available accommodation (i.e., low vs. high accommodation systems tracts) as inferred from the ratio between fluvial architectural elements (e.g., see Eriksson and Catuneanu, 2004a; Ramaekers and Catuneanu, 2004, for Precambrian case studies).

Basins related to plume-controlled first-order cycles (i.e., plume tectonics) are prone to a dominantly nonmarine sedimentation regime because the net amount of thermal uplift generally exceeds the amount of subsidence created via extension above the ascending plume. As plume tectonics was much more prevalent in the Precambrian relative to the Phanerozoic, the low- and high-accommodation systems tracts seem to be more commonly applicable with increasing stratigraphic age. In contrast, basins related to plate tectonic activity are dominated by subsidence, and so they are prone to be transgressed by interior seaways. Even such subsidence-dominated basins, however, may reach an overfilled state under high sediment-supply conditions, in which case the recognition of fully fluvial systems tracts (low vs. high accommodation) becomes the only option for the sequence-stratigraphic approach. Case studies of such overfilled plate-tectonic-related basins have been documented for both Precambrian and Phanerozoic successions (e.g., Boyd et al., 1999; Zaitlin et al., 2000, 2002; Wadsworth et al., 2002, 2003; Leckie and Boyd, 2003; Eriksson and Catuneanu, 2004a; Ramaekers and Catuneanu, 2004).

The application of sequence stratigraphy to Precambrian basins has considerably enlarged the perspective of fundamental principles governing the processes of sedimentary basin formation and the mechanisms controlling stratigraphic cyclicity in the rock record. The latter principles are perhaps the most important contribution of Precambrian research to sequence stratigraphy because the large time span of the Precambrian affords a better understanding of the
allogenic controls on sedimentation and hence of the criteria that should be used in a system of sequence stratigraphic hierarchy. At the broader scale of Earth’s geological history, the tectonic regimes governing the formation and evolution of sedimentary basins are shown to have been much more erratic in terms of nature and rates than originally inferred solely from the study of the Phanerozoic record. This indicates that time is largely irrelevant as a parameter in the classification of stratigraphic sequences; instead, it is rather the change in the tectonic setting that affects the key criteria for subdividing the rock record into genetically related basin-fill successions separated by first-order sequence boundaries. These first-order basin-fill successions are in turn subdivided into second- and lower-order sequences as a function of the shifts in the balance between accommodation and sedimentation at various scales of observation. Such sequences, which may at least in part reflect the influence of local controls, are not expected to correlate to other first- and lower-order sequences of other basins, which most likely have different timings and durations.

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