8 The Future of Time

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8.1 Introduction

The purpose of this chapter is to assess the current status of the measurement of geologic time as stored in the stratigraphic record, and to present some arguments regarding present pitfalls and future potential regarding the measurement and interpretation of geological time.

Modern methods of relative and "absolute" age dating of the stratigraphic record, and the current status of the Geological Time Scale, are discussed in the previous chapter. What these modern methods reveal is that the stratigraphic record is far more fragmentary than most geologists are accustomed to thinking. Many key concepts in sedimentary geology carry an implication of continuity in the sedimentary record, including the practices of stratigraphic classification and correlation, Walther's law, cyclic sedimentation, facies models, and sequence stratigraphy. However, as argued in this chapter, it is becoming increasingly clear that we need to carefully re-evaluate these assumptions of continuity. A key criterion to keep in mind is that of time scale. We tend to assume that ancient sedimentary records representing very long time intervals on the human time scale ($>10^4$ a) may be reliably compared with observations made over the much shorter time scales accessible to human observation ($\leq 10^2$ a). This is the basis of the Hutton-Lyellian aphorism "the present is the key to the past" (and the reverse). But a question that persists is that concerning the relevance and significance of transient processes and ephemeral modern deposits to the interpretation of the rock record, given questions about the highly variable preservability of different sedimentary facies.

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8.2 Where We Are Now and How We Got Here

Barrell (1917), in a review and discussion that was about seven decades ahead of its time, was probably the first to fully recognize the incompleteness of the stratigraphic record. Barrell (1917, Fig. 8.7) constructed a diagram showing the "Sedimentary Record made by Harmonic Oscillation in Baselevel" (Fig. 5.2). This is remarkably similar to diagrams that have appeared in some of the Exxon sequence model publications since the 1980s (e.g., Van Wagoner et al. 1990, Fig. 8.59; see Fig. 5.5 of this book), and represents a thoroughly modern deductive model of the way in which "time" is stored in the rock record. Curve A-A simulates the record of long-term subsidence and the corresponding rise of the sea. Curve B-B simulates an oscillation of sea levels brought about by other causes. Barrell discussed diastrophic and climatic causes, including glacial causes, and applied these ideas to the rhythmic stratigraphic record of the "upper Paleozoic formation of the Appalachian geosyncline" in a discussion that would appear to have provided the foundation for the interpretations of "cyclothems" that appeared in the 1930s. Barrell showed that when the long-term and short-term curves of sea-level change are combined, the oscillations of base level provide only limited time periods when sea-level is rising and sediments can accumulate. "Only one-sixth of time is recorded" by sediments (Barrell 1917, p. 797).

Wheeler (1958, 1959) developed the concept of the chronostratigraphic cross-section, in which the vertical dimension in a stratigraphic cross-section is drawn with a time scale instead of a thickness scale (Fig. 8.1). In this way, time gaps (unconformities) become readily apparent, and the nature of time correlation may be accurately indicated. Such graphs have come to be termed "Wheeler diagrams." They are commonly constructed for use as stratigraphic tables in regional reports, but typically the time scale is arbitrary and variable, which means that information about missing time is distorted and usually not considered beyond qualitative statements about the significance of regional unconformities.

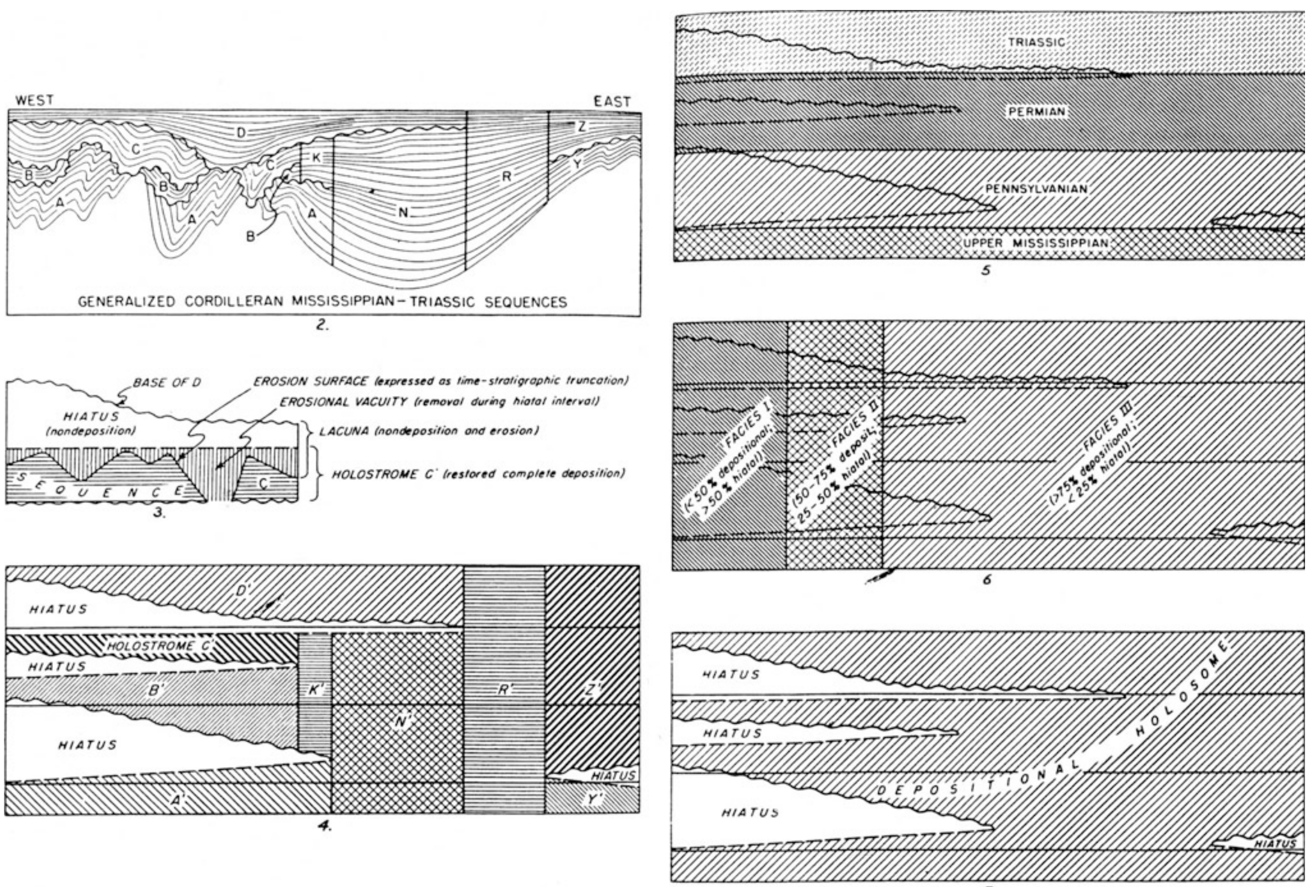


Fig. 8.1 Wheeler's development of chronostratigraphic diagrams. *Diagram 2* shows a complex stratigraphic cross-section containing numerous unconformities. *Diagram 3* explains some of the terminology used, and the remaining diagrams are "Wheeler plots" of the section in *Diagram 2*, ornamented in various ways to highlight different geological features. (Wheeler 1958). AAPG © 1958, reprinted by permission of the AAPG whose permission is required for further use

In fact, this quote from Grabau (1960, p. 1097) would seem to imply that stratigraphic continuity is the norm:

> It is of first importance to the chronographer of earth history that he should find a continuous record, in order that he may have a measure by which to judge the partial records of any given region and to discover the breaks and imperfections in the local records thus presented. The question then arises: under what conditions may we expect to obtain a continuous record and how are we to guard against the introduction of errors?

We return to the use of Wheeler plots later in this chapter.

Ager's (1981) famously remarked that the sedimentary record is "more gap than record." In a later book he expanded on the theme of gaps. Following a description of the major unconformities in the record at the Grand Canyon, he said, (Ager 1993, p. 14):

> We talk about such obvious breaks, but there are also gaps on a much smaller scale, which may add up to vastly more unrecorded time. Every bedding plane is, in effect, an unconformity. It may seem paradoxical, but to me the gaps probably cover most of earth history, not the dirt that happened to accumulate in the moments between. It was during the breaks that most events probably occurred.

Much has now been learned about the significance of unconformities. Sequence boundaries are unconformities, but assigning an age to an unconformity surface is not necessarily a simple matter, as illustrated in the useful theoretical discussion by Aubry (1991). An unconformity represents a finite time span at any one location; it may have a complex genesis, representing amalgamation of more than one event. It may also be markedly diachronous, because the transgressions and regressions that occur during the genesis of a stratigraphic sequence could span the entire duration of the sequence. Ravinement surfaces, which commonly form sequence boundaries, are the product of diachronous erosion during transgression (Nummedal and Swift 1987). Kidwell (1988) demonstrated that transgression results in an offset in sequence-boundary unconformities by as much as one half of a cycle between basin centre and basin margin. Christie-Blick et al. (1990, 2007) pointed out many geological a where unconformities may be diachronous. On a small scale, it has been demonstrated by flume experiments and observations of the rock record that laminated mudstones may preserve less than 10 % of elapsed time as a result of rapid deposition and frequent reworking (Trabucho-Alexandre 2015).

The subaerial erosion surfaces that underlie incised valley-fills at continental margins, and which commonly provide important sequence boundaries, are good examples of unconformities that evolve over time and are not everywhere the same age. Strong and Paola (2008) pointed out an important distinction between a *topographic surface* and a *stratigraphic surface*. The topographic surface that corresponds to the subaerial erosion surface undergoes continual change until it is finally buried and preserved. It is the stratigraphic surface that we map in the rock record, but this is a surface that never actually existed in its entirety as a topographic surface in its final preserved form, because it undergoes continuous modification by erosion or sedimentation until final burial. The subaerial erosion surface may also violate one of the fundamental principles of an unconformity, which is that all the deposits below the unconformity surface are older than all the beds above the surface. Deepening and widening of an alluvial valley may continue during the final stages of the evolution of a subaerial surface, even while a turn-around in the base-level cycle has begun to transgress and bury the surface during the beginning of a transgression. Channel or overbank deposits that are preserved as terrace remnants, resting on the basal erosion surface, could therefore predate the coastal deposits formed during the final stages of base-level fall, and would therefore be older than the sequence boundary at the coast, although resting on it.

Miall (2010, Chap. 14) provided an extensive discussion of the dating and correlation of sequence boundaries.

One of the most significant achievements of modern stratigraphic work is the increasing accuracy and precision of the Geological Time Scale and our ability to provide ever more refined dating of the geological record (Sect. 7.8.6). A particularly instructive example of this advance (although dependent on detailed paleontological work that goes back to the early nineteenth century!) is the biostratigraphic subdivision of parts of the European Jurassic section. In Chap. 7 the work of Callomon (1995) is highlighted (see Fig. 7.40 of this book). The shallow-marine Inferior Oolite, which in the study area of southern Britain is only some 5 m thick, may be subdivided into as many as 56 faunal zones, although the interesting point that is relevant to our discussion here is that none of the thirteen sections examined for this project contains a complete record of the zones, and the preserved record is different in every section. This formation is replete with local diastems that record local areas of negative accommodation (Fig. 8.2). Buckman (1910, p. 90) concluded, after many years of meticulous analysis of this unit that the Inferior Oolite of Dorset, an extremely condensed shelf sequence, '…might be defined as a series of gaps united by thin bands of deposits …. the deposits are so local, the deposits of one place correspond to the gaps of another…'.

Overall, it is impossible to distinguish any ordered pattern to the record of sedimentation and erosion in these sections. How typical is this of shallow-marine sedimentation in general? Does the availability of an unusually-detailed ammonite biostratigraphy enable us to develop a much more detailed record of local change than would otherwise be available? And should this section therefore be regarded as a model for the interpretation of other shallow-marine

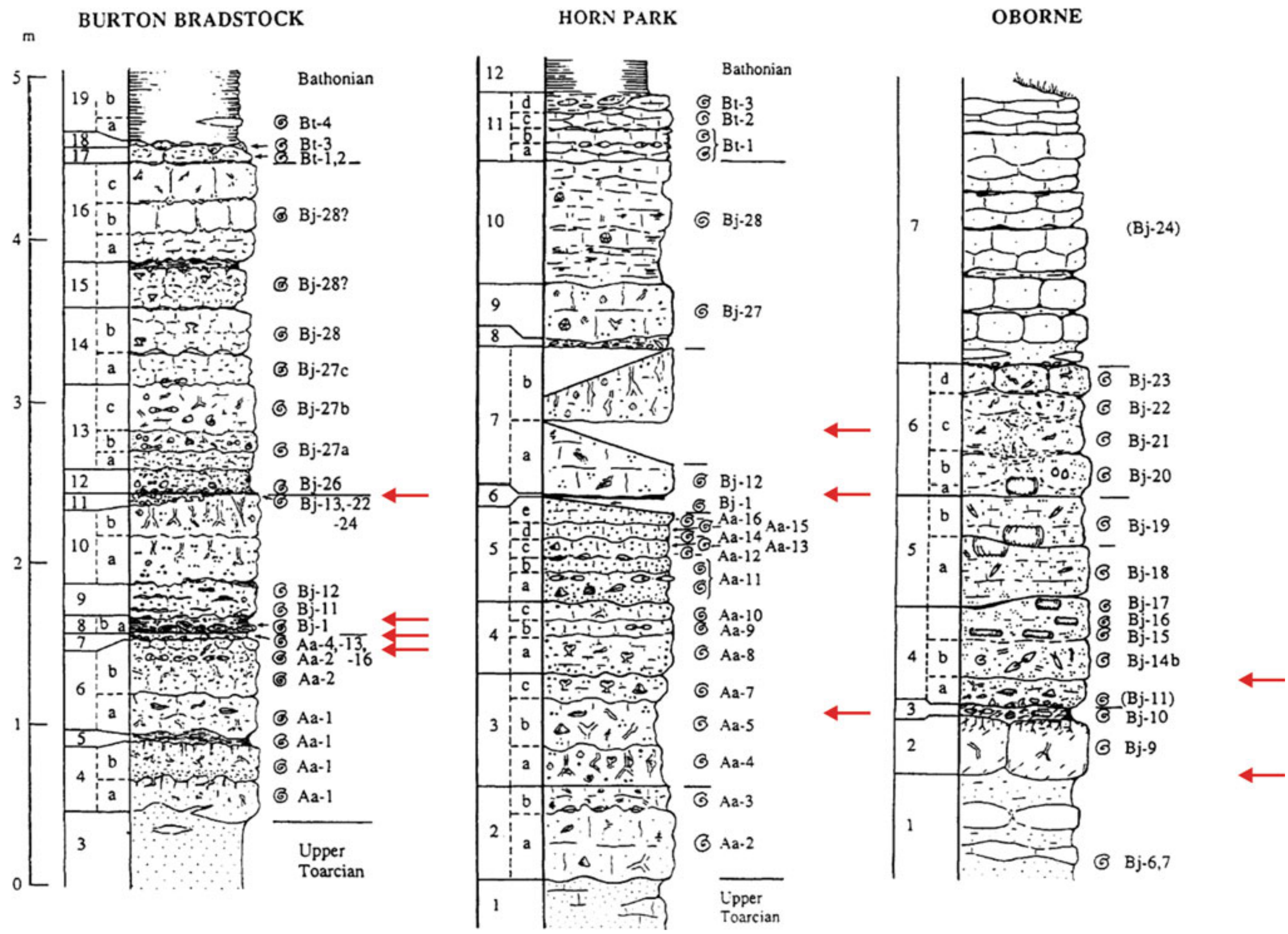


Fig. 8.2 Three of the stratigraphic sections through the Inferior Oolite studied by Callomon (1995) showing (at *left*) the series of faunal zones recorded in the rocks and (at *right*) *red arrows* indicating the likely position of diastems where one or more zones are missing

carbonate sections? Would it be correct to conclude that many other shallow marine (and nonmarine?) successions should similarly be regarded as containing numerous local diastems? If so, what does this tell us about short- to long-term sedimentary processes?

As the study of modern sedimentary environments and facies interpretations evolved during the 1960s (Sect. 1.2.6 and 1.2.7), it began to be realized that there is a wide variation in the energy, magnitude and time scales of sedimentary processes. Some facies, such as turbidites and storm deposits, are clearly formed rapidly over geologically insignificant periods of time. Although he was not the first to discuss this, Ager (1973) is credited with the coining of the term **event sedimentation** to encompass this pattern of rapid deposition. One of his stratigraphic studies was carried out in order to raise the question of the time significance of the preserved record. He re-evaluated the sedimentary history of the Sutton Stone, a beach conglomerate that forms the base of the Blue Lias succession in Glamorgan, South Wales, where it ranges from 10 to 13.5 m in thickness. The conglomerate rests on a transgressive surface, and had long been interpreted as the product of slow sedimentation during a protracted transgression. According to Wobber (1965) it contains the fossils representing at least four ammonite zones of Hettangian and Lower Sinemurian age which, according to the data provided by Gradstein et al. (2004a, Fig. 18.1) span a total of about 4 million years. However, Ager (1986) suggested that the deposit was formed in a single major tropical storm or hurricane. He stated (p. 35) "I do not think it took the three or four million years or so of three or four or five ammonite chronozones." His one-line conclusion: "It all happened one Tuesday afternoon."

The "Tuesday afternoon" remark is, of course deliberately provocative (one might ask, why not Wednesday?), but Ager's point was to emphasize the rapidity by which certain geological processes may accomplish spectacular results. Storms do, indeed, accomplish most of their erosional and depositional work within a space of a few hours or days, at most. A four million-year period includes 208,000,000 Tuesdays. Are we to understand that only one of these days left a sedimentary record? The question is fascinating, and points to a nagging issue regarding sedimentation rates and preservation that has gradually emerged with the accumulation of an ever-increasing volume of data concerning modern and ancient sedimentary processes. The central point is that when an ancient deposit is compared to the sediments accumulating in an equivalent environment at the present day, the rates of modern sedimentary processes and stratigraphic accumulation, if applied to the rock record, would allow for the accumulation of the ancient deposit in a fraction of the time that chronostratigraphic data indicate is available. It is not at all uncommon to find that the accumulation of a given thickness of sediment in any given environment could take place in as little as one tenth of the available time. What happened during the rest of the time that passed, according to the chronostratigraphy of the unit? Callomon's demonstration of numerous diastems in the Inferior Oolite might be pointing the way to a more general conclusion.

It does not materially undermine Ager's (1986) broader arguments about event sedimentation to note that later workers have disputed his claim that the Sutton Stone was deposited in a single event. Evidence of encrusting organisms at more than one level within the conglomerate, and the observations of varying conglomerate facies through the unit suggested an alternative model of cliff collapse on an exposed rocky shoreline, perhaps subsequently influenced by several or many storms (Fletcher et al. 1986; Johnson and McKerrow 1995).

Sadler (1981) compiled thousands of records concerning sedimentation in deposits ranging in age from ancient to modern, and demonstrated that the relationship between sedimentation rate and elapsed time (the time period over which the sedimentation rate is measured) is linear and inverse on a log-log scale (Fig. 8.3). His data base consisted of 25,000 records of accumulation rates. Measured sedimentation rates vary by eleven orders of magnitude, from 10^{-4} to 10^{7} m/ka. This huge range of values would seem to suggest the presence of an increasing number and duration of intervals of non-deposition or erosion that become factored into the measurements as the length of the measured stratigraphic record increases. A comparable range of sedimentation rates was revealed in his later compilation of records focusing on shallow-marine carbonate deposits (Kemp and Sadler 2014).

Although Sadler's (1981) synthesis has been in the public domain for more than thirty years, few stratigraphers have attempted to wrestle with its significance for the geological interpretations that we make based on the Hutton-Lyell Principle of Uniformitarianism: "The present is the key to the past." Although Gould (1965) argued, on logical grounds, that this Principle is no longer necessary, given the assumption of the invariance of natural laws, it nonetheless exerts a powerful influence on the methods of modern sedimentology, which are very firmly based on the practice of seeking modern analogues for an ancient deposit of interest. As argued in this chapter, it is becoming clear that there are some important provisos and limitations that must now be inserted into this practice.

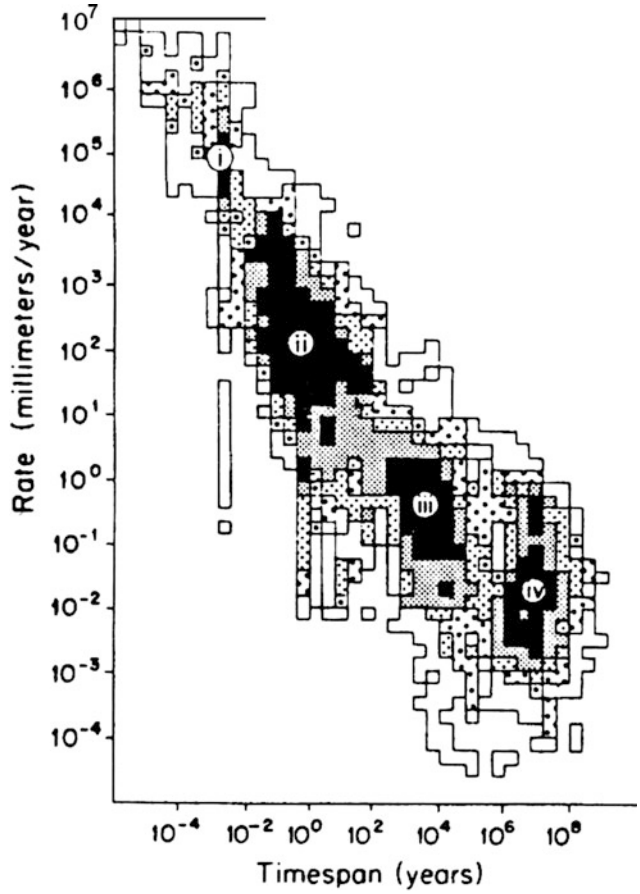


Fig. 8.3 The relationship between sedimentation rate and elapsed time in the stratigraphic record (Sadler 1981)

8.3 A Natural Hierarchy of Sedimentary Processes

Bailey and Smith (2010, pp. 57–58) pointed out the ephemeral nature of most sedimentary processes:

> There would seem to be a very small chance of the preservation in 'stratigraphic snapshots' of, say, one particular ripple-marked shoreface out of the thousands or millions, created and destroyed diurnally through geologic time. Such instances suggest that such stratigraphic records are better viewed as the outcome of temporary cessation of the erosion and redistribution of sediment: 'frozen accidents' of accumulation.

It is now widely recognized that not only the durations of the gaps, but also the distribution of layer thicknesses and sedimentation rates in stratigraphic successions have fractal-like properties (Plotnick 1986; Sadler 1999; Schlager 2004; Bailey and Smith 2005; Smith et al. 2015). However, the practical development of this concept is hampered by the current methods of stratigraphic documentation. Bailey and Smith (2010, p. 58) noted that current classifications of stratigraphic units, based as they are on "a human scale observer" (e.g., lithostratigraphy, sequence stratigraphy) constitute hierarchies that are somewhat arbitrary, and make statistical analysis of bedding and its contained gaps difficult. In addition, it is extremely difficult to operationalize a lithologically, petrologically and statistically reliable practical field definition of what constitutes a "layer", at all scales from the lamina to the basin fill.

To circumvent this problem Bailey and Smith (2010) and Bailey and Schumer (2012) developed a method of analyzing the stratigraphic record termed the "Layer Thickness Inventory". The analysis is carried out on continuous, digitized records, such as wireline logs. The gamma-ray log is particularly suitable for this purpose, because it is readily interpreted in lithologic terms. A computer routine works its way through the digital data records one at a time, searching the data string above and below for records in which the GR reading is higher and lower than that at each sample point, and records the calculated thicknesses. All lithologically defined layers are thereby recorded, ignoring hiatuses. The procedure records layers within layers, which therefore overlap, and in this way "it recognizes that the various sedimentary influences on lithology operate in overlapping time frames, rather than as the succession of discrete process-response effects suggested by conventional hierarchical stratigraphic subdivisions." (Bailey and Smith 2010, p. 59).

Their analysis of a range of geological examples demonstrated that log-log plots of bed thickness against number of records always generate linear distributions, regardless of the scale of the stratigraphic section and the nature of the lithology, suggesting "that there is a universal relationship between layer thickness and frequency of occurrence in the record." (Bailey and Smith 2010, p. 62).

Bailey and Smith (2010) raised the question of the degree to which the evidently fractal record is representative of past surface processes, and made the following points:

- The notion of continuous deposition, on which the historicity of the record depends, has no theoretical or evidential basis. In relation to the accumulation of particulate solids it is, in fact, an impossibility. At best, it is a scale-dependent descriptive convenience.
- If there is no continuity in accumulation, the sequential preservation of laterally contiguous facies, according to Walther's Law, becomes questionable.
- Stratigraphic hierarchies are constructs, commonly tailored to human-scale analysis of the fractal record. They are a practical, convenient, but incomplete, representation of this record.
- Currently-observable sedimentary processes and facies underpin uniformitarian stratigraphic interpretations. Yet there is no way of determining whether a present day deposit will be preserved millions of years hence. Equally, if there is "more gap" there is the question of the degree to which the preserved record is representative of the continuous operations of past sedimentary systems. Specifically, are the snapshot "frozen accidents of preservation" representative?
- As Sadler (1999) has shown, local calculations of accumulation rate are time-scale dependent.

Is the stratigraphic record fundamentally unrepresentative of the geological past? These conclusions would appear to invalidate virtually the whole of the last two centuries of stratigraphic progress!

However, all is not lost!

Miall (1991) suggested that the sedimentary time scale constitutes a natural hierarchy corresponding to the natural hierarchy of temporal processes (diurnal, lunar, seasonal, geomorphic threshold, tectonic, etc.) and the main purpose of this chapter is to develop this idea further, making extensive use of modern quantitative data dealing with sedimentation rates and accumulation rates. Most of the discussion that follows relates to clastic sedimentation in shallow-marine and nonmarine environments. I return to the above discussion points in a later section of this chapter, where it is argued that most may be managed within the context of the appropriate time frame.

In an attempt to understand the log-log sedimentation rate: duration plot of Sadler (1981), Miall (1991, 2010, Chap. 13) undertook an analysis of the relationship between sedimentation rate and sedimentary process in the published record of shallow-marine stratigraphy. It emerged that there does, in fact, appear to be a natural hierarchy of process and preservation based on the natural time scales of sedimentary processes. The model which emerged from this looks remarkably like a fractal analysis, although it was generated entirely in the absence of any guidance from fractal theory (Fig. 8.4). Two cycles with frequencies in the million-year range are plotted on a chronostratigraphic scale (column MC), and successively broken down into components that reflect an increasingly fine scale of chronostratigraphic subdivision. The second column shows hundred-thousand-year cycles (HC), followed by depositional systems (DS) and individual lithosomes (L), such as channels, deltas, beaches, etc. At this scale chronostratigraphic subdivision is at the limit of line thickness, and is therefore generalized, but does not represent the limit of subdivision that should be indicated, based on the control of deposition

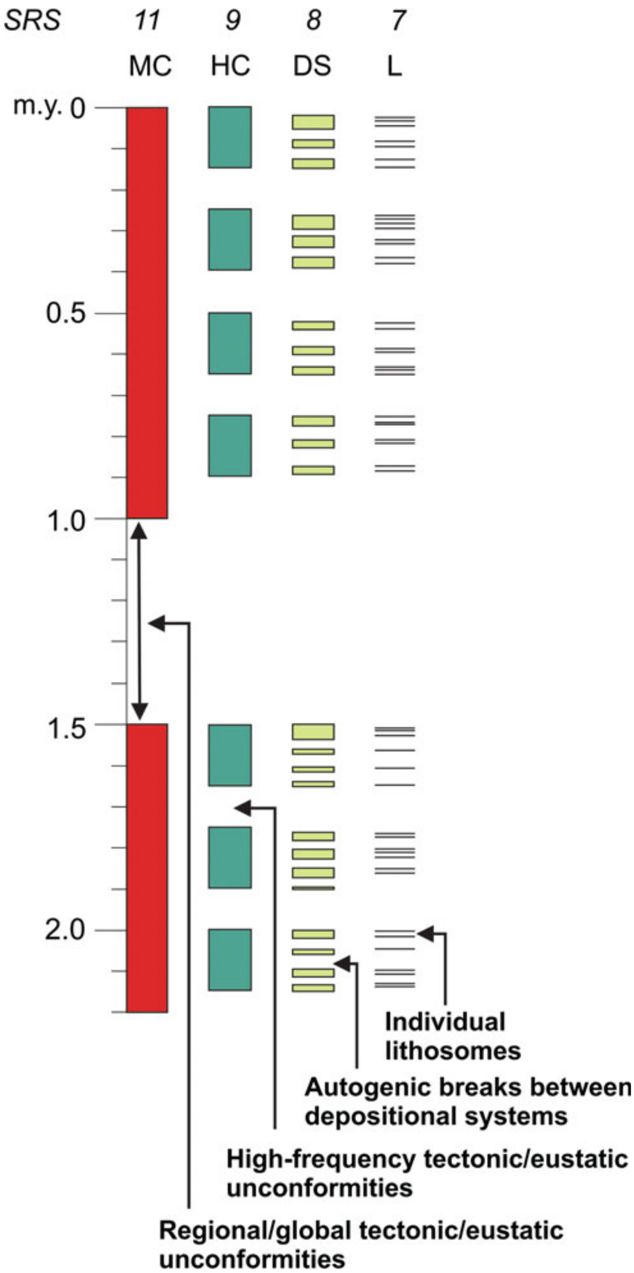


Fig. 8.4 A demonstration of the predominance of missing time in the sedimentary record

by events of shorter duration and recurrence interval (e.g., infrequent hurricanes, seasonal dynamic events, etc.).

The record shows that when measurements of sedimentation rate are calculated at the appropriate scale, they are internally consistent and can be related to natural processes occurring within that time scale. Miall (1991) identified ten informal groupings of sediment packages, based on sedimentation rate. This classification, updated by Miall (2010, Table 8.1; Miall 2015), is reproduced here as column 1 in Table 3.3. It constitutes a natural range of *Sedimentation Rate Scales* (SRS), now expanded to twelve groupings. Column 2 indicates the time scale of measurement, and column 3 provides the instantaneous sedimentation rate for deposits formed over that time scale. Stratigraphic and sedimentologic studies ranging from the micro scale to the regional, and based on time scales ranging from the short-term (e.g., studies of processes in laboratory models or modern settings) to the long-term (e.g., the evolution of major sedimentary basins), are best carried out at the appropriate *SRS*, much as photography uses lenses of different focal length, from macro to telephoto to wide-angle, to focus in on features at the desired scale.

The rest of Table 3.3 is discussed in the section "Accommodation and Preservation".

Many detailed chronostratigraphic compilations have shown that marine stratigraphic successions commonly consist of intervals of "continuous" section representing up to a few million years of sedimentation, separated by disconformities spanning a few hundred thousand years to more than one million years (e.g., MacLeod and Keller 1991, Fig. 15; Aubry 1991, Fig. 8.8). The first column of Fig. 8.4, labeled MC (for cycles in the million-year range), illustrates an example of such a succession. Detailed studies of such cycles demonstrate that only a fraction of elapsed time is represented by sediment. For example, Crampton et al. (2006) demonstrated that an average of 24 % of time is recorded in a suite of Upper Cretaceous sections in New Zealand, when measured at a 10^6-year time scale, whereas in a suite of drill cores through the Lower Cretaceous to Miocene stratigraphic record of New Jersey, the plots of Browning et al. (2008) show that about 82 % of elapsed time is represented by sediments, although some sections are more complete than others. Each million-year cycle may be composed of a suite of high-frequency cycles, such as those in the hundred-thousand-year range, labeled HC in Fig. 8.4.

Chronostratigraphic analyses of many cyclic successions demonstrate that the hiatuses between the cycles represent as much or more missing time than is recorded by actual sediment (e.g., Ramsbottom 1979; Heckel 1986; Kamp and Turner 1990). Sedimentation rates calculated for such sequences (Table 3.3) confirm this, and the second column of Fig. 8.4 indicates a possible chronostratigraphic breakdown of the third-order cycles into component Milankovitch-band cycles (labelled HC), which may similarly represent incomplete preservation. For example, a detailed chronostratigraphic correlation of the coastal Wanganui Basin sequences in New Zealand ("5th-order Milankovitch cycles of *SRS 8* in Table 3.3) shows that at the 10^5-year time scale only 47 % of elapsed time is represented by sediments (Kamp and Turner 1990). Each Milankovitch cycle consists of superimposed depositional systems (column DS) such as delta or barrier-strandplain complexes, and each of these, in turn, is made up of individual lithosomes (column L), including fluvial and tidal channels, beaches, delta lobes, etc.

Devine's (1991) lithostratigraphic and chronostratigraphic model of a typical marginal-marine sequence demonstrates the importance of missing time at the sequence boundary (his subaerial hiatus). Shorter breaks in his model, such as the estuarine scours, correspond to breaks between depositional systems (the DS column in Fig. 8.4), but it is suggested that more are present in such a succession than Devine (1991) has indicated. Additional discontinuities at the lithosome level (L in Fig. 8.4) correspond to the types of breaks in the record introduced by switches in depositional systems, channel avulsions, storms and hurricanes, etc.

According to the hierarchical breakdown of Table 3.3, the four columns in Fig. 8.4 correspond to sediment *SRSs 11, 9, 8, and 7*, in order from left to right. In each case, moving (from left to right) to a smaller scale of depositional unit focuses attention on a finer scale of depositional subdivision, including contained discontinuities. The evidence clearly confirms Ager's (1973, 1981) assertion that the sedimentary record consists of "more gap than record".

Fluvial deposits have long been known to consist of a hierarchy of depositional units accumulated over a wide range of time scales and sedimentation rates (Miall 1978a). An architectural approach to field studies was introduced by Allen (1983), developed by Miall (1988a, b, 1996) and has now been fully documented in a number of detailed field studies (e.g., Holbrook 2001). However, owing to the difficulty of dating nonmarine deposits, assigning ages and calculating sedimentation rates for these deposits is usually not possible.

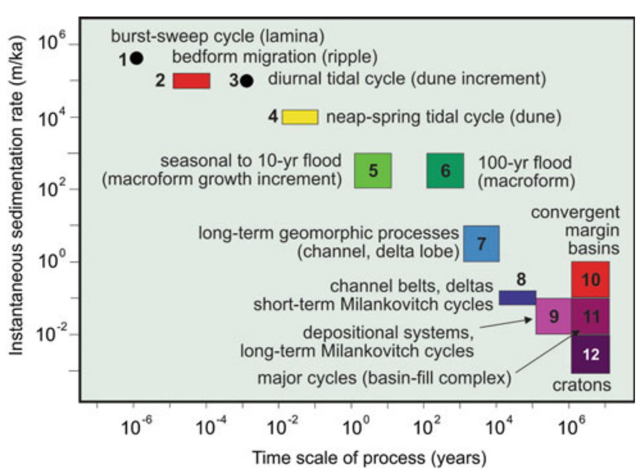


Fig. 8.5 Rates and durations of sedimentary processes. Numerals refer to the Sedimentation Rate Scale (see also Table 3.3)

8.4 Sedimentation Rates

Examples of measured and calculated sedimentation rate from modern and ancient environments provide the basis for the ranges of values indicated in column 3 in Table 3.3 and in Fig. 8.5.

SRS 2: small-scale ripples typically migrate a distance equivalent to their own wavelength in 20–60 min (Southard et al. 1980). A 5-cm-high ripple that forms in 30 min is equivalent to an instantaneous sedimentation rate of 876,000 m/ka. Clearly, this number is meaningless, but it will serve to emphasize the extremes of sedimentation rate, to compare with more geologically typical rates discussed later.

SRS 3: Tidal sand waves have similarly very high instantaneous rates. In the Bay of Fundy Dalrymple (1984) demonstrated that in one tidal cycle sand waves migrate a distance about equivalent to their average height, which is 0.8 m. Bay of Fundy tides are semi-diurnal, and so this migration is equivalent to a sedimentation rate of 584,000 m/ka.

SRS 5: The deposits formed by seasonal or more irregular runoff events have extremely variable instantaneous sedimentation rates. The flood deposit in Bijou Creek, Colorado, described by McKee et al. (1967) was formed by the most violent flood in 30 years. It formed 1–4 m of sediment in about 12 h, an instantaneous sedimentation rate of 730,000–2,920,000 m/ka. Assuming no erosion, and a repeat of such floods every 30 years this translates into a rate of 33–133 m/ka averaged over a few hundred years. In fact, scour depths during the flood ranged from 1.5 to 3 m, and true net preservation of any one flood deposit over periods of hundreds or thousands of years may be negligible. Long-term rates measured over hundreds to thousands of years are likely to be an order of magnitude less, in the range of 10^{-1} m/ka. Leclair (2011) demonstrated that the large-scale dunes that may characterize seasonal to longer-term floods do not necessarily have a higher preservation potential than the deposits formed during non-peak flood periods.

In the Rio Grande valley in Texas, Dean et al. (2011) used tree-ring studies to establish the recent sedimentation history. Over a 13-year period they determined that overbank floods occurred with a recurrence interval of 1.5–7 years, at accretion rates of 16–35 cm/year, an instantaneous sedimentation rate of 10^2 m/ka.

SRS 6: The point bars in the Wabash River are on average about 5 m thick. The active area of each bar is about 200 m wide. If the bars migrate at a maximum rate of 2 km in 50 years (Jackson 1976) they would take 5 years to migrate one point-bar width, which is equivalent to an instantaneous sedimentation rate of 1,000 m/ka.

Comparable rates may be calculated from the migration of distributary mouth bars. The Southwest Pass of the

Mississippi delta migrated a distance of 9 km in 100 years (Gould 1970, Fig. 20). The mouth-bar deposits, from the mouth of the channel to the toe of the distal bar, are about 4 km wide (in a dip direction) and about 70 m thick. This lateral migration is equivalent to an instantaneous sedimentation rate of 730 m/ka. Oomkens (1970) quoted sedimentation rates of 35 cm/year (350 m/ka) for the delta front of the modem Rhone River. A short-term rate of 4.4 cm/month (528 m/ka) was determined close to the mouth of the Yangtze River, China, by McKee et al. (1983), who studied the decay of short-lived radionuclides in the uppermost 15 cm of recent deposits, representing about 100 days of accumulation *(SRS 5*). The uppermost 200 cm of section, representing about 100 years of accumulation (*SRS 6*), yielded a rate an order of magnitude lower, 5.4 cm/a (54 m/ka).

Data from modem Dutch tidal deposits summarized by Yang and Nio (1989) showed that ebb-tide deltas accumulate at rates of 100 to 450 m/ka for periods of about 20 years, before abandonment occurs. Van den Bergh et al. (2007) used ^{210}Pb methods, which provide age information on the 100-a scale (*SRS 6*), to assess sedimentation rates on the prodelta of the Red River off Vietnam. They range from high values of 330 to 940 m/ka on the proximal prodelta slope, to less than 10 m/ka on the distal margin. The distal sedimentation rate is at the lower limit for *SRS 6* sedimentation rates when measured at the appropriate 100-year scale.

Rates calculated for the upper Bengal submarine fan, the world's largest and most active depositional system are consistent with the *SRS 5-6* time scales. Using ^{14}C age determinations for the last 10,000 years of sedimentation, Weber et al. (1997, p. 317) calculated that "on the shelf, sedimentation rates are currently extremely high in the foreset region of the recent delta (as much as 8 cm/a)" where water depth is 30–70 m, "and especially in the head of the canyon" where sedimentation rates reach as much as 1 m/a (10^3 m/ka). A sedimentation rate of 1 m/a places this system in the range of *SRS 5* and *6*, for which such sedimentation rates occur within time spans of 10^0–10^3 years. In this case the preservation machine at work is the removal of sediment by slope failure and slumping, with huge volumes of sediment moving downslope as sediment-gravity flows, Weber et al. (1997, p. 317) noted that "This sediment load would fill the entire canyon in less than 1000 years. Therefore, we conclude that, because of the steep gradients at the head of the canyon, frequent slumping and formation of turbidity currents occur even during the current sea-level highstand." The frequency of turbidite occurrence ranges between 500 and 10,000 years (Stow et al. 1983, p. 58), which is well within the 10^0–10^3-year time range.

SRS 7: Most studies of post-glacial sedimentation are carried out on a "long-term" (10^3–10^4-year) time scale that is assigned to *SRS 7*. Rates of post-glacial sea-level rise (and accommodation generation) reached as high as 18 m/ka (e.g., East China Sea: Wellner and Bartek 2003), although rates of 1–6 m/ka were more characteristic.

In the coastal river valleys of Texas, Blum (1993) demonstrated that late Pleistocene-Holocene cycles of degradation and aggradation depended on climatically controlled variations in discharge and sediment supply, not on sea-level change. Humid periods corresponded to episodes of aggradation. During two such periods, lasting 6 ka, as much as 10 m of valley-fill sediment accumulated in the upper Colorado drainage, indicating sedimentation rates of 1.7 m/ka. Long-term (10^4-a) floodplain aggradation rates reported by Bridge and Leeder (1979) ranged between 0.035 and 0.2 cm/a (0.35–2 m/ka).

Turning to the deltaic environment, if we assume that a distributary will only build out across a given area of the delta front once during the migration of one major delta lobe, we can calculate the sedimentation rate of the mouth bar averaged over the life of the lobe. In the post-glacial Mississippi delta, major lobes are formed and abandoned in about 1000 years (Kolb and Van Lopik 1966; Frazier 1967), giving an average sedimentation rate for that period of 70 m/ka. Lobe sedimentation took place during the post-glacial period of sea-level rise.

The recurrence interval of delta lobes themselves depends on subsidence rates, sediment supply and the configuration of the continental shelf. In the case of the Mississippi complex the river is attempting to switch discharge (and delta construction) to the Atchafalaya River, where one of the earliest lobes developed about 6–8 ka BP. On this scale deposition of a 45-m-thick mouth-bar deposit represents a sedimentation rate of 5.6–7.5 m/ka, although this calculation does not take into account the bay-fill and other facies interbedded with the mouth bar deposit. This compares with typical values for Holocene sedimentation rates of 6–12 m/ka that are commonly quoted for the Mississippi delta complex (e.g., Weimer 1970), and the Rhone delta, which has a thickness of only 50 m, accumulated since about 8.2 ka, indicating an average sedimentation rate of 6.1 m/ka (Oomkens 1970).

Dating of peat layers and other units in the Rhine-Meuse delta indicated that aggradation of ribbon-like (anastomosed) channel belts kept pace with the average sea-level rise of 1.5 mm/a, at sedimentation rates in the order of 10^0 m/ka (Blum and Törnqvist 2000). Highly detailed studies of the development of the Rhine-Meuse system using multiple ^{14}C dates have provided a wealth of detail regarding the aggradation history (Stouthamer et al. 2011). Regional flood basin accumulation rates for the upper delta are in the range of 0.3–1 mm/a (0.3–1 m/ka). Some channel belts indicate local rates as high as 2.8 mm/a (2.8 m/ka). The ratio of local to regional aggradation rate ranges between 0.4 and 4.0, but all these values, measured over time periods of 10^3–10^4 years, are within the *SRS 7* range.

A few sedimentation rates can be calculated for tidal-inlet and barrier deposits. The Galveston Island barrier is 12 m thick and 3.5 ka old at its base (Bernard et al. 1962, Fig. 8.60), indicating an average sedimentation rate of 3.4 m/ka. A tidal inlet at Fire Island, New York has migrated 8 km in 115 years (Kumar and Sanders 1974). The depositional slope from spit crest to channel floor is about 500 m wide, suggesting that at any one point the entire tidal-inlet fill could form by lateral accretion in about 7 years. The sequence is 12 m thick, indicating an instantaneous sedimentation rate of 1,714 m/ka. This migration rate is unusually rapid. Tidal inlets at Sapelo Island, Georgia appear to have migrated only about 2.5 km since the post-glacial sea-level rise (Hoyt and Henry 1967, Fig. 8.6c), indicating a sedimentation rate of 4.5 m/ka. Sommerfield (2006) calculated accumulation rates and stratigraphic completeness for modern oceanic continental margins. His research was based on measures of mass per unit area with time, and translates into sedimentation rates in the *SRS 7–8* range.

Coal seams are estimated to represent 4,000–12,000 years of peat accumulation, at accumulation rates of 1–3 m/ka (Nemec 1988; Phillips and Bustin 1996). Allowing for a gradual 3:1 compaction during accumulation, Nemec (1988, p. 163) calculated an accommodation generation rate in a mire of 0.4–1.1 m/ka, which, as he noted, is one to two orders of magnitude greater than the long-term subsidence typical of the cratonic basins he studied (Illinois, South Wales, SW Poland).

Rates of sedimentation on modem alluvial fans and fluvial floodplains have been measured using ^{14}C dates on plant material, and tephrochronology. Available data were summarized by Miall (1978b) and shown to encompass a wide range, from 0.08 to 50 m/ka. However, these measurements have not been correlated to specific scales of architectural units, such as the depositional groups defined here.

Plio-Pleistocene slope and basin deposits in the Gulf of Mexico are characterized by sedimentation rates ranging from 0.16 to 6.45 m/ka (10^1–10^0 m/ka).The lower values are from areas characterized by slow subsidence rates and a high proportion of hemipelagic sedimentation; the high values were derived from areas with a high proportion of sediment-gravity-flow deposits and accumulation in salt-withdrawal basins. These values were calculated by Fiduk and Behrens (1993) for tectonostratigraphic sequences representing between 0.3 and 1.25 Ma. These are unusually rapid rates of accumulation, the rates corresponding to *SRS 7* or *8*, over time scales of *SRS 9*, confirming the unique setting of the Gulf Coast basins or, alternatively, suggesting that the geological preservation machine (see below) may not yet have completed its work.

Scarponi et al. (2013) used amino-acid racemization data to demonstrate varying accumulation rates at the *SRS 7-8* scale, within the topmost 100-ka Holocene coastal sequence of the Po river coastal plain, Italy. Lowest rates (0.2–0.7 m/ka) were recorded within the nonmarine lowstand systems tract, increasing to 1.4–2.5 m/ka in the transgressive systems tract and to as much as 10 m/ka in the highstand. This variability was interpreted as a response to the systematic change in the probability of preservation of depositional events as accommodation increased with rising base-level, versus changing sediment supply in the shallow-marine realm as the depositional systems shifted from retrogradational to progradational. Higher values of net accumulation rate were recorded in the transgressive and highstand systems tracts, and lower values (with concomitantly more diastems) in the condensed section formed around the time of the maximum flooding surface. The highest values, up to 19.6 m/ka were recorded in homogeneous sandy sediment that may incorporate fewer diastems, in accord with Sadler's (1981) analysis that high accumulation rates scale inversely with time span.

The compilation of sedimentation rates in shallow-marine carbonate sediments by Kemp and Sadler (2014) indicated that when normalized to a 5-ka time scale—the "the typical duration of Holocene and Pleistocene sections lacking major exposure surfaces" (Kemp and Sadler 2014, p. 1290) maximum accumulation rates range between 10 and 60 m/ka, depending on latitude, with rates dropping off in the higher latitudes.

SRS 8 and 9: At time scales of 10^4–10^5 years, measured sedimentation rates are in the range of 0.1–1.0 m/ka (*SRS 8*). At time scales of 10^5–10^6 years, rates are 0.01–0.1 m/ka (*SRS 9*).

Stratigraphic studies based on magnetostratigraphic dating and correlation, and studies of Late Cenozoic deposits using such techniques as high-resolution reflection-seismic data provide the appropriate focus. Cyclic successions developed by orbital forcing typically fall into this category. Examples of such deposits include the Quaternary shelf-margin sequences of Suter et al. (1987), the classic 41-ka cycles of the Wanganui Basin, New Zealand (Pillans et al. 2005), and the minor and major cyclothems of Heckel (1986).

The sequences described from the Gulf Coast by Suter et al. (1987) averaged 25,000 years in duration and range in thickness from about 25 to 160 m, indicating average accumulation rates of 1–6.4 m/ka. Heckel (1986) documented the chronology of 55 cycles of Westphalian-Stephanian age in the U.S. Midcontinent. Estimates of the length of this time span range from 8 to 12 Ma The thickness of the succession varies from 260 m in Iowa to 550 m in Kansas. These values indicate an average accumulation rate of between 0.02 and 0.07 m/ka (*SRS 12*). Many of the cycles contain substantial fluvial-deltaic sandstone units and, according to Ramsbottom (1979), who studied similar cyclothems in Europe, rates of lateral deltaic growth must have been about as rapid as that of the modem

Mississippi; yet the average sedimentation (vertical aggradation) rate is two orders of magnitude less than that of the Holocene Mississippi delta complex and its Pleistocene shelf-margin precursors on the Louisiana Gulf Coast. Part of the explanation for this marked contrast is that the Carboniferous cyclothems that were the subject of Heckel's study are located in a cratonic region, where subsidence rates would be expected to be substantially lower than on the continental margin of the Gulf Coast. As demonstrated by Runkel et al. (2007, 2008) cratonic sequences may develop by very low-angle lateral accretion.

Oxygen isotope and magnetostratigraphic data for the Wanganui Basin sections confirm the predominance of the 41-ka orbital cycle. In several composite sections it can be demonstrated that about 1 km of section accumulated in 1.2 Ma between the Olduvai and Brunhes paleomagnetic stages, indicating an average sedimentation rate of 0.8 m/ka (Pillans et al. 2005, Fig. 11).

A well-known ancient example of interpreted orbitally-forced cyclic sedimentation comprises the Newark-type lacustrine cycles of eastern North America. Olsen (1990), reconstructed characteristic orbital cyclic frequencies based on available chronostratigraphic information, and this yielded average sedimentation rates of 0.27 m/ka at the 10^4–10^5-year time scale.

A magnetostratigraphic study of the Siwalik fluvial deposits of Pakistan provides some control data for an ancient fluvial system (Johnson et al. 1985, 1988). In the Miocene Chinji formation, 400–500 m thick, and deposited over a time span of approximately 3.5 Ma, fluvial cycles representing channel belts up to several kilometres wide (Johnson et al. 1988, Fig. 9.3) range from 12 to 50 m in thickness. At an average sedimentation rate of 0.12 m/ka, these represent cycle return periods of between 10^4 and 10^5 years. Detailed studies reported in their second paper indicate considerable variation in local sedimentation rate, with evidence that specific magnetostratigraphic reversals are missing, indicating gaps in sedimentation on a 10^4-year scale. The formation as a whole corresponds to a *SRS-9* assemblage, but it is likely that the fluvial cycles, containing missing intervals, represent channel belts of *SRS-8*.

Jones et al. (2004) explored sedimentation rates and sediment transport rates in a foreland basin in Spain. The long-term sedimentation rate for their complete section averaged 0.075 m/ka over 12 Ma (*SRS-9*). Magnetostratigraphic dating of short intervals within this section indicated sedimentation rates varying between 0.03 and 0.2 m/ka (*SRS 8-9*), with much of the local variability being attributed to syndepositional folding affecting accommodation rates.

Fluvial cycles representing similar long-term avulsion processes were described by Hofmann et al. (2011) from the Cretaceous Piceance Basin of Colorado. The cycles average 120 m in thickness and are estimated to represent about 400 ka, accumulating at an average sedimentation rate of 0.305 m/ka (*SRS 8*). Clusters of channels develop an alluvial belt, the topographic elevation of which eventually leads to avulsive switching to lower areas on the floodplain, a process termed *compensational stacking*. Magnetostratigraphic studies of the Eocene Escanilla Formation, a braided-stream deposit, in the Spanish Pyrenees yield similar *SRS* values, at 0.17–0.57 m/ka over time periods of 10^5 years (Bentham et al. 1993).

Cores through interpreted precessional cycles of Cretaceous age on the floor of the Atlantic Ocean off tropical west Africa (66 22-ka cycles totalling 37 m of core: Beckmann et al. 2005) yield sedimentation rates of 0.025 m/ka. This is an order of magnitude slower than the *SRS-8* range characteristic of high-frequency orbital cycles.

The long-term sedimentation rates of *SRSs 8* to *12* depend largely on long-term rates of generation of sedimentary-accommodation space. This depends both on basin subsidence, which is controlled by tectonic setting, and by changes in base level, such as eustasy. Miall (1978b) showed that most nonmarine basins, in various tectonic settings, have sedimentation rates averaged over millions of years of 0.03–1.5 m/ka.

SRS 10: Basins in convergent margins are provided their own category in Table 3.3 and Fig. 8.5, because of the exceptionally high rates of subsidence and sedimentation that have been recorded in this tectonic setting. Miall (2010, Table 8.2, pp. 280–281) summarized data from settings such as the Banda Arc, the Himalayan foreland basin, the Cretaceous forearc basin of Baja California and a forearc basin in Japan where sedimentation rates of 10^{-1}–10^0 m/ka have been measured over durations in the order of 10^6 years. Magnetostratigraphic calibration of several sections in Andean foreland basin strata of Argentina indicated sedimentation rates ranging between 0.22 and 1.71 m/ka over intervals ranging between approximately 0.5 and 5 Ma (Echavarria et al. 2003). Hiatuses lasting up to 2 Ma, bring the average sedimentation rates, measured over total sections representing between 7 and 13.5 Ma, down to between 0.183 and 0.571 m/ka.

Growth strata that develop adjacent to active structures, such as basin-margin thrust faults are typically deposited at *SRS-10* rates. Burbank et al. (1996, Fig. 8.8) provided an example where accumulation rates averaged 0.117 m/ka over 1.7 Ma Data provided by Medwedeff (1989) indicate a growth rate of 0.305 m/ka over 8 Ma At the margins of the Tarim Basin, in western China, Sun et al. (2010) used magnetostratigraphic data to determine the rates of accumulation of "growth strata" in proximity to a growing anticline. Sedimentation rates increased from 0.325 m/ka prior to the syndepositional movement of the growth structure, to 0.403 m/ka during the period of active tectonism, over a total time span of about 10 Ma.

Rapid subsidence is indicated in basins developed along the San Andreas Fault system. Dorsey et al. (2011) calculated subsidence rates of between 0.4 and 2.1 mm/a (10^{-1}–10^{0} m/ka) measured over periods of a few million years.

Not all convergent-margin basins are characterized by high sedimentation rates. In deep-water basins, where sediment supply is low, sedimentation rates may be much less. Finney et al. (1996) compiled data indicating that Paleozoic graptolitic shales in the Taconic foreland basin of the southeast USA accumulate at average rates of 0.01–0.03 m/ka measured over time periods of a few million years (comparable to *SRS 9*).

SRS 11: This is the rate characteristic of long-term geological processes. Aschoff and Steel (2011) calculated sedimentation rates for the Upper Cretaceous clastic wedge of the Book Cliffs (Utah-Colorado) in order to explore relationships between sedimentation and tectonism in the Sevier foreland basin. The range of rates is 0.047–0.14 m/ka, calculated over stratigraphic times spans of between 2.1 and 6.5 Ma These are within the range for *SRS 11*, but are low relative to those recorded in some Andean basins (*SRS-10*, above). The Catskill Delta of New York-Pennsylvania accumulated at comparable rates. Data provided by Ettensohn (2008) indicate a maximum rate for the proximal part of the "delta" (in reality a major clastic wedge deposited in a range of nonmarine to shallow-marine environments) of 0.096 m/ka (maximum thickness of 3 km accumulated over about 9 Ma between the Givetian and the Famennian).

Aschoff and Steel (2011) speculated about the possible influence of basement uplift within the Sevier foreland basin, which would tend to cancel out some of the subsidence due to flexural loading. This seems particularly likely for the middle portion of the clastic wedge, that characterized by the Castlegate sandstone, the sheet-like nature of which has, for some time, been attributed to a slow rate of regional subsidence (Yoshida et al. 1996). The incipient activation of Laramide structures within the basin, as suggested by Aschoff and Steel (2011), would be consistent with these characteristics of the clastic wedge. However, no such special influence on rates of accommodation has been suggested for the Appalachian basin.

SRS 12: Long-term sedimentation rates in cratonic environments include the lowest that have been recorded. Runkel et al. (2008) demonstrated that the deposits flanking the Transcontinental Arch in Wisconsin-Minnesota accumulated at an average rate of 0.4 m/ka, measured over a 15-Ma Upper Cambrian depositional record. Detailed biostratigraphic studies indicate that that the section is relatively complete, and accumulated as a series of thin, offlapping shingles. The thickness of each shingle, as indicated by the biostratigraphic zonation, varies from 50 to as little as 5 m, indicating an order of magnitude variation in sedimentation rate within this average rate. The Lower Mannville formation of southern Alberta consists of a series of high-frequency sequences with multiple phases of incised valley cut-and-fill. Long-term sedimentation rates range between 0.0013 and 0.02 m/ka (Zaitlin et al. 2002).

8.5 The Fractal-Like Character of Sedimentary Accumulation

The log-linear relationship between sedimentation rates and time span was addressed by Plotnick (1986), Middleton et al. (1995), and Sadler (1999), who demonstrated that it could be interpreted using the fractal "Cantor bar" model of Mandelbrot (1983). Using the process described by Mandlebrot (1983) as "curdling", Plotnick (1986, p. 885) developed a Cantor bar for a hypothetical stratigraphic section by successively emplacing hiatuses within portions of the section, at ever increasing levels of detail (the result is illustrated in Fig. 8.6):

> Assume a sedimentary pile 1000 m thick, deposited over a total interval of 1,000,000 years. The measured sedimentation rate for the entire pile is, therefore, 1 m/1000 years. Now assume that a recognizable hiatus exists exactly in the middle of the section, corresponding to a third of the total time (i.e., 333,333 years). The subpiles above and below the hiatus each contain 500 m of sediment, each deposited over 333,333 years, so that the measured sedimentation rate for each subpile is 1.5 m/l000 years. We now repeat the process, introducing hiatuses of 111,111 years in each of the two subpiles. This produces 4 subpiles, each 250 m thick, each with a duration of 111,111 years. The measured sedimentation rate is now 2.25 m/1000 years. The process can be reiterated endlessly, producing subpiles representing progressively shorter periods of time with higher sedimentation rates [Fig. 8.6 of this book]. Nevertheless, because the total sediment thickness is conserved at each step, the sedimentation rate of the entire pile remains 1 m/l000 years.

The selection of one third as the length of the hiatus, or gap (g in Fig. 8.6) is arbitrary. Other gap lengths generate Cantor bars that differ only in detail. Figure 8.6 is remarkably similar to Fig. 8.4, which was constructed by Miall

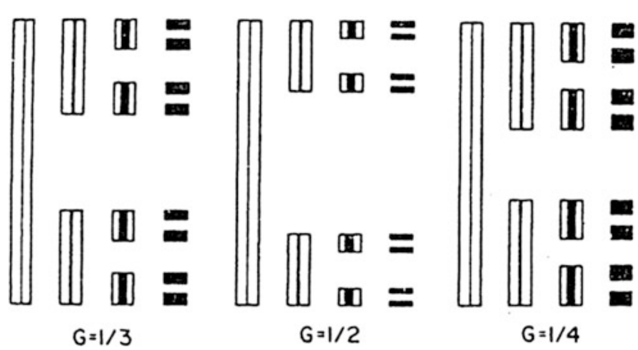


Fig. 8.6 Cantor bars generated using three different gap sizes (G) (Plotnick 1986, Fig. 1)

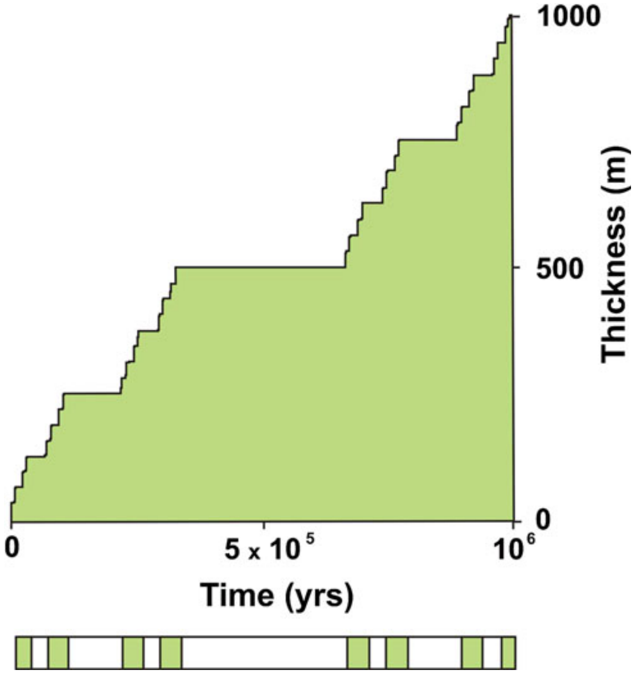


Fig. 8.7 Stratigraphic thickness accumulation viewed as a Cantor function—what has been termed a Devils's staircase—constructed with G = 1/2. The corresponding *Cantor bar* is shown at a lower resolution *below* the graph (adapted from Plotnick 1986, Fig. 8.7)

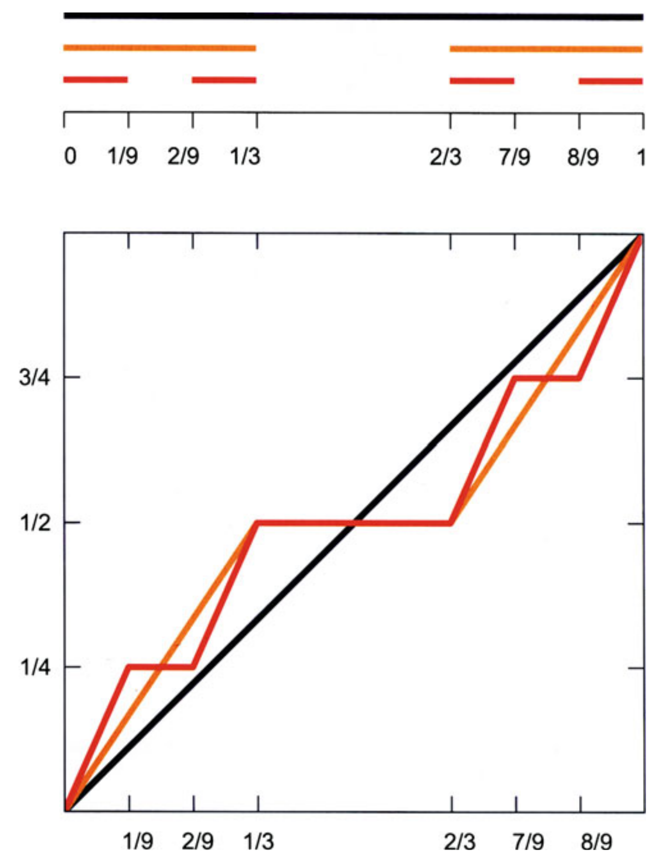


Fig. 8.8 A fractal plot of elapsed time (X-axis) versus sediment thickness (Y-axis) showing how the choice of gap length determines the distribution of hiatuses and sedimentation rate (from Schlager 2005)

(1997) based on the hierarchies of sedimentation rates compiled by Miall (1991), but with no knowledge of fractals.

The dependence of sedimentary accumulation on the availability of accommodation was understood by Barrell (1917; Fig. 5.2 of this book) and is the basis of modern sequence stratigraphy (Van Wagoner et al. 1990). The fractal model provides an elegant basis for integrating this knowledge with the data on varying sedimentation rates and varying scales of hiatuses discussed in the paragraphs above. Mandelbrot (1983) and Plotnick (1986) provided a version of an accumulation graph, called a Devil's staircase (Fig. 8.7). This shows how sediments accumulate as a series of clusters of varying lengths. Vertical increments of the graph correspond to intervals of sedimentation; horizontal plateaus represent periods of non-accumulation (or sedimentation removed by erosion). Sequence stratigraphy is essentially a study of the repetitive cycle of accumulation followed by the next gap, at various scales. The larger, more obvious gaps (the longer plateaus in Fig. 8.7) define for us the major sequences, over a range of time scales. The prominence of particular ranges of "accumulation + gap" length in the first data sets compiled by Vail et al. (1977) was what led to the establishment of the sequence hierarchy of first-, second-order, and so on. That this has now been shown to be an incomplete representation of nature (Miall 1997, 2010; Schlager 2005) does not alter the fact that there is a limited range of processes that control accumulation, and these have fairly well defined rates which, nevertheless, overlap in time to some extent.

As Plotnick (1986, Table 1) and Sadler (1999) demonstrated, the incompleteness of the stratigraphic record depends on the scale at which that record is examined. Sections spanning several million years may only represent as little as 10 % of elapsed time at the 1000-year measurement scale, although this is below the resolution normally obtainable in geological data. Sequences, as we know them, each essentially consist of clusters of the shorter "accumulation + gap" intervals separated by the longer gaps—those more readily recognizable from geological data.

Schlager (2005) illustrated the relationship between sedimentation date and time span in a different way (Fig. 8.8). This diagram highlights the central point that the length and frequency of the gaps determines the calculated sedimentation rate. Almost all actual geological data sets yield correlation lines similar to that indicated by the black line of correlation. This line suggests a relatively slow rate of

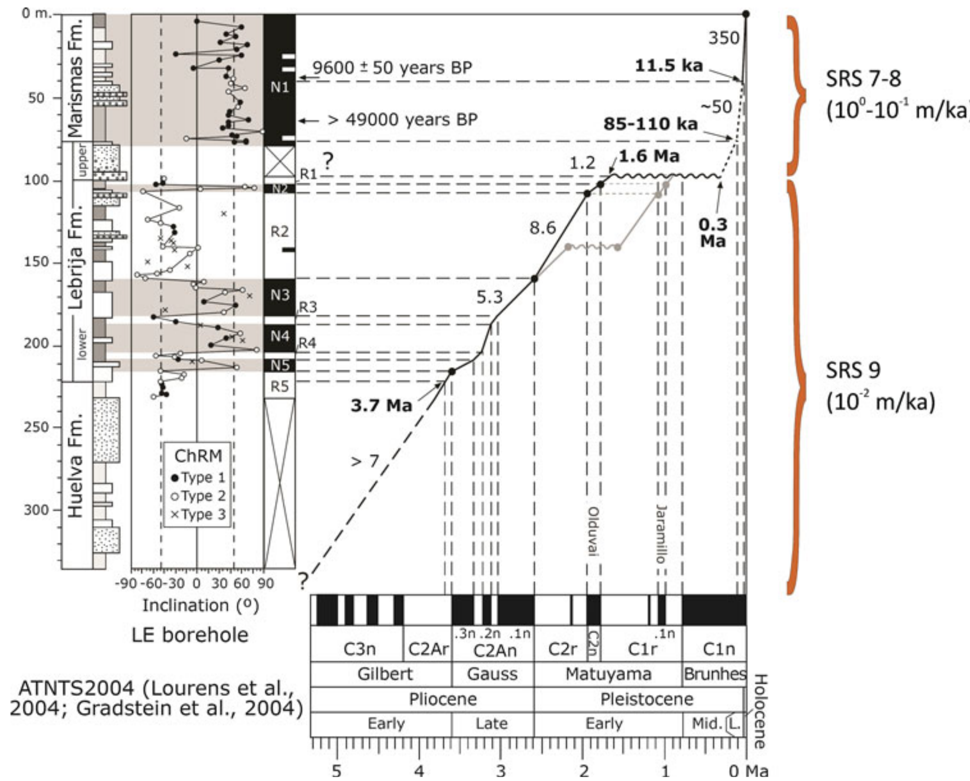


Fig. 8.9 Drill core from the modern Guadalquivir foreland basin in SW Spain. This is the Lebrija borehole, drilled from the surface of the modern, active floodplain, down through post-glacial estuarine deposits and into the older stratigraphic record. Sedimentation rates calculated from paleomagnetic calibration of the section, are indicated by the values, in cm/ka, along the diagonal line of correlation. Adapted from Salvaney et al. (2011), with permission

sedimentation with few, widely dispersed hiatuses. Such an interpretation inevitably follows from (1) the limited ability of geological methods to provide numerous tightly constrained age dates, and (2) the cryptic nature of most sedimentary hiatuses. Reality might be much closer to one or other of the red or orange correlation lines, which incorporate closer spacings of hiatuses and higher short-term sedimentation rates.

8.6 Apparent Anomalies of High Sedimentation Rate Versus Slow Rate of Accommodation Generation

Bailey (2011) highlighted the preservation of fossil tree trunks in some coal-bearing strata as examples of the apparent dilemma posed by what appear to be exceptional modes of stratigraphic preservation. Tree trunks would be expected to decay rapidly, probably within decades (But were decay rates this rapid in the Carboniferous? Was there the same range of microorganisms that we observe at the present?), so the preservation of tree trunks up to 12 m high, in good condition, appears to argue for an unusually rapid rate of burial. Bailey (2011) suggested a rate of ~100 m/ka, well in excess of the 0.005–0.1 m/ka rates of accommodation generation indicated by the setting of the fossil trees within orbital cycles accumulating within tectonically active basins (the *SRS-9* time scale). The trees would seem to qualify as "frozen accidents", to use Bailey and Smith's (2010) term. But how unusual is this? And does it require a special explanation, as Bailey (2011) suggested? He argued for episodic, rapid (indeed, instantaneous) seismogenic subsidence to create the necessary accommodation.

Another example of an apparent stratigraphic puzzle is shown in Fig. 8.9. This is a carefully calibrated and dated stratigraphic record from the Guadalquivir foreland basin in SW Spain. High-precision dating for this Pliocene to Recent succession has been provided by the magnetostratigraphic record. For the purpose of this discussion, the interesting point is the increase in sedimentation rate following a hiatus at 1.6 Ma (calculated sedimentation rates are indicated next to the line of correlation). Prior to the hiatus, sedimentation rates were in the order of 10^{-2} m/ka (*SRS 9*). After the break they rose to 0.5 m/ka (10^{-1} m/ka: *SRS 8*) and then to 3.5 cm/ka (10^{0} m/ka: *SRS 7*). Why? What happened?

Surface sediments in this basin are not yet as compacted as in the ancient record, but this is unlikely to account for more than a few percent of the total thickness of the post-1.6 Ma section. I suggest that what we are seeing is typical sediment accumulations that have yet to be completely processed by the geological preservation machine.

The post-11.5 ka section represents sedimentation in accommodation generated by the post-glacial sea-level rise.

The calculated sedimentation rate is entirely in accord with sedimentation rates calculated over a 1000-year time scale (*SRS 7*). Future events could include a fall in sea level over a 10^4-year period, if the orbital cycles that have characterized Earth history for the last 2.5 Ma continue. That could potentially remove most or all of the top 95 m of the sedimentary record, as rivers grade themselves to the lower base level, thereby completing the work of the geological preservation machine at the *SRS 8* or *9* time scale. It is suggested that the pre-1.6 Ma section consists of short intervals of stratigraphy which accumulated at rates comparable to that calculated for the top of the section, separated from each other by numerous unrecognized hiatuses, a pattern comparable to the red line of correlation in Fig. 8.8. Sadler (1999) had explained a similar pattern of apparently accelerating accumulation in younger sediments, based on his study of sedimentation rates and time scales.

Whereas most published stratigraphic data sets contain the generalization exemplified by the black line of correlation in Fig. 8.8, the reality for the top of the Guadalquivir foreland basin section (Fig. 8.9), as measured at appropriate times scales, would be closer to the red line of correlation in this diagram, where short intervals of time characterized by high rates of sedimentation are separated from each other by hiatuses. For example, this interpretation can explain the intervals of rapid sedimentation (*SRS 5* or *6*) required to preserve the tree trunks described by Bailey (2011). The rapid rate can then be seen as part of a predictable spectrum of sedimentation rates, when measured at the appropriate time scale. As noted above, coal seams represent *SRS-7* deposits. Valley fills and deltas lobes, where many coal seams (and fossil trees) accumulate, are *SRS-7* and *8* deposits.

In a specific attempt to "disentangle time" in the preserved rock record, de Natris (2012) and de Natris and Helland-Hansen (2012) used rates of sedimentation derived from modern shallow-marine environments to calculate elapsed time in the Tarbert Formation (Mid-Late Jurassic) of the northern North Sea. They applied these rates to facies successions interpreted to have been deposited in these environments. A summation of rate versus thickness for each facies explained only 7 % of the 2.8 Ma elapsed time span of the Tarbert Formation as measured at geological time scales (*SRS 9* and higher). However, these calculations were carried out using rates in the *SRS 6-7* range, and therefore did not account for the longer-term events recorded in the system.

Scott and Stephens (2015) addressed the issue of missing time through detailed calculations of sedimentation rates of Carboniferous coal-bearing successions in Britain. They cited sedimentation rates of 10^0–10^{-2} m/ka, based on studies of estuarine and deltaic environments. These are equivalent to SRS 7, 8 or 9. Their results indicate a representation of elapsed time ranging between 4.9 and 33 %, depending on the interval selected and such factors as corrections for compaction of the peat to coal.

8.7 Accommodation and Preservation

The general question arises from the cases discussed in the preceding section: how could sediments accumulate at rates an order of magnitude or more greater than the local rate of accommodation generation (these processes are summarized in columns 4, 5 and 6 of Table 3.3). Blum and Törnqvist (2000, p. 20) noted:

> It … seems that accommodation, as it is commonly used, somewhat imprecisely mixes processes that operate over a range of rates and temporal scales; it is difficult to reconcile the time-scales over which sediments are deposited in the first place, whether or not those deposits will be preserved in the stratigraphic record, and the manner in which ancient alluvial successions are interpreted in terms of changes in accommodation or an accommodation/sediment supply ratio.

Six important points help to explain the types of apparent anomalies described above:

- While accommodation is typically quantified in terms of vertical space relative to sea level (base level) and the rate at which it is created or removed, many important sedimentary processes are dominated by lateral sedimentary accretion. Sediments accumulate on mid-channel bars and on meander bends by lateral (cross-channel) and downstream accretion. Deltas and continental margins accumulate by oceanward progradation.
- Fluvial, tidal, and other channels, and valleys, ranging up in scale to major incised valley systems, are locations where accommodation is not controlled by base level but are best understood with reference to the buffer concept of Holbrook et al. (2006). Accommodation generation on geomorphic time scales is therefore not dependent on tectonic subsidence rates and may be substantially higher (at the appropriate *SRS*).
- In two other major settings, accommodation is not restricted by base level: Deposition landward of the shoreline and in inland nonmarine basins is constrained by depositional slopes that are dependent on upstream controls, such as rates of tectonic uplift, river discharge and sediment load (Holbrook et al. 2006). Also, deep marine sediments are not in any way constrained by rates of accommodation generation, but are largely dependent on sediment supply and slope.
- Allogenic and autogenic sedimentary processes may generate predictable, ordered stratigraphic patterns at all time scales. The order and predictability may include

erosional processes as well as processes of accumulation. This has always been the basis for Walther's Law and, more recently, sequence stratigraphy. Therefore, contrary to the random or chaotic processes of accumulation implied by Bailey and Smith (2010) stratigraphic order, including cyclicity, may be preserved in the rock record and may be understood and interpreted within the focus of the appropriate *SRS*.

- Although sediment preservation is extremely discontinuous and spasmodic at any one location, the shifting locus of accumulation (aggrading channels, delta lobes, prograding clinoforms, etc.) means that substantially more elapsed time is represented by preserved sediment in three dimensions than the percentages relating to vertical accumulation noted earlier in this section. At intermediate time scales (*SRS 5-8*) (and in the experiments of Sheets et al. 2002), sedimentation is continuous for lengthy periods of time, but distributed across an entire depositional system. Our tools for reconstructing these processes in the ancient record are quite limited.
- Actual sedimentation rates in most geological settings are always likely to be much higher—typically orders of magnitude higher—than those calculated from the rock record, based on observable geological data, such as extrapolations from datable ash beds or biohorizons, or rates based on regional rates of accommodation generation. There is no conflict between the rapid sedimentation that can commonly be observed in modern settings, and the rates that prevailed in the past. In that limited sense, traditional uniformitarianism ("the present is the key to the past") is correct, but with the additional proviso that analyses of the past must take into account the ubiquitous hiatuses, many quite cryptic, that occur at all time scales.

There is not necessarily a simple relationship between forcing processes and a stratigraphic result. Many surface processes are characterized by a **geomorphic threshold**, whereby a steady or unsteady process may operate without significant effect until a particular critical level is reached, whereupon sudden and dramatic change may take place (Schumm 1973). Theoretical and experimental studies of nonmarine and coastal environments have confirmed the non-linear relationship between such forcing functions as tectonism and climate change and the resulting effects on erosion patterns and sediment delivery (e.g., Allen and Densmore 2000; Kim and Paola 2007; Allen 2008). In fact, Jerolmack and Paola (2010) refer to the "shredding of environmental signals by sediment transport". Allen (2008, p. 20) suggested that "Large alluvial systems with extensive floodplains should therefore strongly buffer any variations in sediment supply with frequencies of less than 10^5–10^6 years. This has strong implications for the detection of high-frequency driving mechanisms in the stratigraphy of sedimentary basins." Jones et al. (2004) demonstrated that in a foreland basin in Spain, the effects of basin-margin thrust faulting and erosional sediment unroofing would take in the order of 1 Ma to be recorded in petrographic changes 20 km into the basin.

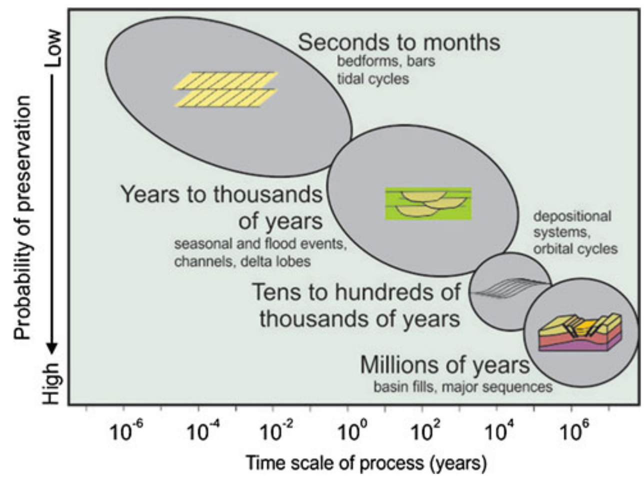


Fig. 8.10 The geological preservation machine (adapted from Fig. 8.5). Geological processes are grouped for the purposes of discussion into four major groups, based on sedimentation rates and durations. The preservation of any unit depends initially on processes operating at a given time scale, but longer-term preservation depends on the set of processes operating at the next longer-term time scale (to the right and down)

Jerolmack and Sadler (2007) examined the relationship between the transience of autogenic processes and the persistence of the "nested hierarchy of beds and bedding planes" constituting "the patchwork record of former landscape surfaces" that are ultimately preserved over the longer-term. The purpose of their paper was to develop a quantitative stochastic diffusion model to simulate the multitude of overlapping processes.

Sadler supplemented his data compilation on vertical aggradation rates (Sadler 1981) with a similar compilation on lateral accumulation rates (the lateral growth of ripples, bars, delta lobes, continental margin clinoforms, etc.) (Sadler and Jerolmack 2012, 2015). They demonstrated that, in cross-sectional area perpendicular to strike, growth rates of fluvial, coastal and shelf clastics are fairly constant at around 1 m^2/a, at all time scales, as measured over time spans from months to hundreds of millions of years. This continuity of sediment flux is, of course, not evident from the geologic record but, as noted above, non-deposition or erosion in one location is expected to be contemporaneous with deposition elsewhere,

In the next sections I discuss how specific sedimentary processes operating over a range of rates can lead to the generation of "frozen accidents" over a range of time scales (see also Fig. 8.10).

8.7.1 Preservation at a Scale of Seconds to Months

Ripples and dunes form and migrate continuously under running water. Typically, trains of bedforms migrate down channels and across bar flanks, with one bedform replacing another, resulting in no net sedimentation. Temporary accumulations may form by lateral accretion where bedform trains build into areas of increasing water depth, such as scour pools or the flanks of bars. Under conditions of high bedload, ripple sets may become superimposed, to form climbing sets. Sedimentation on tidal flats can be affected by the lunar cycle from neap- to spring-tide conditions, which has been observed in some cases to be recorded as rhythmicity in lamina thickness (e.g., the Dutch tidal flats: Visser 1980). Mud in marine systems of all types is constantly undergoing deposition, erosion and transportation as tides, storms and other processes affect the sea floor (Traboucho-Alexandre 2015). How do such ephemeral deposits become preserved? Some must be so preserved, because we see them in ancient deposits in settings that clearly indicate the types of environmental processes just described (e.g., Archer et al. 1991).

Channels in flowing systems are ephemeral over a wide range of physical and time scales. Bank erosion, bar and meander migration are a result of the ever-changing structure of turbulence in the system. Minor changes in discharge or the direction of flow in one channel may trigger a cascading set of changes downstream. Sediment movement and deposition are therefore dynamic and ever changing. However, these autogenic processes will lead to the abandonment of channel reaches and bars, which serve as areas of temporary sediment storage, even while sedimentation may be relatively continuous when the system is considered as a whole. When we walk across a tidal flat or a fluvial point bar, it is these temporary deposits that we see. Returning to the same location days or years later, the deposits may have the same appearance, but there is a high degree of probability that the specific deposits we took note of have been replaced by others. What happens next is again a matter of chance. Long-term preservation depends on the events at the next time scale.

8.7.2 Preservation at a Scale of Years to Thousands of Years

The time scale of years to thousands of years is what Sheets et al. (2002) termed the stratigraphic "mesoscale." Within this time frame, "the depositional pattern shifts from reflecting the short-term flow pattern to reflecting long-term basinal accommodation. Individual events are averaged to produce large-scale stratal patterns" (op. cit., p. 288). This process is what Duller et al. (2012) termed the transition from "noisiness" to "drift."

Walther's Law is based on the concept of shifting depositional environments that are represented by deposits stacked in a vertical succession. Many of the environments to which this law has been applied generate the characteristic vertical profiles (e.g., fluvial fining-upward cycles, deltaic mouth bars and crevasse splays) over time spans of 10^1–10^3 years, and may, therefore be interpreted within the framework of SRS 5-7. Examples are summarized below. Longer-term processes are described in the next section.

Most changes in fluvial systems take place during episodes of maximum discharge, which may be regular spring floods, or rarer flood events. Tidal systems are most affected during spring tides and during storms. These can result in large-scale changes in channel and bar location and orientation. In braided fluvial systems, entire minor channel systems may be abandoned. In meandering systems, meander chute and neck cutoff can leave earlier deposits behind. The deposits that fill scours, such as those which form at channel confluences, have a particularly high preservation potential at this time scale. Holbrook et al. (2006) defined what they termed the buffer zone, the zone of instantaneous preservation space for fluvial systems. For graded rivers, this is the space between the deepest level of scour and the highest level to which levees and floodplains can aggrade during normal year-to-year flow conditions.

At a somewhat longer time scale, from hundreds to a few thousand years, nodal avulsion of river channels is an important process for deposit abandonment (Schumm 1977), which considerably increases the preservability of the deposits so affected.

Deposits that form by flow expansion, including alluvial fans, crevasse splays and delta lobes are abandoned by switching of the distributary system as a result of slope advantages. This is a well-known process based on the example of the Mississippi delta, from the scale of the interdistributary bay-fill delta (Coleman and Gagliano 1964) up to the scale of the major delta lobes (Kolb and Van Lopik 1966; Frazier 1967). Once abandoned, the larger delta lobes undergo natural compaction and subsidence, which gradually takes them below the level of active scour and increases their chance of long-term preservation.

In tidal systems, channels, bars and tidal deltas evolve in the same way. Long-shore drift can displace inlet mouths, with resultant abandonment of inlet fill and bar-flank deposits. Scarponi et al. (2013), as noted earlier, demonstrated how accumulation rates and the probability of preservation of individual depositional events changed through a 100-ka base-level cycle.

In the experimental braid-delta constructed by Sheets et al. (2002), localized episodes of rapid aggradation occurred by avulsive channel switching across the experimental tank, eventually evening out "regional" deposition to the point that average aggradation equaled subsidence. Sheets et al. (2002, p. 300) scaled this up to a scenario whereby at a long-term aggradation rate of 1 m/ka the "depositional transition from flow control to subsidence control would occur on a time scale of the order of 15,000–30,000 years." This corresponds exactly to the conditions prevailing within the *SRSs 7* and *8* scale of depositional units. Sheets et al. (2002) demonstrated that in their model, after the deposition of a sediment layer equivalent to between five and ten channel-depths, which required an equivalent number of avulsion events to occur, the resultant layer had evolved a relatively consistent thickness and that the regional variation in this thickness could be related to the pattern of subsidence. What this means from the perspective of this chapter is that sedimentation rates for individual channels in a fluvial or deltaic system differ from the sedimentation rate for the entire depositional system by one half to about one order of magnitude (*SRS 5-6* versus *SRS 7-8*).

Fans and deltas illustrate the important point that (as expected following the arguments of Sadler and Jerolmack 2012, 2015) a continuous sediment flux still yields a discontinuous record because of the patterns of channel, channel-belt and lobe switching that take place as a result of natural avulsion processes. Sediment bypass in one area is contemporaneous with sediment accumulation elsewhere.

At these time scales, several processes are repetitive, and can result in deposits that preserve an element of internal repetition or cyclicity. Channel aggradation and bar accretion will record the range of flow conditions from higher-velocity flow at the base of the channel, the bar toe or the base of the bar flank, to low-flow at the bar crest or the channel bank. Seasonal flooding and flash floods can impose a crude cyclicity of minor erosion followed by sedimentation that decreases in grain size as flow energy dissipates. All these processes tend to generate upward-fining successions which have a chance of being preserved at the decadal to millennial scale. Progradational deposits develop an upward-coarsening profile as deeper water environments are gradually filled with sediment.

All the processes described here include erosional episodes operating at the same time scale, and constituting integral components of the geological preservation machine.

8.7.3 Preservation at the Scale of Tens of Thousands to Hundreds of Thousands of Years

At this time scale, sedimentary processes (the generation and removal of accommodation, sediment accumulation and erosion) may be dominated by high-frequency tectonic processes, or by Milankovitch processes (including sea-level change), or by both. Walther's Law may be applicable to processes operating at *SRS 7-9*. The section illustrated in Fig. 8.9 illustrates the geological preservation machine in action at this scale, the topmost 100 m of the section representing preservation at the *SRS 7-8* scale, but with long-term geological processes, that would most likely remove much of this section, still to come (Fig. 8.10).

As the discussion in this chapter has demonstrated, in most settings, local sedimentation rates are more rapid than the rate of accommodation generation, and complete preservation of any succession at any time scale is unlikely. For example, the detailed Jurassic ammonite studies of Callomon (1995) reveal an extremely variable and fragmentary record of shallow-marine preservation over the 10^5-year time scale in the Jurassic deposits of Dorset (see discussion of Fig. 8.2).

Clastic wedges or *tectonic cyclothems* (Blair and Bilodeau 1988) are cycles developed under tectonic control over time scales of 10^4–10^7 years. Accommodation is generated by differential movement at basin margins. Episodic thrust loading within a foreland-basin setting may generate regional basement adjustments at this time scale, and has been suggested as one of the generating mechanisms for tectonic cyclothems (Peper et al. 1992). The angle or direction of tilt of depositional slopes may be changed by changes in intraplate stress, by extensional subsidence or faulting, or by changes in the supracrustal load in the case of contractional settings (e.g., foreland basins). Heller et al. (1993) modeled localized crustal flexure (uplift and subsidence) at rates of up to 0.16 m/ka over time periods of 10^5 years caused by tectonic reactivation of lines of crustal weakness in response to far-field intraplate stresses. Zecchin et al. (2010) compared the architecture of Milankovitch cycles generated under conditions of high-frequency sea-level change and tectonism, with accommodation changing at rates of 1–10 m/ka.

Entire depositional systems may be affected by these processes, leading to formation, and then abandonment and preservation of previously formed deposits. Kim and Paola (2007) modeled a coastal fluvial-deltaic system and demonstrated that autogenic cycles of delta and channel switching may, under the influence of fault movement, develop cyclothem-like cycles over time periods of 10^5 years (*SRS 8-9*). Allen (2008) suggested that the response time of fluvial systems to tectonic perturbations of an alluvial landscape would be in the order of 10^{5-6} years. Tectonic cyclothems are discussed further in the next section.

Autogenic switching of alluvial channel belts at a 10^3–10^5-year time scale has been described by Hajek et al. (2010) and Hofmann et al. (2011). Clusters of channels generate an alluvial ridge leading to instability and avulsion into neighbouring low areas on the alluvial valley. A greater degree of compaction of the adjacent floodplain units relative to the channel deposits is a factor in creating the additional accommodation. This process, termed *compensational stacking*, generates cycles of about 120 m in thickness, and clearly requires the switching mechanism to be superimposed on a long-term process of tectonic subsidence.

In nonmarine successions, major surfaces of nondeposition may be difficult to distinguish from autogenic scour surfaces. Miall and Arush (2001b) labeled such unconformities "cryptic sequence boundaries." They may be recognized by careful petrographic work, and also by the application of special petrophysical methods that reflect the subtle diagenetic signatures of such surfaces (Filomena and Stollhofen 2011).

Sequence models for nonmarine systems have long incorporated the concept of variable stacking patterns of channelized sand bodies. Following the modeling experiments of Bridge and Leeder (1979), the standard interpretation has been that the architecture of channels and channel belts depends largely on the balance between the rate of avulsion and the rate of accommodation (Wright and Marriott 1993; Shanley and McCabe 1994). The models assert that rapid accommodation generation may increase the likelihood of a given channel deposit being buried as an isolated sandbody by floodplain deposits before channel migration and scour removes it from the record. Slow accommodation generation favours the accumulation of channel bodies that erode laterally into each other, as a fluvial system slowly migrates across a floodplain, developing laterally-amalgamated sand bodies. Such interpretations must, however, be consistent in terms of time scale. Alluvial architecture—the preserved complex of amalgamated macroforms, is determined by sedimentary processes that occur within the *SRS-6* to *SRS 8* range, that is, on time scales of 10^2–10^5 years and sedimentation rates of 10^{-1} to 10^2 m/ka. These are the rates used by Bridge and Leeder (1979) based on information they compiled from modern rivers. However, this means that the formation of the elements of alluvial stratigraphy occurs within time scales that are several orders of magnitude more rapid than the rate at which accommodation is typically generated by regional geological subsidence (*SRS 11*). Therefore it seems likely that in the ancient record there would be a genetic relationship between fluvial architecture and rates of accommodation only in the case of high-frequency sequences, those formed within the *SRS-8* range, e.g., orbital cycles. Nonmarine sequences formed over longer time periods (many have been documented on a 10^6-year time scale) require different interpretations, in which changes in alluvial architecture are related to migration of facies belts or to changes in fluvial style in response to tectonic or climatic forcing.

Orbital cycles are superbly exposed in pelagic sedimentary records in southern Italy, and have been studied as a basis for erecting a cyclostratigraphic time scale (Hilgen 1991; Hilgen et al. 2007, 2015). In this setting, accommodation is not an issue. Sea level, water chemistry, sediment supply, and every other important aspect of the environment, including even the regularity of processes generating hiatuses, is controlled by orbital forcing, and a clear orbital signal and a representative sedimentary record can be expected to be preserved. Calibration of the cyclicity against a retrodicted astronomical record confirms this. Lacustrine settings may also provide the necessary environment of total control by orbitally-forced parameters for development and preservation of a cyclostratigraphic signature (e.g., Aziz et al. 2003), and the classic cyclothems of the US Midcontinent, controlled as they were by substantial climatic and glacioeustiatic sea-level change, also provide excellent examples of preservation at this time scale (other examples include the Triassic cycles of the eastern US: Olsen 1990; Green River Formation of Wyoming: Fischer and Roberts 1991). Some ancient carbonate-platform margins also offer convincing cases. In other settings, however, questions of preservability of the cyclostratigraphic record arise, particularly because of the likelihood of overprinting by autogenic processes (Miall and Miall 2004; Bailey 2009; Miall 2010). As Kemp (2012) demonstrated by numerical modeling, in the case of marine cycles, if sea-level changes occurring at a higher than Milankovitch frequency are embedded in the preserved record, the evidence of orbital control may be masked. Even in deep-marine sections, the sedimentary record may not be complete (Trabucho-Alexandre 2012), and so caution must be applied. Each putative example needs to be examined on its merits. Strasser et al. (2006, p. 81) said:

> It is clear that astronomical climate forcing is most accurately recorded in depositional settings where the preservation potential is highest (deep marine basins, rapidly subsiding shelves, long-lasting deep lakes).

Recent developments in the field of cyclostratigraphy and astrochronology are discussed in Sect. 8.11.

8.7.4 Preservation at the Scale of Millions of Years

On extensional continental margins, subsidence rates ranges from 0.2 m/ka at the initiation of rifting, decreasing to less than 0.05 m/ka during the flexural subsidence phase, at time scales of 10^6–10^7 years. Foreland basins subside at rates of 0.2–0.5 m/ka, and cratonic basins at 0.01–0.04 m/ka (rates from Allen and Allen 2005, pp. 364–365). Intraplate stress changes can generate regional accommodation changes at 0.01 to 0.1 m/ka at time scales of 10^6 a. (Cloetingh 1988, p. 216). Detailed studies of offsets on growth faults in the

Niger delta, based on measuring the displacement of maximum flooding surfaces, indicated rates of accommodation generation on the downthrown side of 0.01–0.12 m/ka, over time scales of 10^5–10^6 years (Pochat et al. 2009). These rates are all within the range of *SRS 9-11*.

Where accommodation generation is rapid, sedimentation rates comparable to the "long-term geomorphic" rates of *SRS 7* (10^0 m/ka) have been recorded over intervals of several millions of years. Such settings include forearc and foreland basins and some basins associated with strike-slip faults (Miall 2010, pp. 280–281). These are categorized as convergent-margin basins (including transpressive settings) in Fig. 8.5 and assigned to *SRS-10*. As discussed above, variations on these long term rates may provide clues concerning subsidence and uplift mechanisms.

Sedimentation and long-term preservation by lateral accretion may be the key to understanding the thin sedimentary succession present in cratonic-interior settings (*SRS 12*). It required the highly detailed chronostratigraphic reconstructions of Runkel et al. (2007, 2008) to demonstrate that the Upper Cambrian-Lower Ordovician succession on the flank of the Trans-Continental Arch in Wisconsin and Minnesota developed by gradual offlapping of successive sedimentary shingles on a very gently-dipping ramp.

On continental margins, given the importance of lateral progradation, total accumulation is not limited by vertical accommodation generation, and sedimentation is supply-dominated. The following generalizations are adapted from Stow et al. (1983, p. 58): Typical long term accumulation rates on carbonate or clastic shelves are from 10 to 40 m/ka (10^1 m/ka). Pelagic ooze sedimentation will normally not exceed 0.03 m/ka, although under upwelling areas it may reach 0.1 m/ka (10^{-1} m/ka). Resedimentation of material to deeper water results in accumulation rates on modern deep-sea fans from 0.1 to 2 m/ka, and up to 10 m/ka (10^{-1}–10^1 m/ka) in small tectonically active basins.

8.8 Implications of Missing Time for Modern Stratigraphic Methods

8.8.1 Sequence Stratigraphy

It has been reasoned that sequences are scale independent. Catuneanu (2006, p. 10) argued this point, citing the observations by Posamentier et al. (1992) on a small delta only 1 m across that was observed building into a pool of water from a gully, where every sequence process associated with base-level change and systems tract development could be observed on a tiny scale. Paola et al. (2009) also argued this point, suggesting that their scaled laboratory experimental systems run over periods of seconds to hours in a tank a few meters across could legitimately be interpreted to explain geological-scale processes in major sedimentary basins.

Fragmentary the stratigraphic record might be, but as the construction of the Devil's staircase (Fig. 8.7) indicates, the fractal nature of the record means that it consists of intervals of succession fragments separated by larger gaps that developed at higher time scales. These larger gaps can legitimately be considered as the sequence boundaries. Several decades of analysis have now indicated that there is a limited number of sequence types, which develop because of the occurrence of particular allogenic processes that are characterized by particular time scales (Miall 1995a, 2010). These natural time scales, because of their predominance, tend to lead to enhanced preservability, and it is for this reason that sequence stratigraphy "works." The original concept of a sequence hierarchy—the five or six "orders" of Vail et al. (1977) has been shown to be unworkable (Schlager 2004), but a crude hierarchy does exist, based on the nature of the processes that develop sequences, which range over time scales from 10^4 to 10^8 years (Table 3.3; Miall 1995a, 2010, Table 4.1).

8.8.2 Implications for Stratigraphic Continuity, the Concept of Correlation and the Principal of the GSSP

The discipline of stratigraphy is dependent on the principle that the sedimentary record is amenable to dating and correlation. The thrust of this chapter has been to demonstrate the fragmentary nature of the stratigraphic record, whereas the existence of the property of correlatability—which has been amply demonstrated by two hundred years of stratigraphic practice, implies continuity. There is no contradiction here. Consider the evolution of time at *SRS 1*, the present moment. At this time more than half of the Earth's surface is under water and accumulating water-laid deposits in fluvial and marine environments, or otherwise in a condition which is favourable to instantaneous sediment accumulation, e.g., the migration of an eolian dune, or alluvial fan deposits banking up against a fault. Therefore there are countless locations where the deposits that could constitute a future GSSP for "Now" are accumulating. Many of these will survive the rigours of *SRS 2* to *10*, *11* or *12* (depending on tectonic location) to provide the framework for the correlation of "Now" at some distant point in the future. This work of the geological preservation machine is all that stratigraphers have ever assumed and depended upon. However, as Smith et al. (2015) have pointed out, most of the officially ratified GSSPs that currently form the basis of the Geological Time Scale are defined in shallow-marine strata, where there is a high probability of multiple hiatuses and significant missing time.

8.8.3 Discussion

It has long been known that the sedimentary record is fragmentary. However, this has not stopped stratigraphers from making calculations about sedimentation rates and the ages of key beds, based on assumptions of continuous sedimentation and extrapolation from known horizons. For example, the study of cyclostratigraphy requires the conversion of the "depth domain" to the "time domain" using age calibration points (Strasser et al. 2006, p. 82). This type of analysis should always be treated with considerable caution, and the arguments presented here only serve to emphasize this point. This could be argued before on an ad hoc basis, but not until the advent of the fractal concept has it been possible to systematize these observations and place them into a framework that suggests a continuity of process over all time scales. The fractal framework constitutes a useful method of statistical description of the geological preservation machine, but because the time frames of geological processes are not genetically related, there is no reason to expect that the framework will constitute anything other than a mathematical approximation. Accordingly, it may be more appropriate to describe the relationships as "fractal-like."

The significant differences highlighted in this chapter between (1) the preservation of the products of modern sedimentary processes, (2) those preserved in the recent (post-glacial) record, and (3) those preserved in the more ancient record, indicate the need for a modified use in geological work of the concepts of *uniformitarianism*, hence the title of the paper from which this section has been adapted (Miall 2015). The same applies to the comparable term "*actualism*", which is "the principle that the same processes and natural laws applied in the past as those active today" (Donaldson et al. 2002). With the exception of some unique conditions in the Precambrian relating to marine and atmospheric chemistry (Eriksson et al. 1998), the *processes* of sediment creation have been comparable throughout geological time. It is the issue of *preservation* that has required a reevaluation. Interpretations of the geological record that use modern, active, post-glacial depositional systems as analogues (e.g., deltas, valley-fills, prograding continental margins) need to take into account that these deposits can only illustrate the working of the geological preservation machine up to the time scale of *SRS 7* or *8* Fig. 8.10). Application of uniformitarianist concepts to the longer-term geological time scale (*SRS 9-12*) needs to be carried out with these cautions in mind. In this sense, the concept of uniformitarianism, as applied in practice, is incomplete.

These concepts likely hold a key to an improved way of studying and interpreting the sedimentary record, requiring us to go back and look at that record again, ironically, to document what is not there in greater detail: the record of missing time. Sedimentary units at all scales need to be evaluated in terms of the sedimentation rates they indicate over the full range of scales, at the appropriate *SRS*, in order to unravel the complexity of preservation and removal. De Natris (2012) and de Natris and Helland-Hansen (2012) have made a start at this form of analysis. Amongst other consequences, this research will re-emphasize the value of the "mesoscale" experiments described by Paola et al. (2009). For example, he and his colleagues have demonstrated that incised valleys formed by shoreline incision and fill during cycles of base-level change do not represent single chronostratigraphic surfaces (as commonly assumed for the purpose of sequence definition) but represent amalgamated fragments of surfaces and deposits that evolve both during falling and rising stages of the base-level cycle (Strong and Paola 2008). The experiments of Sheets et al. (2002) provided a quantitative basis for the transition from an autogenic to an allogenic time scale in the gradual filling of an alluvial-deltaic basin by avulsive switching of channel belts. All of these findings will help to clarify the concepts of time and the behaviour of the geological preservation machine.

Quantitative stratigraphic studies (e.g., those based in time-series analysis) are becoming increasingly popular. However, lest the new fractal concepts tempt geologists to focus in future on quantitative studies based on fractal theory, the warning of the field sedimentologist needs to be heard. Quantitative analyses too frequently ignore the field reality of the rocks under study (e.g., see Sect. 8.11). Without careful analyses of facies details, a careful search for grain size and lithologic changes, and a focus on the nature of facies contacts (sharp versus transitional), researchers can mistake mathematical or statistical rigour for geological reality.

The examples used here to illustrate the *Sedimentation Rate Scales* merely brush the surface of a potentially instructive form of deductive investigation in which tectonic and geomorphic setting, sedimentary processes and preservation mechanisms can be evaluated against each other both qualitatively and quantitatively, leading to more complete quantitative understanding of the geological preservation machine, and a more grounded approach than earlier treatments of stratigraphic completeness. For example, wide variations in sedimentation rate in foreland basins, and in continental margin sedimentation have been touched on here, and may help to refine future geological interpretations. Once tectonic setting is taken into account, the variability in the data in Sadler's (1981, 1999) linear log-log plot become comprehensible. When accommodation generation is particularly rapid, as in many convergent-margin settings, and where accommodation is essentially limitless, as on continental margins, and sedimentation is supply-dominated,

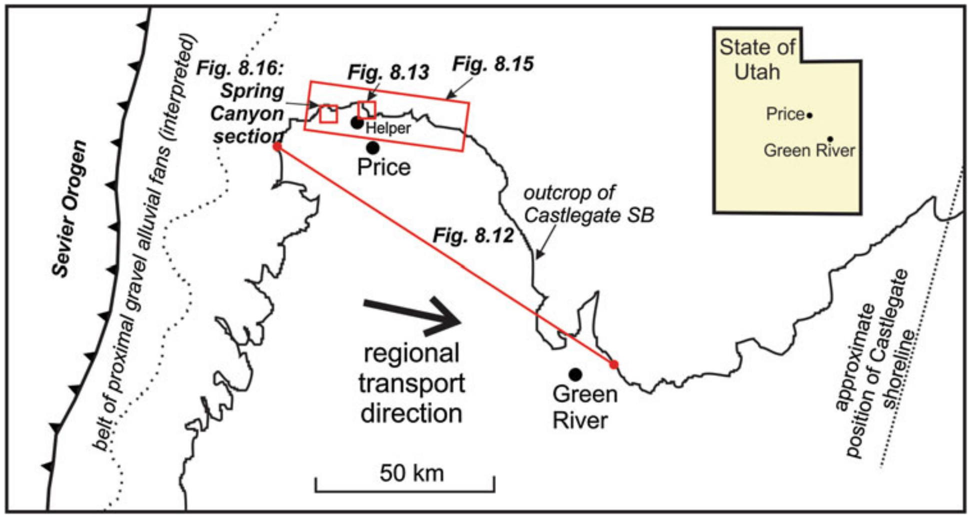


Fig. 8.11 Location of the Book Cliffs study area, showing the locations of detailed sections and other illustrations

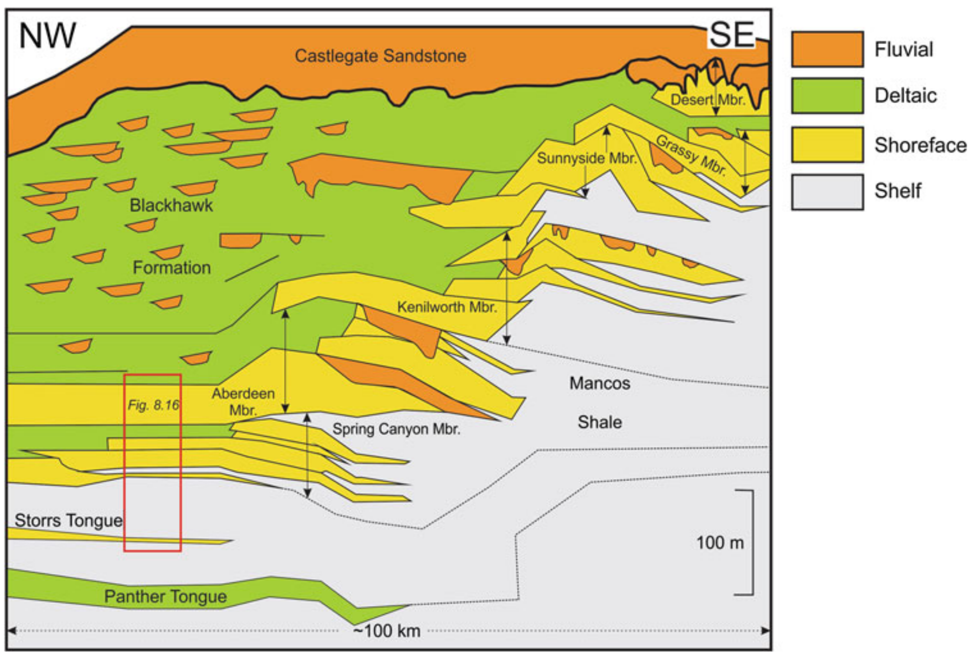


Fig. 8.12 Regional cross section of the Mesaverde Group. Adapted from Seymour and Fielding (2013), after the detailed mapping of Young (1955)

long-term sedimentation rates may be one to two orders of magnitude greater than Sadler's compilation would suggest. Sediment flux may be relatively constant over a wide range of time scales (Sadler and Jerolmack 2012, 2015), but processes of sediment distribution, sedimentation and preservation "shred" the resulting record, as explained in this chapter. We return to this debate in Sect. 8.10.2, which is a discussion of the construction and interpretation of chronostratigraphic charts (Wheeler diagrams) for stratigraphic successions.

It is now clear that the stratigraphic record is more than just incomplete. To extend Ager's famous thought: there are gaps within the gaps, and the record is permeated with them, at every scale. The frozen accidents that the gaps enclose can still tell us a great deal, but only if we get the time scale right.

8.9 An Example of the Evaluation of Missing Time: The Mesaverde Group of the Book Cliffs, Utah

The Mesaverde Group is well exposed in the Book Cliffs of east-central Utah and western Colorado. It constitutes a classic foreland-basin clastic wedge, which developed in response to uplift and erosion along the Sevier Orogen during the Late Cretaceous. A resistant nonmarine sandstone, the Castlegate Sandstone, constitutes a prominent cliff-forming unit that caps the cliffs over a distance of about 200 km (Figs. 8.11 and 8.12).

The stratigraphy of the group was mapped in detail by Spieker and Reeside (1925) and by Young (1955, 1957). In the 1990s these rocks served as one of a set of worked examples used to explain the principles of sequence stratigraphy (Van Wagoner et al. 1990; Van Wagoner and Bertram 1995), and largely because of this work the area has been a favorite destination for field trips by academic and corporate groups (e.g., Cole and Friberg 1989; Van Wagoner et al. 1991).

In more recent years the Mesaverde Group has become the focus for examinations of many concepts about stratigraphy and sedimentation. The most detailed treatment, in which the author explored many quantitative models concerning sedimentation in an ancient foreland basin, was provided by Hampson (2010). However, the issue of fragmentary preservation of the record has not been discussed. This is not an inconsequential issue because, as the work of Hampson (2010) exemplifies, the stratigraphic and sedimentologic detail that are now available for the Mesaverde Group are amongst the most extensive available for clastic wedges of this type, and the unit should, therefore, provide an ideal test bed for the exploration of advanced sedimentological concepts. Amongst the few workers who have addressed the issue of missing time in the Mesaverde Group, and speculated about its implications for correlations and sequence stratigraphy, are Howell and Flint (2003), who reviewed the chronostratigraphy of the succession and the presence of gaps at the parasequence scale, and Bhattacharya (2011), who discussed alternative sequence models for the Castlegate Sandstone. The discussion presented here was first published in Miall (2014b).

Fig. 8.13 View from Helper of a portion of the Mesaverde Group

8.9.1 Chronostratigraphy of the Mesaverde Group

The Mesaverde Group of the Book Cliffs encompasses two formations, the Blackhawk and the Castlegate. The Blackhawk Formation consists of undifferentiated fluvial, shoreface, and deltaic deposits in the western Book Cliffs (Hampson et al. 2013), and passes eastward into a series of shoreface to shallow-marine tongues that were assigned to six members by Young (1955) (Fig. 8.12). The shoreface sandstones constituting the thicker, proximal portions of these members form a series of cliffs (Fig. 8.13), the appearance of which, from a distance, is what suggested to early explorers the pages of a book lying on its side; hence the name Book Cliffs.

As summarized by Hampson (2010), the six members of the Blackhawk Formation have now been subdivided into a total of 23 submembers. The first sequence-stratigraphic studies of these rocks interpreted them as the product of eustatic sea-level change (Van Wagoner et al. 1990), but these units have subsequently been much discussed as examples of a type of high-frequency sequence stratigraphy controlled by regional tectonism and its effect on accommodation (e.g., Krystinik and de Jarnett 1995; Hampson 2010; Aschoff and Steel 2011).

The Castlegate Sandstone, named after the Castle Gate, a prominent landmark in the Price River Canyon north of Helper, was interpreted as a third-order sequence by Olsen et al. (1995), but comprises two sequences, according to Miall and Arush (2001a), although, as suggested by Bhattacharya (2011), and as discussed later, other interpretations must be considered.

The age range of the Mesaverde Group and its constituent units has been interpreted primarily from the ammonite fauna contained in the marine portions of the Blackhawk and in the Mancos Shale, with which it is interbedded to the east. Howell and Flint (2003), Hampson (2010), Aschoff and Steel (2011), and Seymour and Fielding (2013) provided overviews of the biostratigraphic and other work that has been carried out on these rocks since mapping began in the 1920s. Three of the ammonite zones can be correlated to the global time scale, providing numerical-age tie points. The following data are taken from Aschoff and Steel (2011).

The base of the Blackhawk Formation is Lower Campanian in age, and is dated at 81.86 Ma. The top is placed at 79 Ma, and the top of the Castlegate is Middle Campanian, at 77 Ma. The time span of the Mesaverde Group is therefore 4.86 million years. Near Price the section is up to 700 m thick, which indicates an average sedimentation rate of 0.14 m/ky. This rate (10^{-1} m/ky) is at the upper end (more rapid) of rates characteristic of long-term geological subsidence measured over periods of 10^5–10^7 year, including thermal subsidence and flexural loading of the crust (*SRS 10-11*), and is comparable to rates associated with low-frequency orbital cycles (*SRS 9*) (Miall 2013). If all six members of the Blackhawk plus the two constituent sequences of the Castlegate Formation are assumed to represent equal time spans (for which there is no evidence), this equates to an average duration of 607 ky per unit, a value that corresponds to no known geological frequency. Furthermore, each of the members has now been subdivided into submembers, totalling 23 for the Blackhawk Formation (the individual shoreface tongues in Fig. 8.12), averaging 125 ky in duration. At this time there is no method by which the ages and time spans of the constituent units of the Mesaverde group may be individually dated with greater precision.

A comparison of Book Cliffs stratigraphy with that of the Henry Mountains area, some 200 km to the south of Prince (Seymour and Fielding 2013) indicates that there is no detailed correlation between the Blackhawk members and comparable units in that section. This, and the lack of spatial regularity of the Blackhawk members, argues against orbital cyclicity as a major mechanism for the generation of the members and submembers of the Blackhawk Formation.

Following what is essentially traditional practice, correlation diagrams for the Mesaverde Group, including chronostratigraphic charts, show the Blackhawk Formation and its constituent members as the product of continuous sedimentation (e.g., Hampson 2010, Figs. 2, 7; Aschoff and Steel 2011, Fig. 3; Seymour and Fielding 2013, Figs. 2, 7). That continuous sedimentation is unlikely is indicated by the large lateral shifts of proximal and distal facies and the facies contrasts across the sequence boundaries, which indicate significant changes in accommodation and/or sediment supply.

What now follows is speculative, representing an attempt to apply the *Sedimentation Rate Scale* concept to the Blackhawk formation. Following Sadler (1981, 1999), it may be suspected that the representation of elapsed time by the preserved record of this formation would be very low (cf. de Natris 2012). The log-normal distribution in time of sedimentation rates that was demonstrated by Sadler (1981, 1999) is likely paralleled by a log-normal distribution in the duration of sedimentary gaps. Miall (2015; Figs. 8.5 and 8.6 of this book) suggested that these distributions are fractal-like in character. A significant proportion of the elapsed time might, therefore, be represented by intraformational hiatuses, member and submember boundaries and other surfaces of erosion or nondeposition. There is little evidence of major erosion at the Blackhawk member or submember boundaries, except for

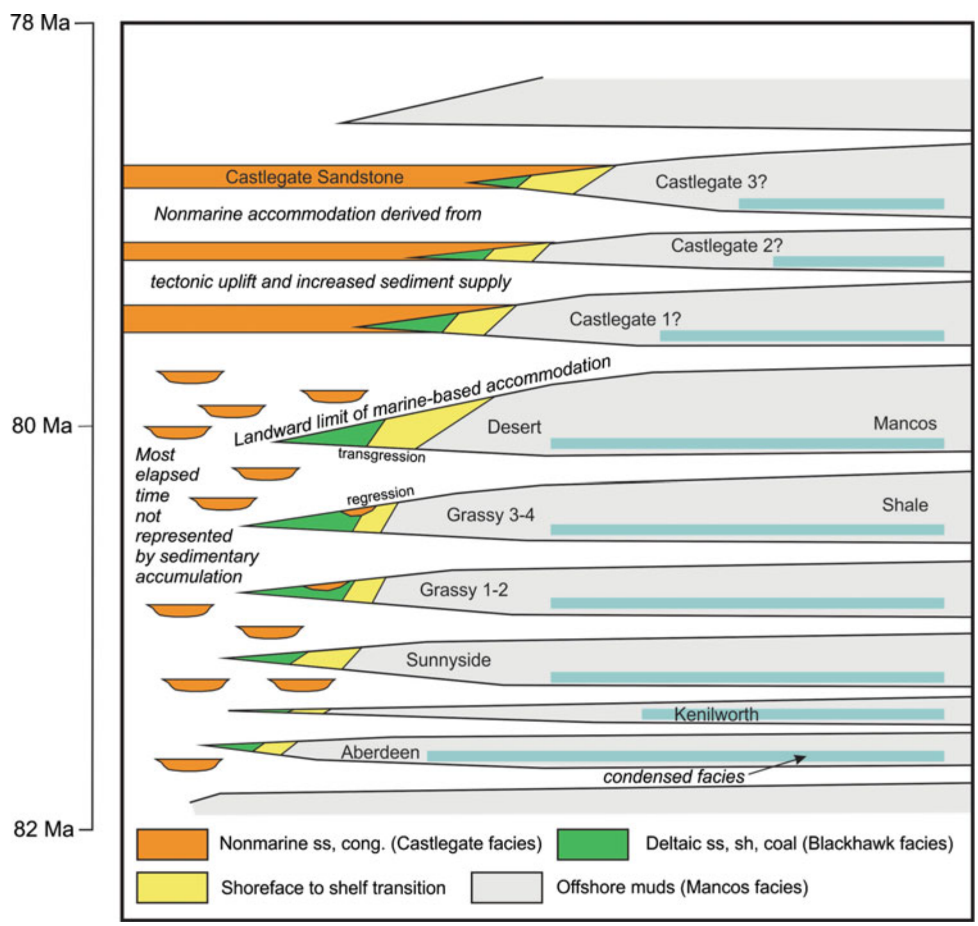


Fig. 8.14 An interpretation of the chronostratigraphy of the Mesaverde Group. Age information is from Hampson (2010) and Seymour and Fielding (2013)

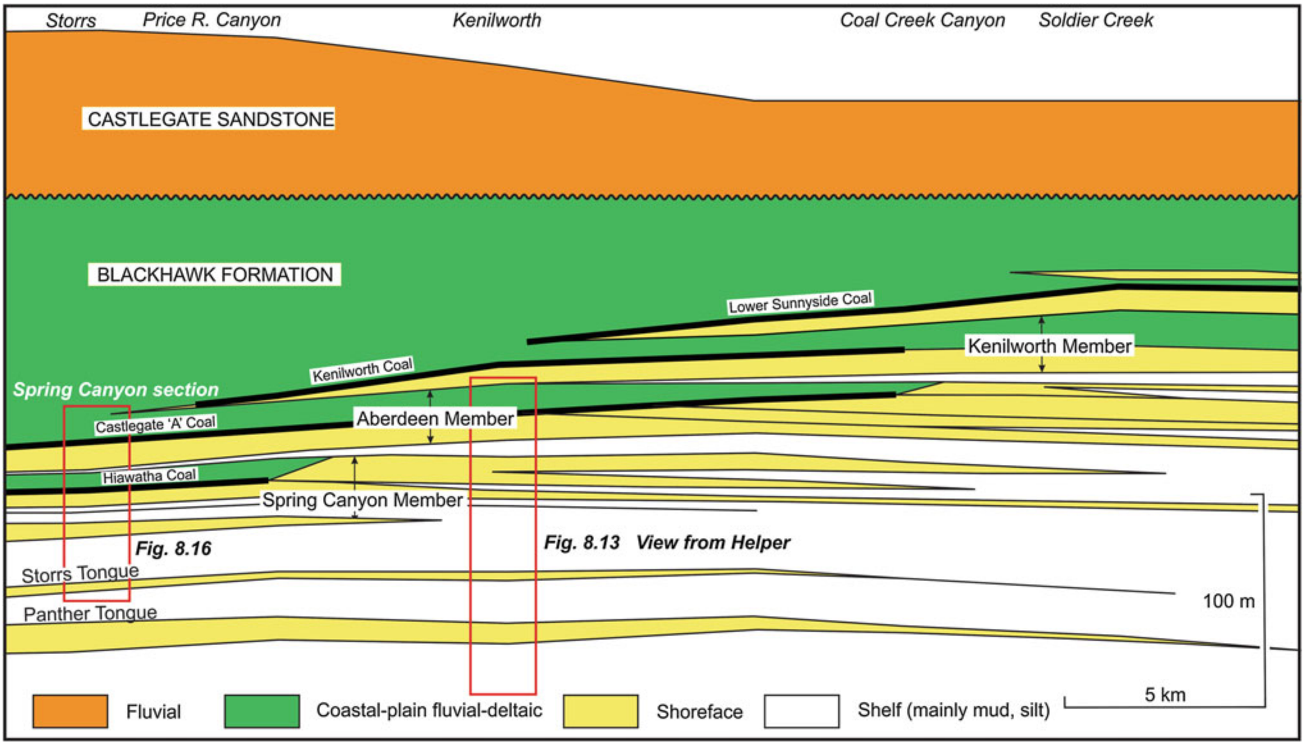


Fig. 8.15 Detailed stratigraphy and correlation of the Mesaverde Group in the western Book Cliffs. Based on Young (1955)

the rare presence of incised valleys that indicate erosion during the falling stage of the base-level curve at the end of each progradational episode. East of Green River, erosional relief at the base of the Desert Member reaches 30 m (Van Wagoner 1995, p. 151), and incised valleys at the top of the Grassy Member are up to 20 m deep (O'Byrne and Flint 1995, p. 242). It seems very likely that at least the member and submember boundaries represent significant breaks in sedimentation, with durations in the high 10^4-year to 10^5-year range. This is consistent with the pattern that emerged from a forward-modeling exercise by Howell et al. (1999). As a preliminary model, the six member boundaries are set here arbitrarily so that the preserved sedimentary record represents a total of approximately half of the elapsed time, with an average sedimentation rate for the preserved deposits of 0.29 m/ky. Sediment bypass, with sedimentation taking place by lateral progradation of shelf clinoforms, may explain much of the time "missing" through any given vertical section.

This rate is comparable to that of deposits measured at the *SRS 8* time scale of 10^4–10^5 years, including the late Cenozoic glacioeustastic cycles of the Wanganui Basin in New Zealand and the Triassic Newark cycles of the eastern United States (details for all these comparative rates are, unless otherwise stated, provided in Miall 2015).

A speculative chronostratigraphic chart for the Mesaverde Group that includes the suggestion of significant gaps at the sequence boundaries is presented here as Fig. 8.14. This follows the approximate timing of the sequence boundaries shown by Hampson (2010, his Fig. 7), but otherwise differs substantially from that chart in the following principal ways: (1) in the updip coastal-plain region represented by the Blackhawk Formation, most of the elapsed time is completely unrepresented. Some of this unit consists of fluvial deposits formed above marine base level (Hampson et al. 2013) and here, accommodation can be explained by the buffer concept of Holbrook et al. (2006), as discussed later. These deposits are shown schematically in Fig. 8.14. (2) The arrangement of sequence boundaries in Hampson's (2010, Fig. 7) chart suggests that the completeness of the Blackhawk and the contemporary shallow-marine record (that of the Blackhawk members) decreases basinward, whereas the opposite is more likely to be the case. Sedimentation of the Mancos Shale towards the basin center is likely to be much more continuous and therefore more complete at the 10^4–10^6 time scale than the proximal sediments of the coastal region, but may contain substantial disconformities, as shown in Fig. 8.14. The pattern shown here in Fig. 8.14 is more like that developed by Krystinik and DeJarnett (1995, Fig. 3), in which it was suggested that the proximal region to the west of the basin was a region of uplift and erosion. Units of condensed (slow) sedimentation may be expected to develop offshore at times of regional transgression, and there is also evidence that sediment gravity flows occurred on distal clinoform slopes during the falling stage of some of the sequence cycles (Pattison 2005; as shown by Hampson (2010, his Fig. 7), but not included in Fig. 8.14 of this book). (3) Following from the previous point, the time span represented by the member (sequence) boundaries increases landward, and the undifferentiated proximal, deltaic Blackhawk formation represents, in total, much less than one half of the available elapsed time, with substantial erosional breaks embedded in this coastal succession.

8.9.2 Chronostratigraphy of the Spring Canyon and Aberdeen Members

The next step in this analysis is to examine sedimentation rates and preservation at shorter time scales. *SRS 7* is the time scale for long-term geomorphic processes, those occurring over time periods of 10^3–10^4 years. Such processes include the development of major delta lobes and alluvial channel belts, regressive shoreface complexes, major coal seams, etc.

Sedimentation rates that have been calculated for such deposits include the following examples of post-glacial successions (details in Sect. 8.4): Fluvial channel aggradation in coastal-plain rivers in Texas, up to 1.7 m/ky; modern floodplain rates compiled by Bridge and Leeder (1979) as the basis for their simulation experiments, 0.35–2 m/ky; the Holocene Mississippi Delta, 6–12 m/ky; Rhone delta, 6.1 m/ky; Rhine-Meuse system, 1.5 m/ky; Galveston barrier island, 3.4 m/ky; Sapelo Island tidal inlet, 4.5 m/ky. The rate of post-glacial sea-level change is comparable, at 1–18 m/ky. All of these rates are in the range of 10^0–10^1 m/ky, which is up to an order of magnitude greater than the *SRS 8* range, which applies to high-frequency orbital cycles, and up to two orders of magnitude greater than long-term geological rates (*SRS 11*).

To study sedimentation at this scale, a more detailed examination is presented here of the Spring Canyon section, located west of Helper (location shown in Fig. 8.11). The stratigraphic framework of this section is shown in Fig. 8.15, and the section is illustrated in Fig. 8.16. The section is shown in Fig. 8.16 in the traditional form, as a continuous succession of facies units, just as it appears in actuality in the field. However, as first pointed out by Barrell (1917), this

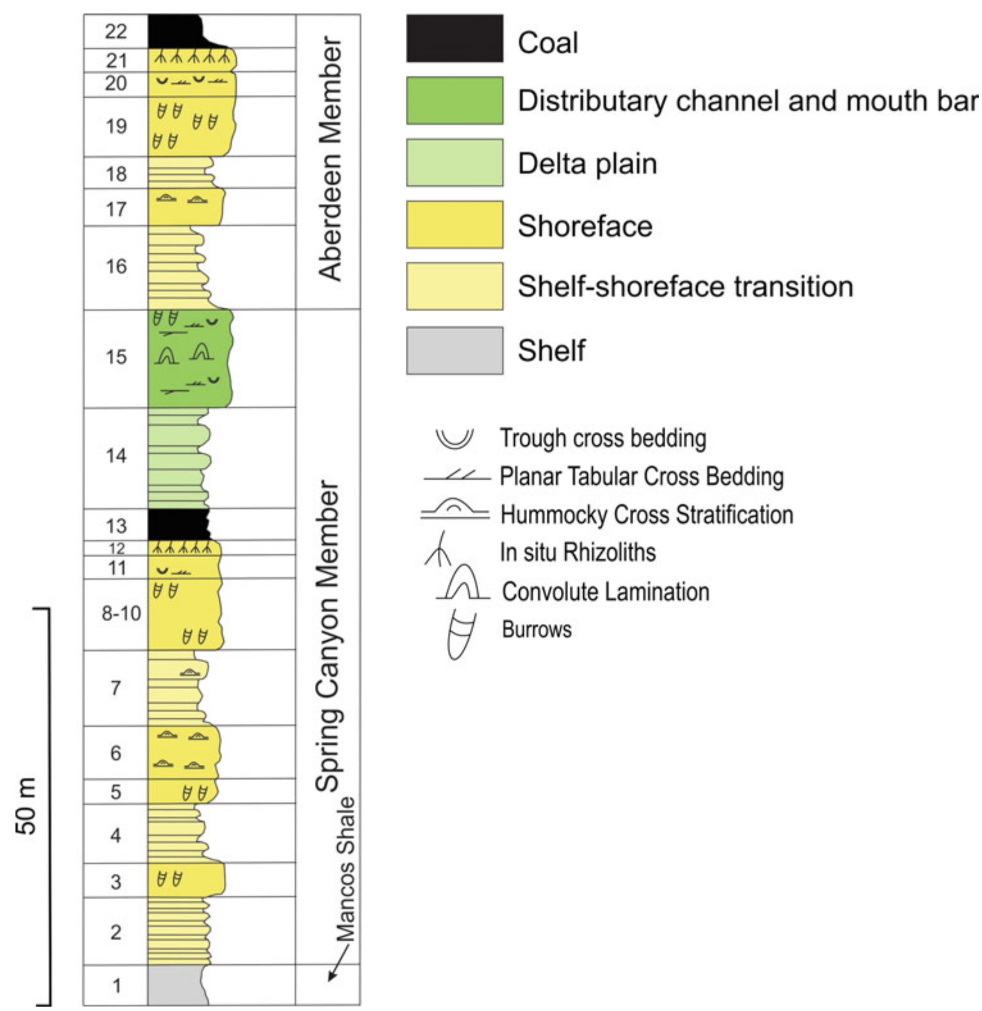


Fig. 8.16 The section at Spring Canyon. Based on Cole and Friberg (1989) and Kamola and Van Wagoner (1995). The section is subdivided into 22 lithofacies units, as numbered at *left*

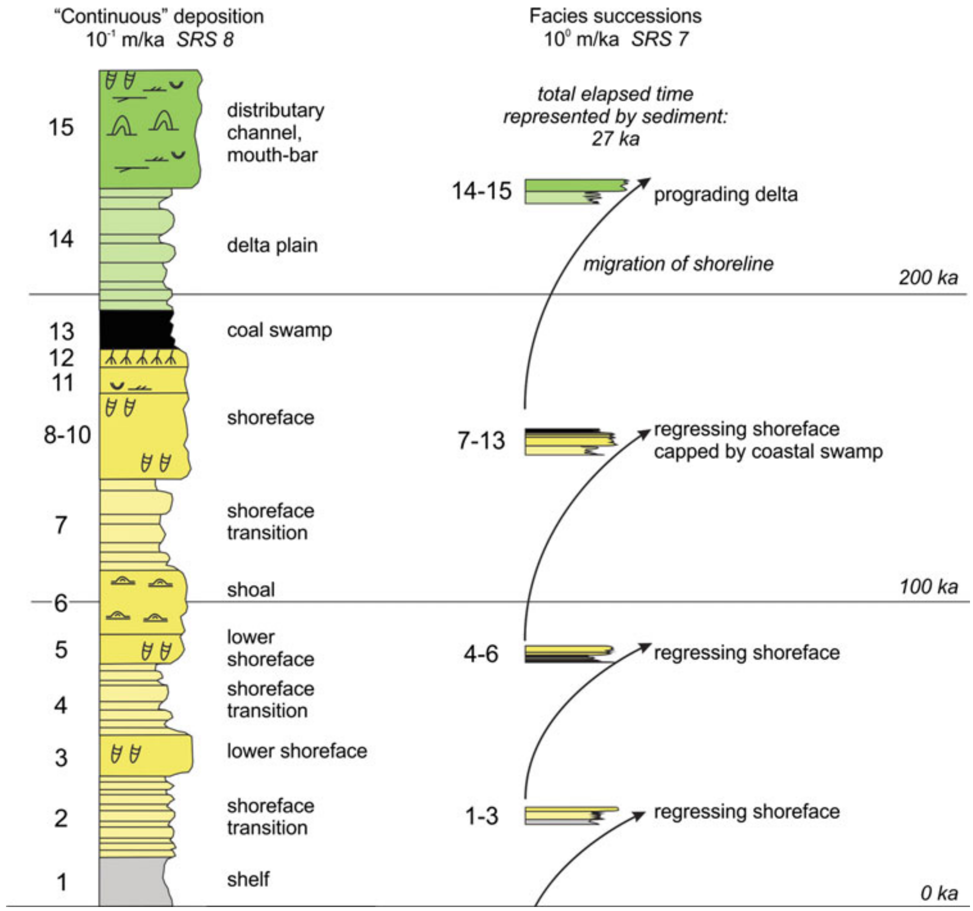


Fig. 8.17 The Spring Canyon Member dismembered. Bed unit numbers are as in Fig. 8.16. At *left*, the section is plotted to correspond to a *SRS 8* time scale, suggesting an approximate 273 ky timespan for the accumulation of the succession. At *right*, the same section is evaluated in terms of an *SRS 7* time scale, for which sedimentation rates are an order of magnitude more rapid. The section is subdivided into a set of progradational coastal-plain and shoreface successions

form of plot obscures the numerous cryptic hiatuses that permeate all stratigraphic sections.

In Fig. 8.17 units 1–15 of the same section are plotted against an *SRS 8* time scale. At the *SRS 8* sedimentation rate of 0.29 m/ky employed in the previous section, the 79.2 m of Spring Canyon section (units 2–15) shown in this figure would represent 273 ky of elapsed time. The same fifteen units are shown at the right re-plotted using *SRS 7* rates. At an *SRS 7* sedimentation rate range of 1.5–6 m/ky, this 79.2 m of section would accumulate over a time span of between 52.8 and 13.2 ky. A mid-range of 27 ky used here (arbitrarily) as an average for illustration, is one tenth the time assumed for the sequences timed at the longer-term *SRS 8* rate in the previous section (and comparable to the 7 % of elapsed time represented by sediment that was calculated by de Natris 2012). How is preservation and non-preservation distributed through the estimated 273 ky represented by the section?

As suggested in Fig. 8.17, and following all previous interpretations, the section can be interpreted in terms of four progradational successions, or parasequences. Using the same lithofacies unit numbers as in the original section, these are displayed at the right in this figure. Three regressive shoreface successions, the last capped by a coal swamp (unit 13 is the Hiawatha coal), were followed by a progradational delta.

Figure 8.17 provides an illustration of the problem that sedimentologists have yet to address fully, that of the lengthy periods of empty time, time for which there is no sedimentary record within apparently continuous successions. For example, Hampson's (2010) detailed examination of the clastic wedge includes an analysis of the trajectory of shorelines in time and space through the evolution of the Mesaverde Group. The outcome of the analysis (Hampson 2010, his Fig. 14) is displayed in the form of a height-versus-distance diagram that provides quantitative estimates of forestepping (progradation) and backstepping (flooding) and is interpreted in terms of changing bathymetry and sediment supply in the basin as the succession gradually prograded eastward across the foreland basin. The analysis is keyed to the evolution of the Blackhawk and Castlegate members, but timing is not discussed beyond the labelling of each eastward movement in the shoreline with the name of the appropriate prograding submember. However, the plotting of the trajectory as a continuous zig-zag line implies continuity, and does not include the possibility that the shoreline may have regressed entirely across the basin (leading to lengthy periods of exposure and erosion), even though this possibility is hinted at by the way his chronostratigraphic diagram is constructed (Hampson 2010, his Fig. 7), nor does the trajectory diagram provide any indication of the point argued in this section, that there were lengthy periods of time for which we have no preserved record from which to construct such a diagram. This problem is addressed further in the next section.

8.9.3 The Representation of Time in a Coastal Clastic Succession

The Book Cliffs should offer an excellent opportunity to examine the problem of how time is represented in the sedimentary record, given the quality and completeness of the exposure and the amount of detail now amassed by recent field studies. However, having said this, they also exemplify the major problem with such analyses. The absence of any techniques for chronostratigraphic dating with a greater precision than a 10^6-year time scale means that all such analyses are speculative. Some of the key portions of the Spring Canyon section are illustrated in Fig. 8.18, and are discussed next.

The grouping of lithofacies units into progradational successions, and their interpretation in terms of the *SRS 7* time scale in Fig. 8.17, is based on the analysis of comparable successions, which accumulated over a similar time scale in the post-glacial record. As discussed elsewhere (Miall 2015) it is possible to extend such an analysis to a shorter time scale and correspondingly higher sedimentation rates. For example, each of the major units identified in the progradational shoreface successions illustrated in Fig. 8.18c, d consist, in turn, of thinner component units a few meters thick, or less, that can be interpreted by comparison with modern shoreface successions that accumulate from individual storm events or by fair-weather aggradation over periods of a few years to a few hundreds of years (*SRS 5, 6*). Episodes of non-deposition or bottom storm scour

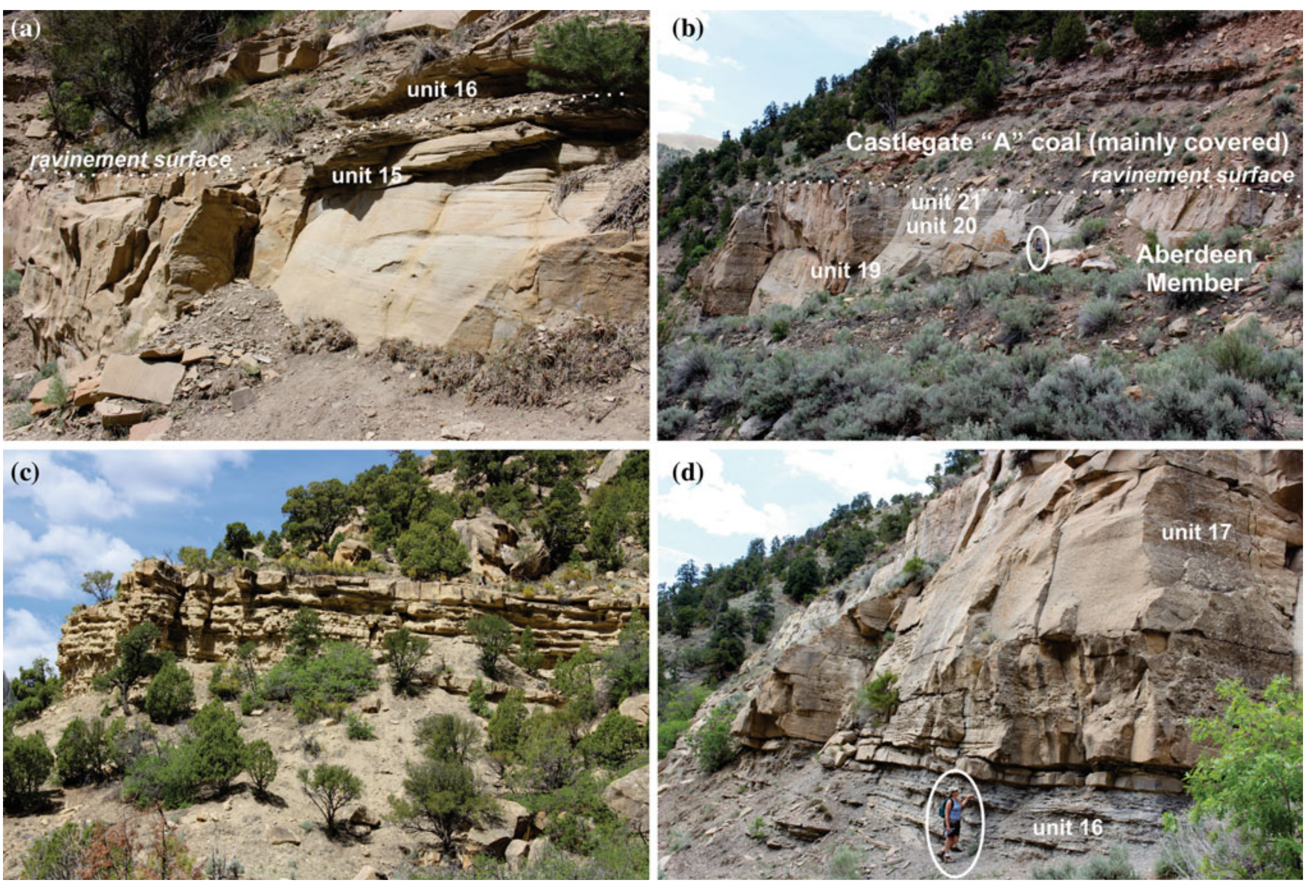


Fig. 8.18 **a** The top of a distributary-channel and mouth-bar complex that forms the top of the Spring Canyon member. Unit 15 is 12 m thick. **b** The top of the Aberdeen member, consisting of a shoreface to foreshore complex. Person for scale. **c** The Storrs Tongue, a shoreface succession 9 m thick exposed at the base of the Spring Canyon section. It is capped by a ravinement surface. **d** A shoreface-transition to lower-shoreface succession that forms the base of the Aberdeen Member. Person for scale. Unit numbers for **a**, **b**, and **d** are as in Fig. 8.16

appear as distinct bedding surfaces in these outcrops, but their time significance, which could be considerable ($10^0 - 10^3$ years), is cryptic.

At the *SRS 7* scale, the most significant time-related events represented in the Spring Canyon outcrops are the ravinement surfaces that cap the shoreface successions (Fig. 8.18a–c), and include the surfaces that cap each of the Blackhawk constituent members. Ravinement occurs during a rise in relative sea level. Nummedal and Swift (1987), in their original definition of this process, described various examples of ravinement developed during post-glacial sea-level rise, a process that during the Holocene, continued for thousands of years. We cannot know the duration of this process during the Cretaceous, but we can speculate. The driving process for episodicity in stratigraphic accommodation seems likely to include flexural subsidence and changes in intraplate stress (Miall 2010; Aschoff and Steel 2011). These are processes that operate over rates and time scales in the *SRS 8-9* range, that is, time periods of 10^4–10^6 years. It is conceivable, therefore, and consistent with the interpretations of Howell and Flint (2003), that lateral clinoform progradation and the subsequent flooding and ravinement that preceded each of the progradational shoreface successions could have taken many tens of thousands of years, a significant proportion of the time available for each of these cycles.

Would it not be expected that there would be more evidence of such significant episodes in the development of the clastic wedge? Not necessarily. Ravinement is an erosional process and may cut down through significant thicknesses of shelf and shoreface deposits. Complete removal of contemporary deposits emplaces the post-ravinement shelf deposits over the eroded top of the preceding cycle, and in that case the ravinement surface corresponds to the sequence boundary (Nummedal and Swift 1987). There are many examples of such configurations now described in the literature. One of the first was the description of the E/T surfaces in the Cardium Sandstone of Alberta by Plint et al. (1986). When first proposed, the sequence interpretation was highly controversial, and one of the reasons for this was the implication that basin-wide sequence boundaries extending for hundreds of kilometers could be accompanied by little to no evidence of the elapsed time, and of the depositional and erosional events that must have transpired during their formation and subsequent burial. Draping the transgressive surfaces in some places are beach conglomerates, which the model indicates were transported there initially by fluvial processes from the basin margin hundreds of kilometers away during the falling stages of the base-level cycles. But the evidence for such rivers, in the form of remnant valleys and fluvial deposits draping the surfaces, is almost entirely absent.

Likewise in the Blackhawk Formation the ravinement surfaces could represent periods of up to 10^5 years, with all evidence of basin-margin exposure and the basinward transport of continental detritus long gone, except for the rare presence of incised valleys at the tops of the members, as noted above. Hampson (2010, p. 107) refers to paleocurrent data in the shoreface sandstone indicating “persistent longshore currents” directed towards the south and southwest. These could have been the currents that removed the evidence of long-lasting episodes of exposure and of ravinement erosion. Some of this detritus may have contributed to the contemporaneous Muley Canyon and Masuk formations in the Henry Mountains area to the south (Seymour and Fielding 2013), although longshore drift is not described by these authors.

8.9.4 Sequence Stratigraphy of the Nonmarine Facies of the Blackhawk Formation and Castlegate Sandstone

The first sequence-stratigraphic analysis of the Castlegate Sandstone was carried out by Olsen et al. (1995). They divided the formation near the type section (Castle Gate, at the mouth of the Price River Canyon, north of Helper; location shown in Fig. 8.19) into a lower, sandstone-dominated member, deposited in a braided-stream environment, following the fluvial architectural analyses of Miall (1993, 1994), and an upper member containing a significant proportion of interbedded mudstones, units of inclined heterolithic strata (terminology of Thomas et al. 1987), and evidence of marine, tidal influence in the form of flaser bedding and *Skolithos* burrows. They interpreted the formation thus subdivided as a “third-order” sequence. To explain the subdivision into the two members Olsen et al. (1995) turned to the fluvial models of Wright and Marriott (1993) and Shanley and McCabe (1994). The sandstone-rich lower member and the more heterogeneous upper member were interpreted, respectively, as low- and high-accommodation systems tracts. Miall (2014a, Sect. 6.2) has argued that such interpretations are untenable, given the issue of dramatically different sedimentation rates for the models and for the Castlegate Sandstone.

In a further analysis McLaurin and Steel (2000) subdivided the upper member into five higher-order (fourth-order) sequences and mapped a transition within these sequences between the fluvial deposits in the west into barrier, deltaic, and estuarine deposits near Green River, and ultimately into the offshore mudstones of the Buck Tongue. However, Willis (2000), who recognized a high-frequency sequence stratigraphy in the Sego Sandstone east of Green River, was unable to trace these sequences westward into the predominantly fluvial upper Castlegate Sandstone.

In an alternative analysis based on detailed mapping north of Green River, Yoshida et al. (1996), Willis (2000), and

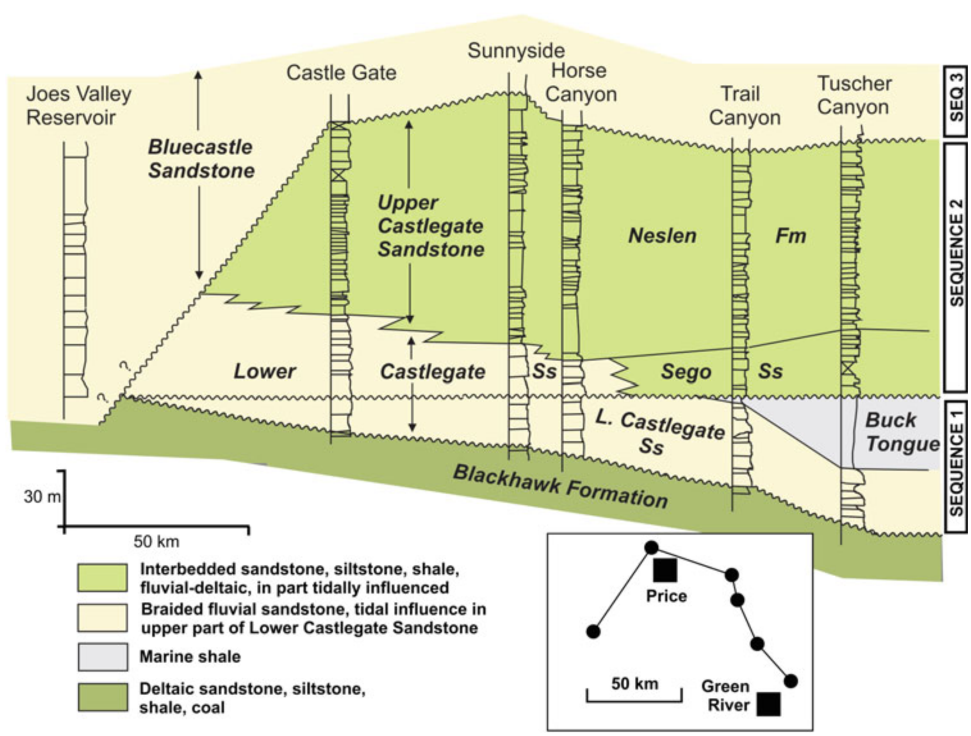
Yoshida (2000) argued that the Buck Tongue is truncated by the upper member of the Castlegate, at an angular unconformity that cuts gradually down section along the Book Cliffs to the northwest. According to this interpretation (shown in Fig. 8.19) the beds overlying the unconformity above the Buck Tongue in the east (Sego Sandstone) are stratigraphically equivalent to the upper part of the lower Castlegate Sandstone at the type section. As noted by Miall and Arush (2001a), based on this interpretation, the truncation of the Buck Tongue implies that updip from the pinch-out of this unit, approximately 1 million year of section is missing in proximal parts of the Book Cliffs, including at the type section of the Castlegate Sandstone.

The evidence to enable a choice to be made for any of these interpretations depends on the ability to trace ("walk out") key surfaces between sections. Even in the case of the Book Cliffs, where exposure is much better than average, it is not possible reliably to trace key surfaces based on facies and outcrop characteristics for long distances within what is a very heterogeneous succession. Accordingly, Miall and Arush (2001a) sought to develop other means to analyze the stratigraphy and determined, on the basis of petrographic evidence, that the best evidence for missing time at the type section consists of changes in detrital composition and evidence for early cementation at surface "D" in the type section (Fig. 8.20). According to this interpretation, the lower Castlegate at this location comprises parts of two sequences (sequences 1 and 2 in Fig. 8.19), and the upper part of this unit at the type section passes laterally (downdip) through a facies transition into the more heterogeneous beds of the upper Castlegate and the Sego Sandstone to the east and southeast (Willis 2000).

Yet another interpretation of Castlegate sequence stratigraphy was offered by Bhattacharya (2011, his Fig. 17), in which he speculated about the relationship between the lower Castlegate Sandstone and the underlying Desert Member in the area east of Green River. The original interpretation of Van Wagoner et al. (1990) and Van Wagoner (1995) was that the Desert Member is entirely older than the Castlegate. However, Bhattacharya (2011), referring to a discussion by Van Wagoner (1995) about the whereabouts of the coastal marine equivalents of the Castlegate fluvial sandstones (i.e., where are the mouths of the Castlegate rivers?), suggested that the Castlegate may in fact comprise a suite of high-frequency sequences, each with its own attached "Desert" shoreface (Bhattacharya, 2011, his Fig. 18). Again, this is a debate that could be answered only by detailed local correlations for which the evidence is not available, and a definitive answer is beyond the scope of this discussion to provide. However, we can speculate. It is entirely possible that the Castlegate Sandstone consists of a set of sequence fragments, number unknown.

Turning to the Blackhawk Formation, Hampson et al. (2013) documented the changes in fluvial style through the Blackhawk Formation in the proximal part of the Book Cliffs, west of Price, where the formation is not differentiated into members (see Fig. 8.12). Detailed reconstructions of alluvial architecture revealed a range of fluvial styles

Fig. 8.19 Stratigraphy of the Castlegate Sandstone (from Miall and Arush 2001a; based on Willis 2000, and Yoshida 2000)



throughout the Blackhawk Formation but no systematic changes with stratigraphic position. They also made reference to earlier studies (Adams and Bhattacharya 2005; McLaurin and Steel 2007) which demonstrated no systematic variation in fluvial style through the overlying sequence boundary into the Castlegate Formation. The conclusion of Hampson et al. (2013, p. 166) is that the "internal architectures of the sandbodies do not result from systematic, short-term changes in accommodation such as those that characterize incised-valley fills formed by relative sea-level change in coastal-plain settings" but they "appear to reflect local changes in the balance of sediment flux and transport capacity due to upstream controls, such as high-frequency climatic variations, and autogenic responses." As noted above, Miall (2014a, Sect. 6.2) has argued that the Wright and Marriott (1993) and Shanley and McCabe (1994) fluvial sequence models are not applicable to interpretations of fluvial sequences that represent long-term geological accommodation rates (*SRS 9-12*). The interpretations by Hampson et al. (2013, pp. 166–167) are consistent with the alternative explanations offered by Miall (2014a).

Preservation of a nonmarine deposit such as the Castlegate Sandstone and the nonmarine Blackhawk depends on a different set of controls than those that operate in marine environments. At time scales up to *SRS 7* or *8*, deposition and preservation are limited by the alluvial "buffer", in the sense described by Holbrook et al. (2006). The buffer is defined by two surfaces, one above and one below a river's graded profile. The lower surface corresponds to the maximum depth of scour, the upper surface to the maximum height to which the floodplain could accumulate fine-grained overbank sediment. Aggradation within this buffer zone will typically generate a fining-upward succession. The position of the buffer in space over time depends on long-term changes to the alluvial basin, including subsidence of the basin, and changes to the elevation of the source area, which, in turn, depend on the balance between tectonic uplift and erosion. Long-term preservation at *SRS 9-12* time scales requires that accommodation be generated rapidly enough that part or all of the buffer zone descends below the lower scour limit. This can happen either by basinal subsidence or by source-area uplift. Preservation of a complete buffer-zone succession will depend on such a succession being abandoned by changes in position of the channel belt for a long-enough time that it is not partly or entirely removed by erosion at a later time. Fragmentary preservation, typically of the lower portion of a buffer succession, will generally be the norm, and this will tend to favor the coarser, channel-fill parts of the succession unless increases in accommodation are unusually rapid. Variations between a succession dominated by the coarse (channel-fill) member and those in which significant thickness of floodplain fines are preserved may simply represent chance changes in erosion versus preservation of the buffer zone as alluvial systems migrate or avulse across an alluvial plain, or they may represent back-and-forth migration of facies belts in response to changes in paleoslope or sediment supply, as in the experiments performed by Strong et al. (2005). It has been a common misconception to interpret such changes in vertical profile only in terms of changing fluvial style (Miall 1980).

8.9.5 The Representation of Time in a Fluvial Succession

The largely unconsidered element in the preceding discussion is that of time. The 170 m of Castlegate Sandstone at the type section (Fig. 8.20) represents about 2 million years, at an average *SRS 9* sedimentation rate of 0.085 m/ky. However, shorter-term sedimentation rates reveal the extent of missing time in this section (Fig. 8.22). The 170 m of section at the type section, at a *SRS 7-8* sedimentation rate of between 10^0 and 10^{-1} m/ky, represents an elapsed time of between a minimum of 17 ky and maximum of

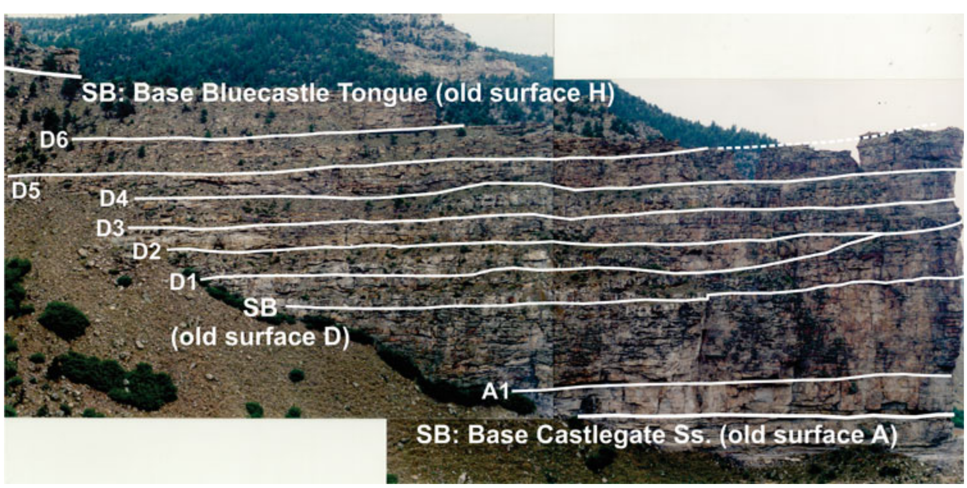


Fig. 8.20 The type section of the Castlegate Sandstone, with key bounding surfaces. Surface D of Miall and Arush (2001a). is tentatively identified as a major intraformational unconformity and sequence boundary. Width of field of view is about 250 m

1.7 million years. At an average rate of 0.29 m/ky, the same *SRS 8* rate used for the Spring Canyon Section in Fig. 8.17, the preserved sediment would represent an elapsed time of 586 ky. Many of the numerous well-developed near planar bounding surfaces visible in all Castlegate sections may account for significant time spans. Surface "D" provided some evidence of significant missing time, and was labelled a "cryptic sequence boundary" by Miall and Arush (2001a, b). As noted earlier, surface "D" at the type section could represent about half of the total 2-million years time span, or it is possible that this missing time is distributed through more than one of the prominent surfaces mapped at and near the type section (Figs. 8.20 and 8.21). Fragmentary preservation with more time missing than preserved as sediment seems the more likely scenario (and the same also seems more probable for the undifferentiated Blackhawk Formation). In Fig. 8.14 the Castlegate Sandstone is shown as a set of three superimposed units separated by significant time breaks, following the suggestion of Bhattacharya (2011), but other interpretations are possible.

Figure 8.22 represents a speculative attempt to account for the distribution of elapsed time between preserved deposits and bounding surfaces in the Castlegate Sandstone at the type section. At left is the sequence model of Olsen et al. (1995). The interpretation of the two-part succession in terms of low- and high-accommodation depositional environments is not consistent with the data now available on the relationship between channel migration and avulsion rates and rates of accommodation (Miall 2014a, Sect. 6.2). Fluvial sequence models, such as those of Wright and Marriott

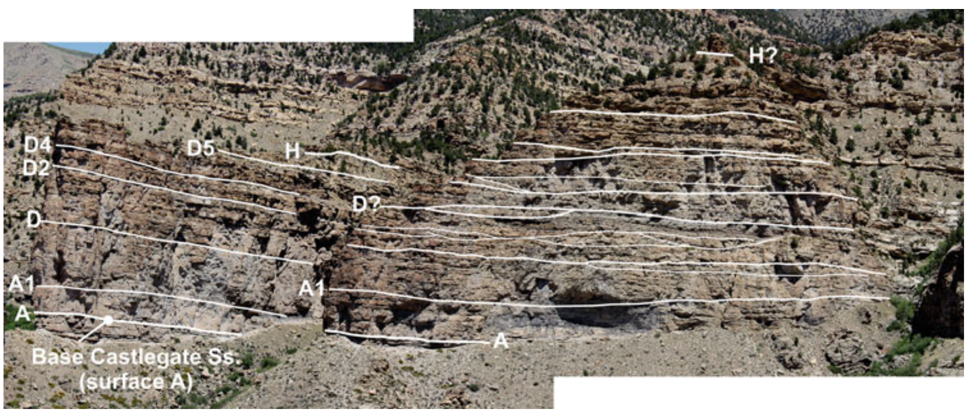


Fig. 8.21 The Lower Castlegate Sandstone south of the type section. The south face of the Castle Gate is seen at *left*. Lettering of the surfaces is as in Fig. 8.20. Width of field of view is about 300 m

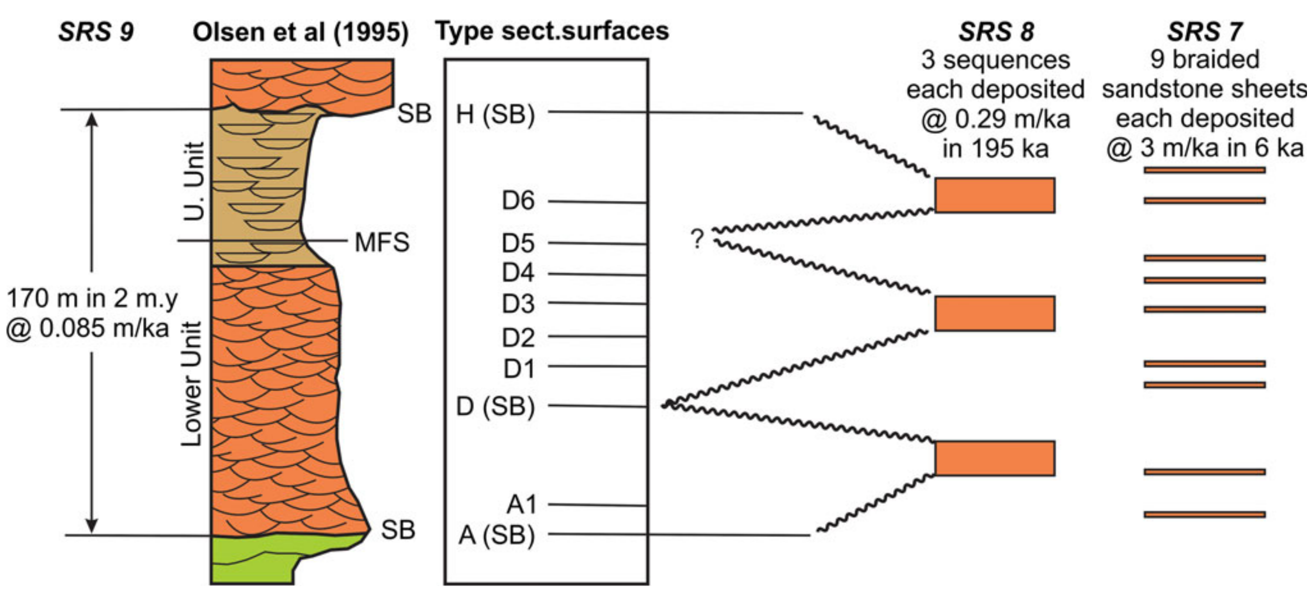


Fig. 8.22 Different interpretations of the Castlegate Sandstone at the type section. See text for explanation

(1993) and Shanley and McCabe (1994) are based on observations at *SRS-7* rates, that is, a time scale of 10^3–10^4 years, and sedimentation rates of 10^0–10^1 m/ky. They used modern studies and simulations that assume an accommodation rate up to three orders of magnitude more rapid than is typically represented in the preserved ancient record.

During this study it was not possible to replicate the two-part subdivision of the Castlegate Sandstone proposed by Olsen et al. (1995), at least not at the type section. This exposure is shown in Fig. 8.20, and the bounding surfaces there are repeated in Figs. 8.21 and 8.22 (the lettering is shown for convenience, using the original labeled surfaces A, D, and H from Miall and Arush 2001a). The type section consists of a succession of braided sandstone sheets bounded by surfaces of at least fifth-order rank (Miall 1993), in the terminology of Miall (1996). At least one of these, surface D of Miall and Arush (2001a), is interpreted as a sequence boundary (a sixth-order surface) but we have no evidence about the greater or lesser significance of the other surfaces in this outcrop. More than one could be "cryptic" sequence boundaries, in the terminology of Miall and Arush (2001a, b).

At the right hand side of Fig. 8.22, two other scenarios for the Castlegate Sandstone are shown. One shows a version of Bhattacharya's (2011) speculation about three Castlegate sequences. The sequences would likely represent a response to allogenic forcing, such as flexural loading and/or changes in intraplate stress (Deramond et al. 1993; Naylor and Sinclair 2007). The sequence boundary between the two lower sequences is correlated to surface D at the type section. The upper sequence boundary cannot be located in the type section. None of the surfaces between D and H exhibit any features, such as cut-and-fill relief, extensive lag deposits, or evidence of early cementation, that would indicate their significance. This could be a characteristic of a "cryptic" sequence boundary, of the type suggested by Miall and Arush (2001b). The observation of tidal sedimentary structures in the upper part of the Castlegate Sandstone at locations east of the type section (Olsen et al. 1995; Yoshida et al. 1996) may be explained by long-term (SRS 9-11) changes in paleoslope that permitted periodic tidal influx into the Castlegate rivers. The three sequences are envisaged as sequences formed at *SRS 8* rates, deposited at average sedimentation rates of 0.29 m/ky and each representing 195 ky of elapsed time. As seen in Fig. 8.22, this leaves a substantial amount of "Castlegate" time unrepresented, with only 29 % of the 2 million years of time allotted to this formation represented by sediments, at the *SRS 8* time scale.

Another interpretation of the Castlegate Sandstone is that it consists simply of a set of unrelated braided sandstone sheets, some formed successively over a limited time range, some separated by longer intervals such as the unconformity represented by surface D. These would represent long-term geomorphic processes, and should be evaluated at *SRS 7*. This is how they are presented at the right side of Fig. 8.22. Nine braided sandstone sheets, averaging 19 m thick (bounded by the ten surfaces A to H at the type section), deposited at an average *SRS 7* rate of 3 m/ky would require in total only 57 ky to accumulate, which is less than 3 % of the 2 million years age range of the Castlegate Sandstone. Each sheet would represent an average of about 6 ky. How to account for the remaining elapsed time? Intervals of non-deposition or erosion between each sheet would average 216 ky. The sandstone sheets are probably accidental remnants of long-lived braid-plain deposits across which temporary sediment storage and remobilization were the norm, with preservation taking place only because of abandonment following avulsion events. The lengthy intervals between each sheet have not left any identifiable signature, such as mature paleosoils, or evidence of early cementation (except for surface D) or of deep erosion. As Willis (2000, his Fig. 17; Fig. 6.62 of this book) demonstrated, paleocurrent patterns shifted significantly during deposition of the Castlegate Sandstone, from southeastward during the deposition of sequence 1 (sequence definitions as in Fig. 8.19), to S to SSE in sequence 2, to E to NE in sequence 3. Such shifts presumably reflect subtle tectonic tilts in regional paleoslope at SRS 9-11 rates, and could have facilitated switches in local flow directions, particularly where aggradation of a channel belt created slope advantages for alternative flow directions, the same type of process that leads to the fan shape of alluvial fans and the distributary pattern of deltas. Some of the younger sheets contain evidence of tidal influence, indicating a slow but steady rise of sea level during the deposition of this formation.

It is possible that both the *SRS 8* and *SRS 7* scenarios of Fig. 8.22 are correct, with the latter nested within the former. In other words, the Castlegate Sandstone consists of sequences that are themselves composed of unrelated braided sandstone sheets.

8.9.6 Conclusions

Sedimentation rates derived from studies of modern nonmarine and shallow-marine environments deposited over periods of decades (*SRS 5*) are in the range 10^2–10^3 m/ky. This is up to four orders of magnitude more rapid than the rates derived from geological studies, such as that of the Mesaverde Group. When rates comparable to the post-glacial record (10^4–10^5-year records; *SRS 7, 8*) are applied to the preserved facies successions that comprise this group, less than 10 % of the 4.86 million years elapsed time represented by the group can be accounted for. The remainder is "missing" at bedding planes and other bounding surfaces of all types, a pattern predicted by Sadler (1999). Nearshore sediment bypass with progradation of shelf clinoforms could account for a significant proportion of the elapsed time. In the shallow-marine environment, widespread non-deposition or erosion are thought to have preceded ravinement and the development of flooding surfaces from which shoaling-upward successions (parasequences) then prograded. In the Mesaverde Group there are 23 such major surfaces that define the boundaries of the six members and submembers. Each of these could account for a time span of up to ~100,000 years. The major sequence boundary at the base of the Castlegate Sandstone, which can be traced for more than 150 km eastward into Colorado, could represent as much as 1 million year, and the surface that truncates the Buck Tongue could also represent a comparable interval of missing time. Many other bounding surfaces simply represent long-term sediment bypass, with no net accumulation. The Castlegate Sandstone may consist of a set of unrelated fragments of braided sandstone sheets separated by significant erosional or non-depositional breaks.

Analyses of long-term processes, including mass-balance transport models, and interpretations of shoreline trajectories through time, need to take into account the fact that far more time is missing than is represented. Continuity is the exception in nonmarine and shallow-marine stratigraphy. Bounding surfaces are the "dark matter" of sedimentology. We know they are there, but means are not yet available for a complete analysis of their range of characteristics and time significance.

In the next section we close in somewhat on this problem, by examining some examples of detailed stratigraphic studies where much better chronostratigraphic control is available, providing some insights on the level of interpretive detail that is now available using modern, current, chronostratigraphic methods.

8.10 The Future of Conventional Chronostratigraphy

8.10.1 Current Examples of Outstanding Work

The modern geological time scale (GTS2004: Gradstein et al. 2004a, b, 2012, and the updated scale maintained at www.stratigraphy.org; see Fig. 7.33 of this book) takes into account the types of potential error discussed in Sect. 7.8.5 by collating data from multiple sources. The construction of Composite Standard Reference Sections using graphic correlation methods (Sect. 7.5.4) is part of this process. Currently finalized global stratotypes for systems, series and stages are identified in Gradstein et al. (2004a, b, 2012) and on the website, with references to published documentation, most of which consists of reports in the journal *Episodes* by representatives from boundary working groups. Realistic error estimates are provided for Phanerozoic stages, and range from very small values (10^4-year range) for most of the Cenozoic, the time scale for which is increasingly linked to an astrochronological record, to as much as ±4 million years for several stages between the Middle Jurassic and Early Cretaceous. Figure 8.23 illustrates the expected error in age estimation through the Phanerozoic, based on information available in 2007. The refinement of the scale expected to accrue from the integration of astrochronology into the data base (Fig. 8.23e) may be regarded as optimistic, but the key workers in this field make a good case for such a development, as discussed in Sect. 8.11.

Miall (2010, Chap. 14) provided a discussion of the global scale as applied to the issue of the global correlation of sequences, particularly as this relates to the possible global extent of sequences based on their presumed origin as a result of eustatic changes of sea level. An example of this type of work is illustrated in Figs. 8.24 and 8.25. The stratigraphy of the New Jersey continental margins has been extensively studied by K. Miller and his colleagues, in part to provide a chronostratigraphic baseline for global sequence studies. Figure 8.24 shows the sequence subdivision and generalized lithologies in relevant boreholes along a transect across a portion of the continental margin which consists of a series of prograding Oligocene clinoform sets. Figure 8.25 is an example of the highly detailed chronostratigraphic documentation of the Oligocene-Miocene stratigraphy that can now be developed, based on integrated biostratigraphy, oxygen isotope stratigraphy, strontium isotope stratigraphy and magnetostratigraphy. The details of this work are presented several major regional studies (Miller et al. 1998, 2008; Browning et al. 2008; Kominz et al. 2008) and are discussed in detail by Miall (2010, Sect. 14.6.1). The following is a brief summary.

Figure 8.26 reproduces a correlation diagram developed by Betzler et al. (2000) comparing the Miocene-Pliocene 10^6-year sequence record on the Bahamas Bank and the Queensland plateau, to which I have added the sequence boundaries from the same interval of the New Jersey continental margin succession (from Kominz et al. 2008). The Queensland-Bahamas study is based on correlations of calcareous nannoplankton and planktonic foraminifera. The density of the biostratigraphic data ranges from one to three biohorizons per million years, calibrated to the Berggren et al. (1995) time scale. Gradstein et al. (2004a, b, Fig. 1.7) indicated that stage-boundary ages have been adjusted by between about 0.1 and 0.8 million years. from the Berggren et al. (1995) scale, not enough to significantly affect the level of correlation with the more recently dated New Jersey section.

Figure 8.26 indicates a high degree of correlation between Queensland and the Bahamas. Betzler et al. (2000, p. 727) stated that throughout the Miocene-Pliocene "The isochroneity of sea level lowstands in two tectonically unrelated carbonate platforms is strong evidence for eustatic

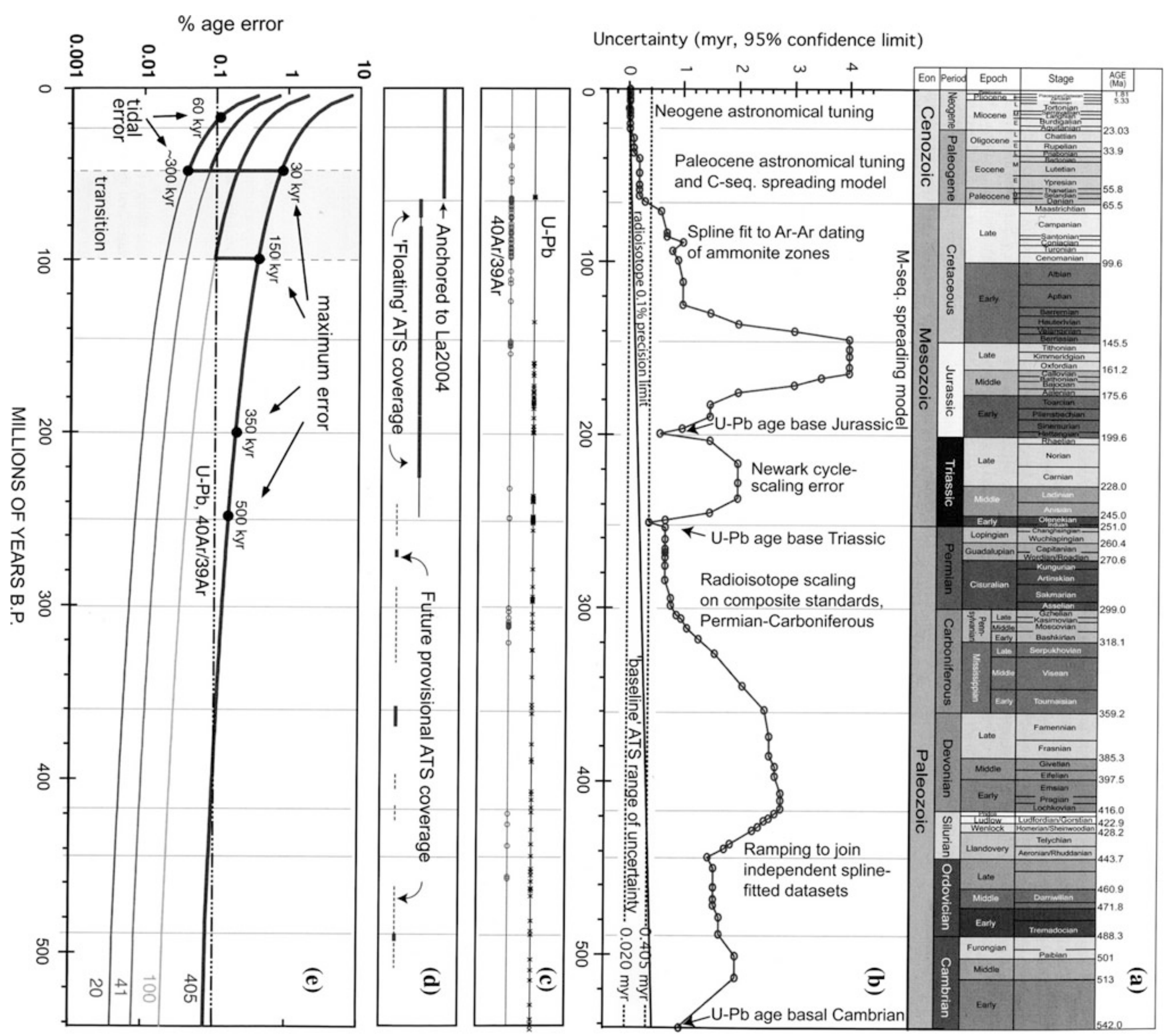


Fig. 8.23 **a** The standard divisions of the Phanerozoic International Geologic Time Scale (Gradstein et al. 2004a). **b** Estimated uncertainty (95 % confidence level) in the ages of stage boundaries. **c** Distribution of radiometric ages used in the construction of the time scale. **d** Documented and potential astrochronological time series. **e** Estimated error to be expected when the astrochronological time scale through the Phanerozoic is completed and integrated into the International Geologic Time Scale (Hinnov and Ogg 2007)

sea level changes as the controlling factor on large to medium-scale (1–5 Ma) stratigraphic packaging." Betzler et al. (2000) went on to note that the number of sequence boundaries in their data does not correspond to the number of boundaries in the Hardenbol et al. (1998) chart—an issue that, as discussed by Miall and Miall (2001) constitutes one of the criteria for sequence correlation that has consistently misled and confused stratigraphers. We do not consider the lack of correlation with the Hardenbol chart further, for reasons discussed elsewhere (Miall 2010). Betzler et al. (2000) suggested that the accuracy of their sequence boundary correlation might be improved by more intensive biostratigraphic analysis. However, for our purposes, it is much more significant to evaluate the Queensland and Bahaman correlations with the sequence boundary record from New Jersey (accurate sequence boundary ages for the succession younger than 10 Ma are not available from this area). This is a comparison between two independent studies and therefore fulfills one of the most important criteria for a meaningful test of the global-eustasy paradigm. In this case, the evidence indicates a strong degree of correlation between New Jersey, The Bahamas, and Queensland. Despite the small differences in the time scales used in these two different interpretations, the comparisons between the data sets

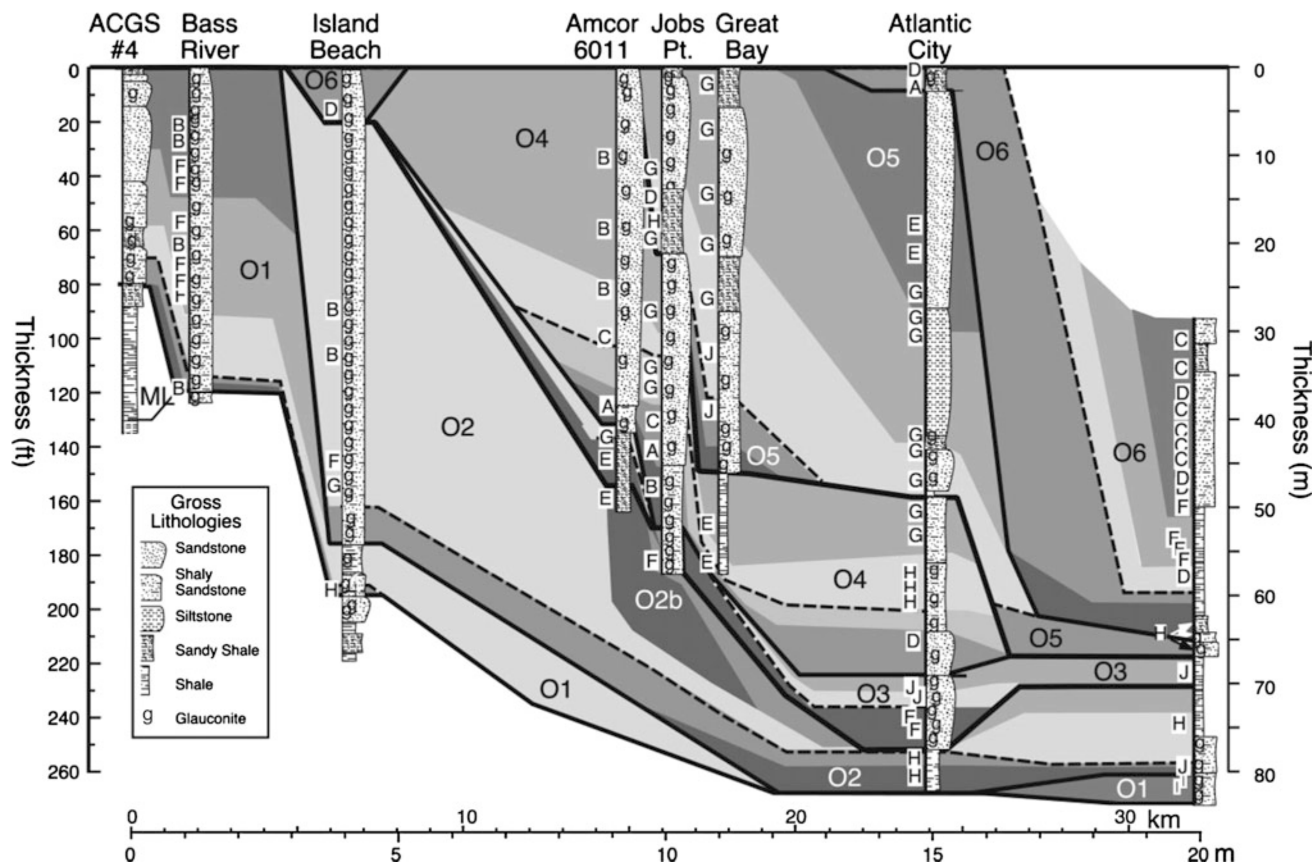


Fig. 8.24 Details of the Oligocene sequences O1–O6 forming a set of seaward-dipping clinoforms along a NW-SE transect across the New Jersey continental margin. Gross lithologies for each borehole are indicated. Upper-case letters to the left of each borehole indicate foraminiferal biofacies, identified by factor analysis (Kominz and Pekar 2001)

are striking. The adjustments that would be required to recalibrate the Betzler et al. (2000) study to GTS2004 would not significantly change the pattern visible in Fig. 8.26. The case for eustatic control of Miocene stratigraphy is considerably strengthened by this comparison.

Also shown in Fig. 8.26, for reference purposes, are the sequence boundaries documented in the "great Neogene sedimentary wedge" (wording of McGowran 2005, p. 190) reconstructed by Vail et al. (1991), based in part on an analysis of the Antarctic margin (Bartek et al. 1991). Their model of the Neogene wedge claims to illustrate a global pattern of sea-level change and accompanying stratigraphic architecture that can be recognized worldwide. However, there is very little correspondence between these sequence boundaries and the New Jersey-Queensland-Bahamas events documented in Fig. 8.26, which calls into question the chronostratigraphic basis on which the wedge model was drawn. McGowran (2005, p. 191) indicated that the number and ages of the sequence boundaries has been modified by Hardenbol et al. (1998), but the boundaries and ages indicated in his redrawn version of the Vail et al. (1991, Fig. 12) diagram are the same as in that diagram, which were, in turn, based on the Haq et al. (1987, 1988) global cycle chart.

This discussion of the New Jersey margin and what the chronostratigraphy tells us provides an excellent example of the capabilities of modern chronostratigraphic methods. The demonstration of the correlatability of Neogene sequences between tectonically unrelated areas that is shown in Fig. 8.26 supports the interpretation of glacioeustatic control for the sequence stratigraphy, a not unexpected result given the likely extensive development of the Antarctic ice cover by the Neogene (Miller et al. 2005).

The second example discussed here is the detailed study of late Cenozoic sedimentation of the Brazos-Trinity depositional system in the Gulf Coast margin by Pirmez et al. (2012) and Prather et al. (2012). This study was discussed in Sect. 6.3.2 as an example of the construction of a regional stratigraphy using 2-D seismic data integrated with well and core data. Here I focus on the chronostratigraphic methods used in the study. Figure 8.27 provides the basis for chronostratigraphic dating and correlation used in this study. Biostratigraphic zonation of planktonic

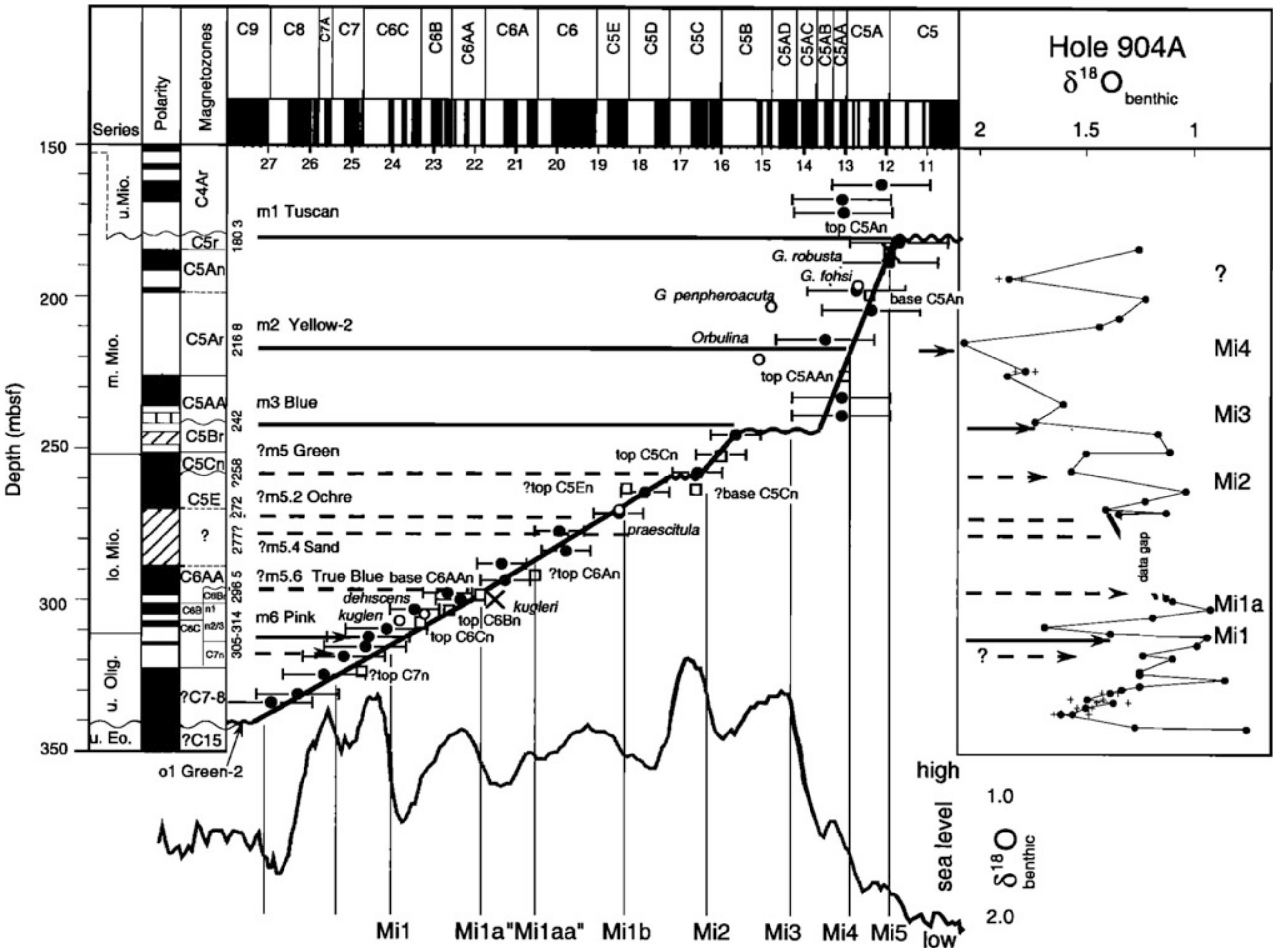


Fig. 8.25 Age-depth diagram for Hole 904, New Jersey continental slope. The core record, with magnetozones, is indicated at *left*. Sequence boundaries, recognized from seismic and facies studies, are shown by the *horizontal lines* extending from the core log across to the *right*, to the sloping line of correlation. Sequences are named, from the top down, "m1 Tuscan", etc. The standard magnetostratigraphic time scale is shown across the *top* of the figure and the $\delta^{18}O$ record is shown along the *bottom*. Dated sample points are indicated by symbols along the line of correlation: strontium isotope values, with error bars *black circles*), planktonic foraminifer lowest occurrences (*open circles*) and highest occurrences (*crosses*), and magnetostratigraphic reversal boundaries (*squares with chron number*). $\delta^{18}O$ from hole 904A are indicated in the *box* at *right*. Unconformities are indicated by *wavy lines* in the line of correlation (Miller et al. 1998)

foraminifera and nannofossils obtained from core was supplemented by oxygen isotope measurements. Additional age and correlation information was provided by volcanic ash geochemistry (correlated to Caribbean volcanic events). For deposits younger than 40 ka, radiocarbon dating was used on planktonic foraminifera, reworked plant debris and shell material. Magnetostratigraphy proved not be useable because of the presence of sand and silt layers, which did not provide magnetic information, and because of highly variable sedimentation rates, making the "bar-code" matching of the magnetic signal to the standard record difficult to impossible. The absolute ages of first and last appearance datums provided key datable and mappable horizons, as shown in Fig. 8.28. Their ages are based on standard studies referenced in Pirmez et al. (2012, p. 119).

The average sedimentation rate for the entire succession examined in this project averages 2.1 m/ka (a maximum of 300 m of section deposited in about 140 ka). This corresponds in time range and sedimentation rate to *SRS-7* (Table 3.3). However, the detailed chronostratigraphy reveals that there are significant sedimentation breaks and condensed intervals, and intervals within which sedimentation rates are substantially higher (Fig. 8.29). Hemipelagic units reveal sedimentation rates between 0.1 and 9 m/ka, which is a similar order of magnitude to the long-term rate but in at least one instance more than four times the long-term rate, which emphasizes the importance of knowing the time scale over which the measurement is made. Sand-rich ponded apron deposits yield sedimentation rates an order of magnitude greater, ranging between 20 and 64 m/ka, which corresponds to the higher-rate end of *SRS-7*.

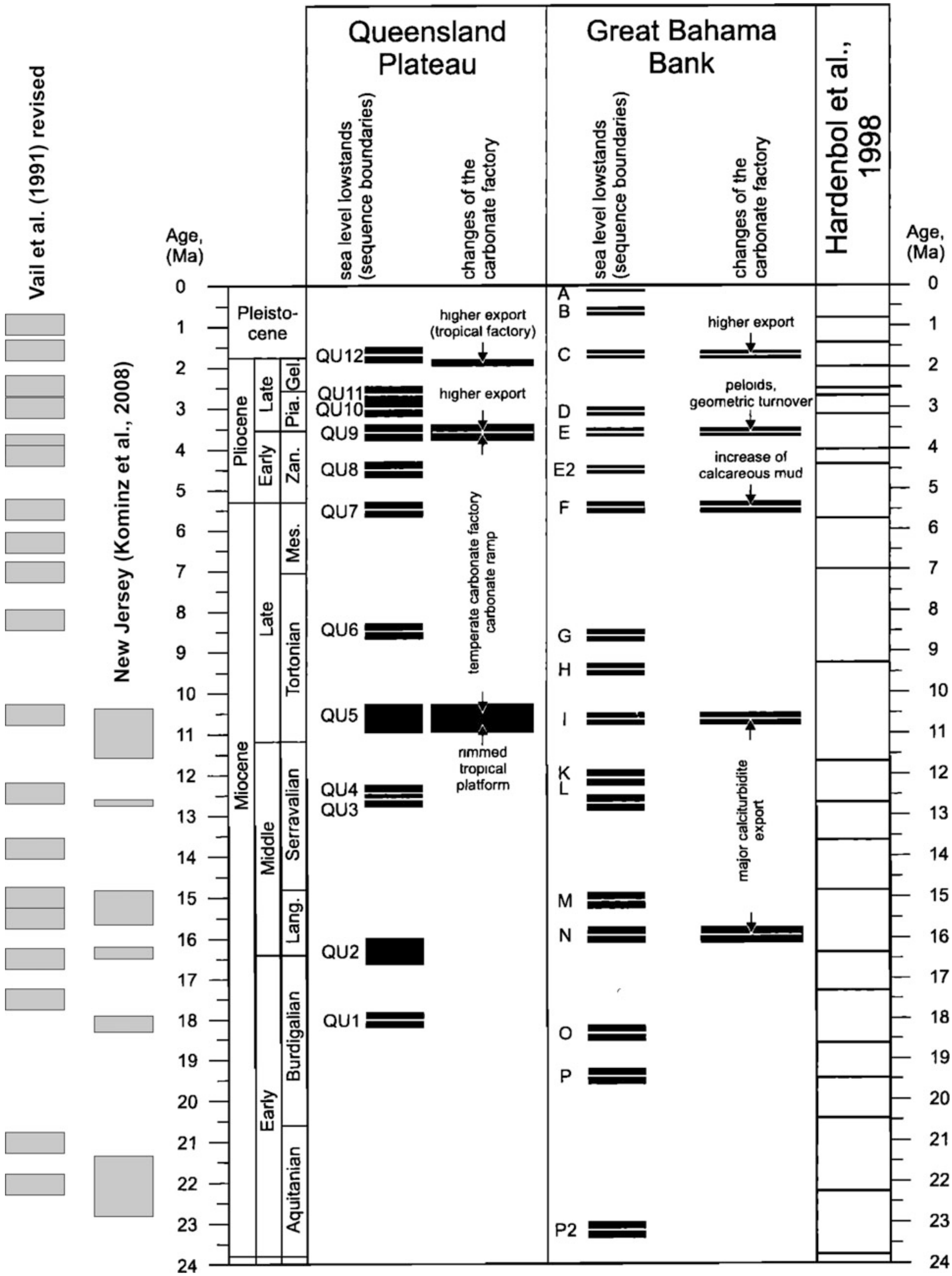


Fig. 8.26 Comparison of Neogene sequence boundaries in the platform carbonate margins of Queensland and the Bahamas Bank. The sequence boundaries from the Hardenbol et al. (1998) scale are shown at *right*. From Betzler et al. (2000). Two additional sets of sequence boundaries have been added, at *left*, the sequence boundaries from the Miocene portion of the New Jersey record (from Kominz et al. 2008), and the Neogene record of the Antarctic (from Vail et al. 1991, with boundary ages revised by Hardenbol et al. 1998)

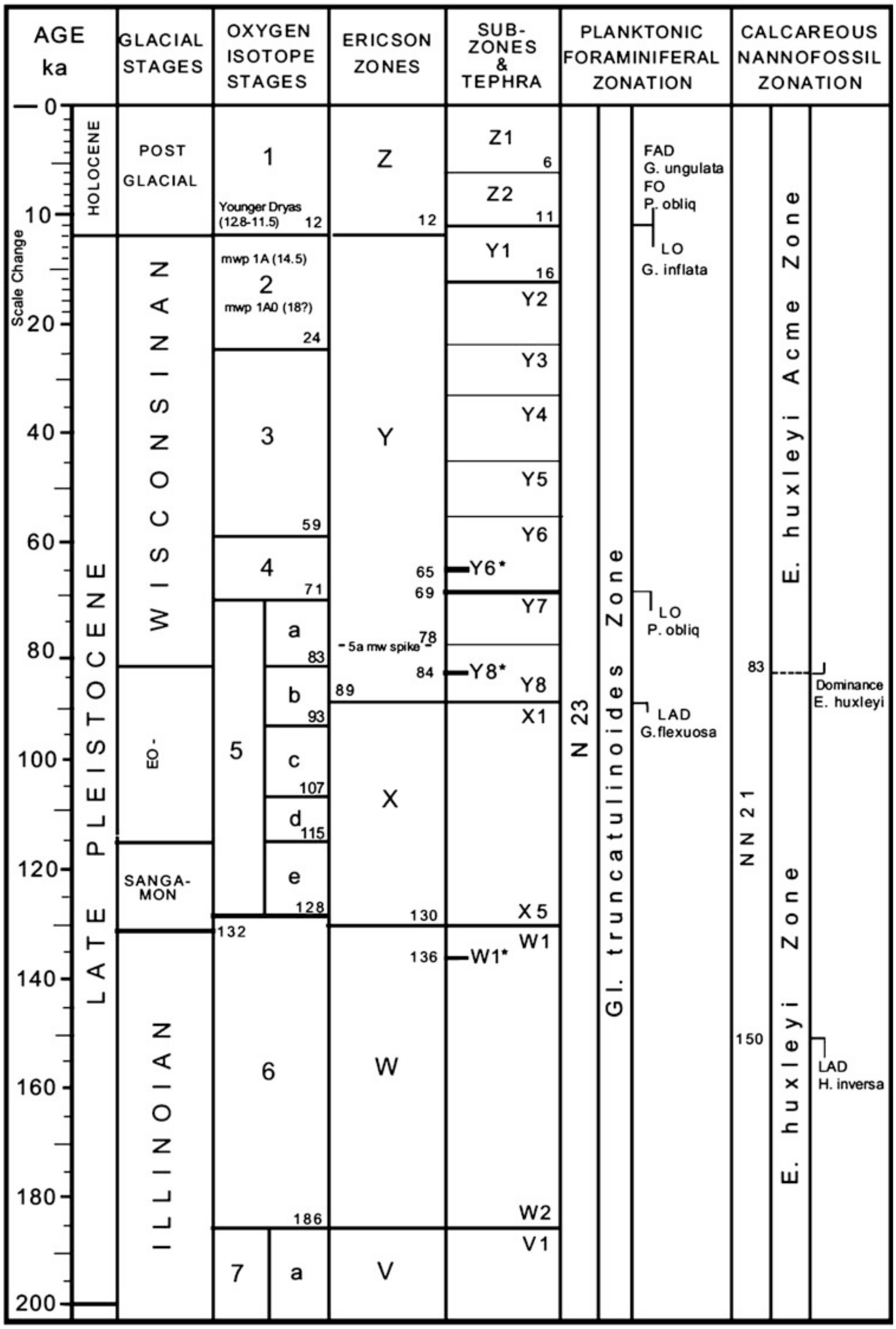


Fig. 8.27 Chronostratigraphic chart used for the Brazos-Trinity depositional system. *Mwp* meltwater pulse. *LO/FO* last/first occurrence locally observed in the area. *FAD/LAD* first/last appearance datum. Ash layers are identified by an *asterisk* (Pirmez et al. 2012, Fig. 7, p. 119)

Many additional details may be gleaned from detailed study of these data, including the partitioning of the sediment flux between different basins within the project area. This, in turn, throws light on the evolution of the dispersal system as it crossed the shelf and fed several separate basins arranged along a downstream trend through the Sigsbee Knolls.

The first example discussed in this section, the Neogene stratigraphy of the New Jersey continental margin, indicates that modern conventional chronostratigraphic techniques may be able to provide ages and regional to global correlations for the late Paleogene (Oligocene) to within about ±0.5 million years. In the case of the second example, much younger rocks were under discussion, and accuracy appears to be in the 10^5-year range, with at least an order of magnitude greater accuracy attainable for the last 40 ka of stratigraphic time through the use of radiocarbon dating.

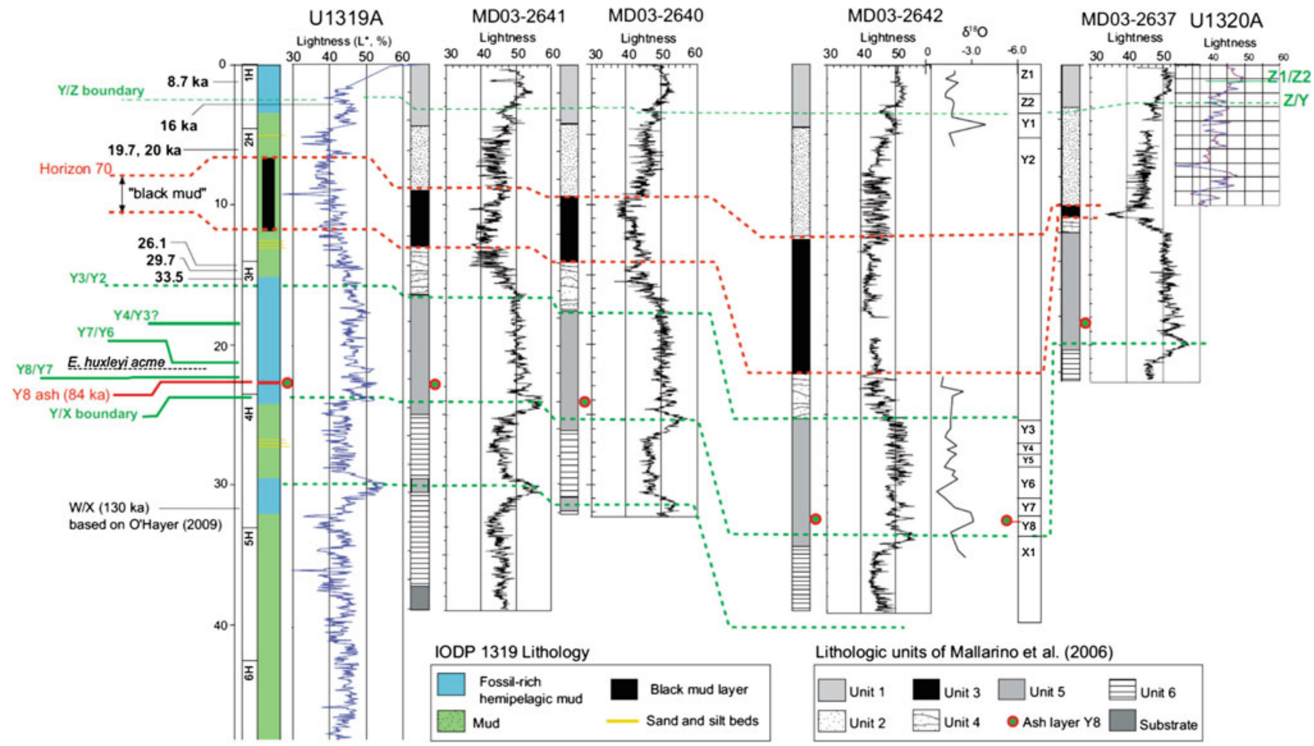


Fig. 8.28 Correlation of wells in the Brazos-Trinity depositional system, showing identified unit boundaries at *left* (Pirmez et al. 2012, Fig. 10, p. 122)

Each of these examples were approached by their authors as studies of typical stratigraphic problems, making use of all available chronostratigraphic data. This is different from the objective of perfecting the geological time scale, when field locations are selected specifically to maximize the chronostratigraphic information available, rather than to answer some sedimentological or tectonic question. This is an important distinction because, as noted earlier (see Fig. 8.23), accuracy and precision of the Geological Time Scale in the 10^5-year range is expected to be attainable for the Mesozoic when cyclostratigraphic studies are completed. Even if this proves to be correct, this does not mean that every Mesozoic section will then be capable of dating and correlation at that level of accuracy, because accuracy depends on the chronostratigraphic tools available in each case for each section.

8.10.2 The Use of Wheeler Diagrams

The construction of Wheeler diagrams focuses attention on the issue of elapsed and missing time (Fig. 8.1). Given the modern improvements in chronostratigraphy and the availability of modern sequence-stratigraphic methods, the use of this device can help to throw considerable light on sedimentary processes, and provide diagrammatic constructs that force the stratigrapher to think through the implications of their reconstructions.

A Wheeler diagram for the Brazos-Trinity deposits discussed in the previous section (Fig. 8.30) helps to emphasize the substantial variability in sedimentation rates that characterized this region. Most of the elapsed time between 140 and 25 ka is represented by hemipelagic or condensed intervals. Sand-rich intervals (seismic units 30–70) were deposited rapidly during a relatively very short interval (25–15 ka), corresponding to the Last Glacial Maximum, when sea-levels were low, and immediately before a meltwater pulse from the Mississippi system corresponding to the commencement of rapid post-glacial sea-level rise.

The use of sequence methods for mapping and correlation, while providing much more logical architectural reconstructions of complex sedimentary units (Sect. 6.2.3), may raise questions that can take interpretations to an entirely new level (Bhattacharya 2011). For example, Fig. 8.31 is a detailed sequence correlation of a delta in the Ferron Sandstone of Utah. At first sight the incised valley-fill complexes (units at several levels coloured red in the figure) that mark the base of sequences 1 and 2 would appear to define a relatively simple, almost layer-cake stratigraphy. This is essentially the interpretation shown in Fig. 8.32a, in which all the incised valleys are assigned to Sequence 2. However, there is no definitive proof that this is the correct

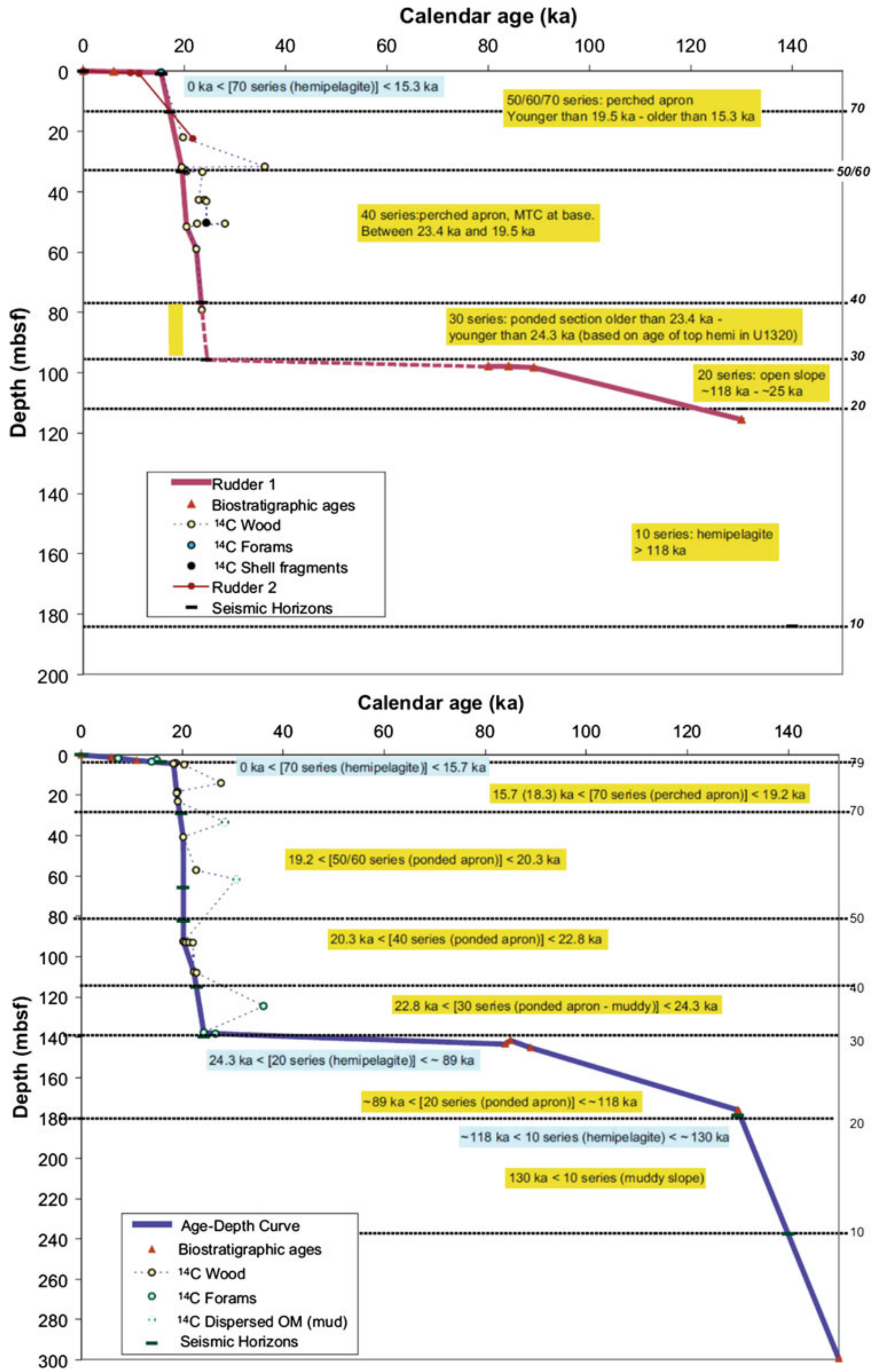


Fig. 8.29 Age-depth curve for two wells in the Brazos-Trinity depositional system. Numbers 10–79, at *right*, refer to seismic units (see Fig. 6.20) (Pirmez et al. 2012, Fig. 12, p. 125)

interpretation. The regional erosion surface that marks the base of sequence 2 across the left-hand end of the section could be a composite of erosion surfaces cut at different times after the end of deposition of parasequence 12. This is the basis for the interpretation shown in Fig. 8.32b, in which it is suggested that the incised valley-fills that comprise the first valley-fill complex were formed at different times following the deposition of para sequence 9, each one correlated in time to a different shoreface tongue. The alternative interpretations may be followed through with questions

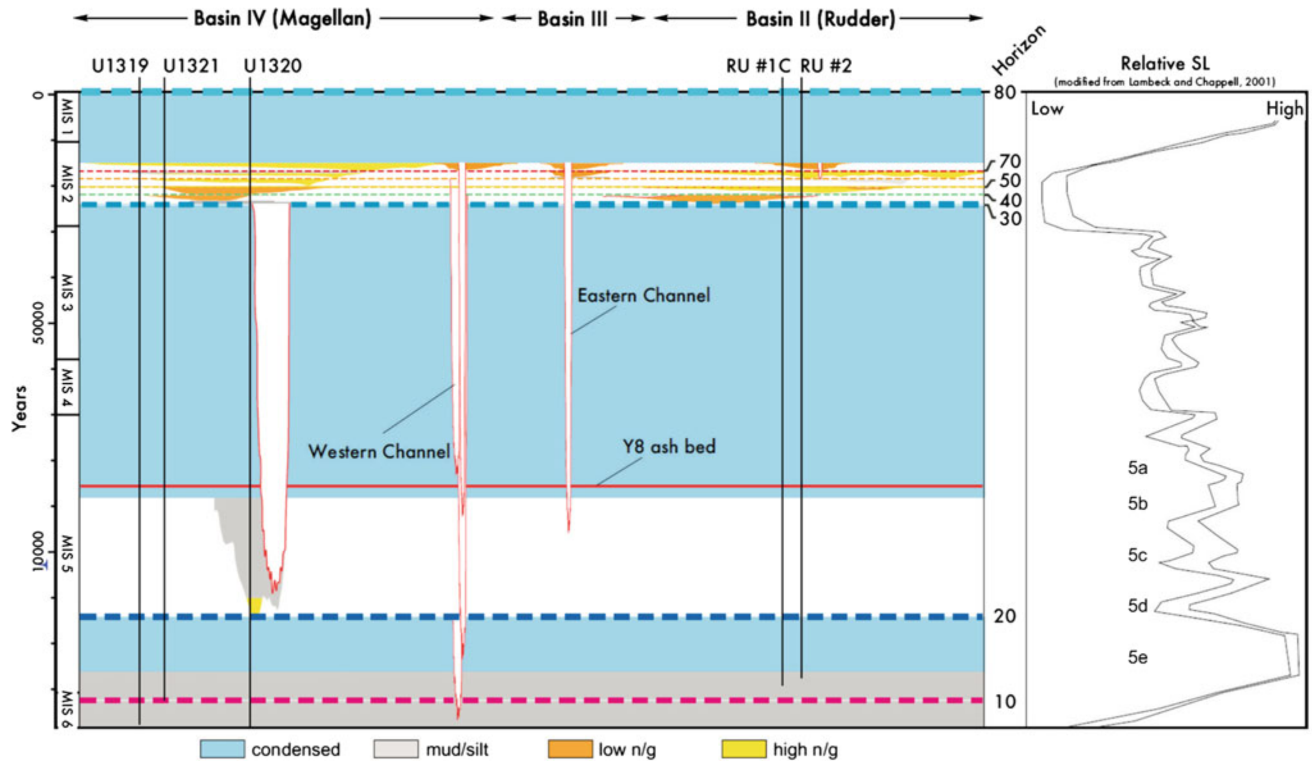


Fig. 8.30 Wheeler diagram for the Brazos-Trinity system (Pirmez et al. 2012, Fig. 14, p. 128)

about sedimentation rates and missing time, of the type raised in Sect. 8.9. What differences in fluvial style, if any, may be suspected from the different interpretations shown in Fig. 8.32? Was there a single rapid episode of changing accommodation or sediment supply that gave rise to a single, amalgamated incised valley complex (Fig. 8.32a)? Or was this a more drawn-out process, reflecting longer-term processes, or a more distant signal that became distorted ("shredded"?) down the transport direction, which is what could be implied by the interpretation indicated in Fig. 8.32b?

Comparable questions may asked regarding the age and correlation of the sandstone sheets comprising the Castlegate Sandstone (Sect. 8.9.5). The original interpretation of this unit as a single sheet extending basinward for more than 150 km (e.g., Van Wagoner et al. 1990) was called into question by the suggestion of Bhattacharya (2011, Fig. 18) that it comprises several sequences, each correlated to a shoreface tongue representing part of the Desert Member.

Developments in the acquisition and processing of 3-D seismic data have provided the possibility for the automated generation of Wheeler diagrams for subsurface sections, including four-dimensional visualizations that illustrate paleogeographic evolution in a temporal framework. Stark et al. (2013) described the evolution of a technique for extracting time information from seismic data called "computational seismic chronostratigraphy." Qayyum et al. (2015) discussed the method and provided worked examples. Other worked examples are available in the special issue of "The Leading Edge" edited and introduced by Stark et al. (2013).

The procedure is as follows: automatic tracking software is used to generate multiple mapped horizons within the seismic volume. Seismic terminations, corresponding to such real structural features as unconformities or downlap surfaces, can be recognised and mapped by the software by the convergence of reflections to within a pre-set spacing value. A Wheeler diagram may then be constructed by flattening each surface to the horizontal. In this way thickness, the Z dimension (the y-axis of a 2-D plot), is converted to relative time. Structural and thickness information are lost in this process, and the resulting diagram emphasizes non-depositional and erosional hiatuses by the presence of blank space. The horizontal extent of each surface reflects either (1) its erosional extent, for example the technique provides a clear time-space map of subaerial unconformities, or (2) the original depositional extent, such as that of a clinoform unit, extending from its coastal origins at the mouth of a delta, down the continental margin to its lapout at the foot of the continental slope (this is, of course, within the limit of seismic resolution. In fact, distal clinoform sets may extend for considerable distances into a deep basin as thin

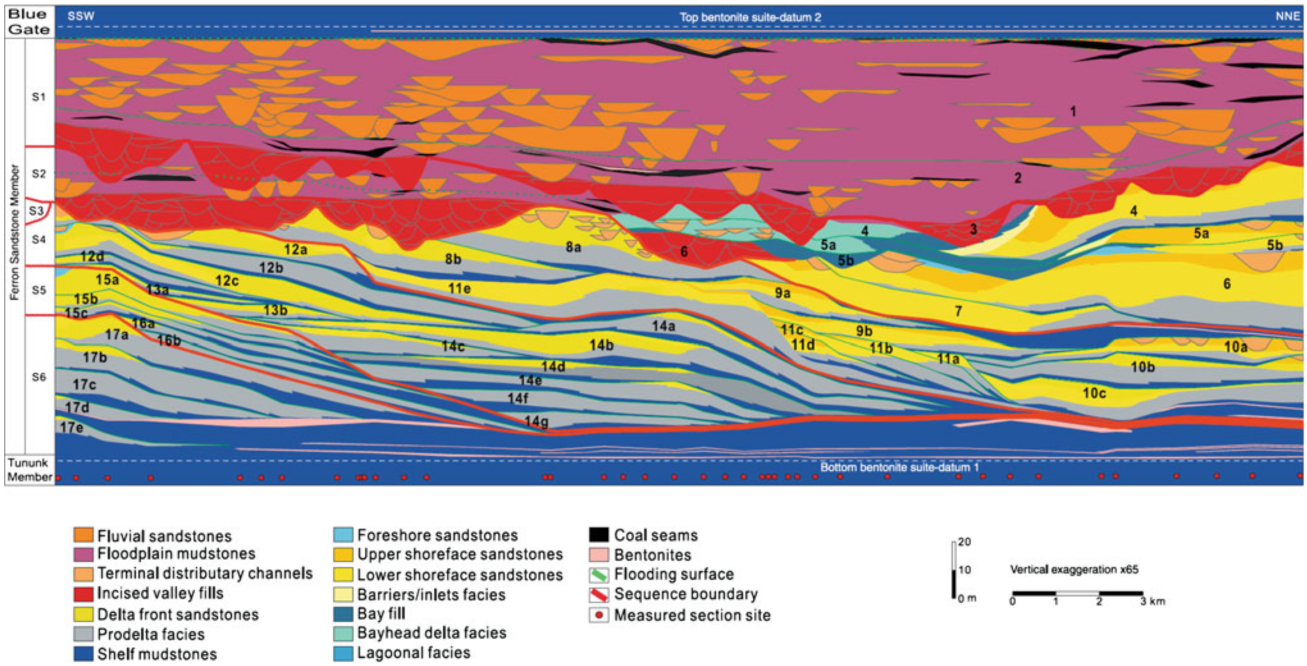


Fig. 8.31 Cross-section through the Ferron Notom delta (Turonian), Utah, hung on bentonites. Para sequences are numbered 1–17, and are grouped into six sequences. Two alternative Wheeler diagrams for this cross-section are shown in Fig. 8.32 (Bhattacharya 2011, Fig. 11, p. 135)

pelagic units). The vertical dimension of the plot depends on the number of autotracked horizons, which means that it varies in scale depending on the heterogeneity of the section and is also dependent on seismic resolution. The time scale to be derived from the vertical axis is therefore relative, and variable. Nonetheless, the resulting ability to visualize missing section, reflecting non-depositional or erosional hiatuses may provide a valuable addition to the tools for sequence interpretation and the development of paleogeographic models.

An example of the use of this technique is illustrated in Figs. 8.33 and 8.34. The gradual stepping out of the axis of deposition as the clinoforms prograde across the continental margin is graphically seen in the Wheeler plot, and the substantial age span of the hiatus at right representing a subaerial unconformity is particularly striking. This hiatus spans essentially the entire interval from one basal surface of forced regression to the next such surface above.

One problem with this method of developing Wheeler plots is the distortion of time that results from variable sedimentation rates and would also result from long-continued deposition of homogeneous sediment, resulting in reflection-free records. For example, in Fig. 8.33 note the two pale-coloured reflections labelled “condensed section”. The labeling arises from the seismic interpretation of the section, which suggests a thin unit that blankets sequence 1. The term “condensed section” typically indicates condensation of time, such as is commonly seen in the thin units that form offshore during rapid transgression (Loutit et al. 1988). However, in Fig. 8.33 there is no suggestion of the condensation of time because time, here, is in fact a distorted representation of seismic heterogeneity. Compare this with the lengthy intervals of condensation shown in Fig. 8.30, which are based on careful chronostratigraphic calibration of the seismic and well records. The Wheeler plot shown here was drawn by the seismic interpretation algorithms, but it is possible to imagine a further step, in which information on sedimentation rates and chronostratigraphic tie points is used to adjust the vertical scale (y-axis) of the plot to more accurately represent elapsed time.

8.10.3 Improving Accuracy and Precision

Several developments are underway that promise to improve chronostratigraphic accuracy and precision, both for the purposes of local to regional correlation (for which, relative dating would suffice) and also for the purpose of improving the Geological Time Scale. Developments in cyclostratigraphy and astrochronology are discussed in Sect. 8.11. In this section we discuss briefly the work to maximize the information available from the biostratigraphic record.

The rapid increase in computer power, in addition to enormously increasing the utility of 3-D seismic data, is also providing the opportunity for many different approaches to the consolidation, sorting, selection and correlation of all the different types of chronostratigraphic information that are

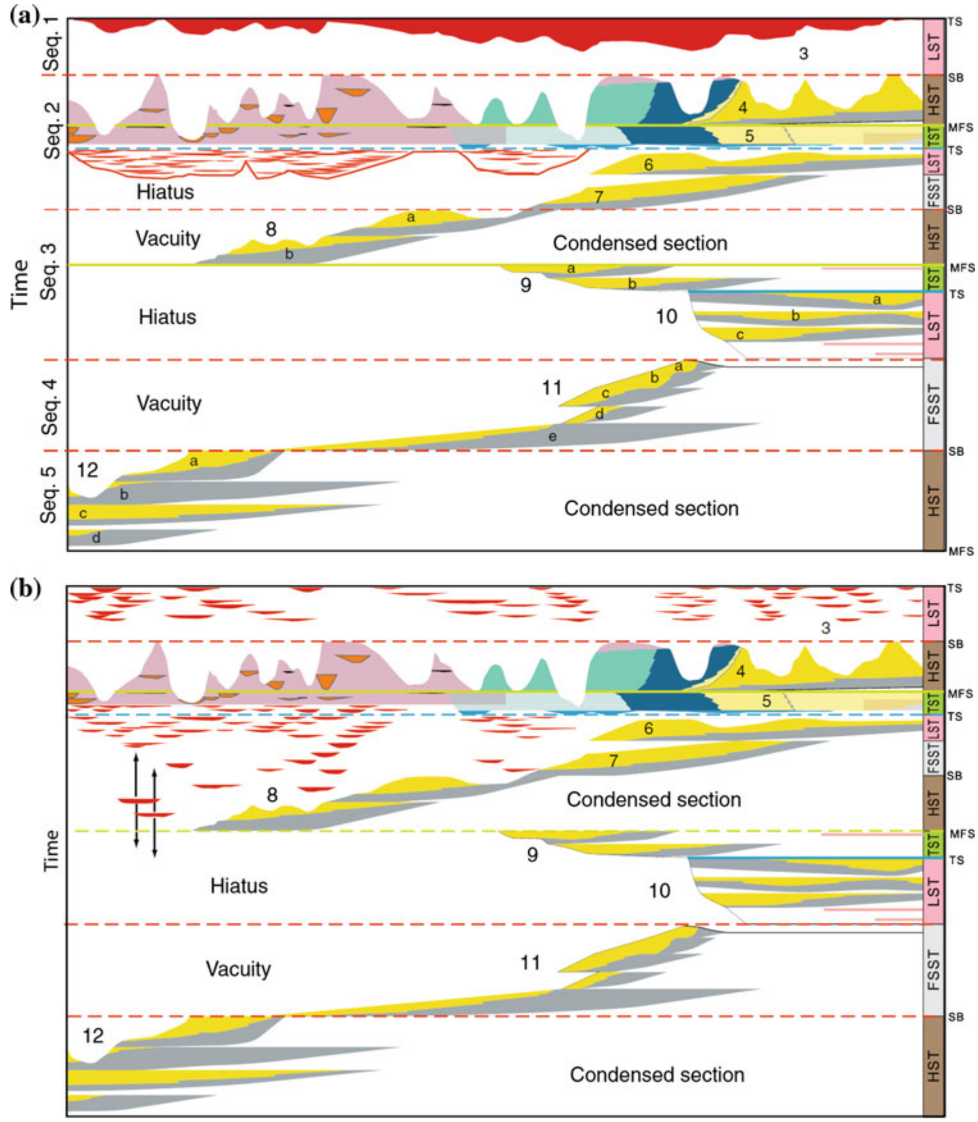


Fig. 8.32 Two alternative Wheeler diagrams for the cross-section shown in Fig. 8.31. The differences between them focus primarily on the chronostratigraphic interpretation of the incised valley-fills (Bhattacharya 2011, Fig. 14, p. 138)

increasingly available from the rock record. The concept of the **composite standard reference section** (Sect. 7.5.4) can be vastly expanded by adding such observational data as isotopic excursions, key seismic reflections, paleomagnetic reversals, chemostratigraphic determinations, dated volcanic ash beds and bentonites to the data on taxon ranges. Taxon ranges, as observed in any given section, may be incomplete, for reasons explained in Sect. 7.5, and where subsurface information is used, borehole caving may introduce inaccuracies into the record, which is why the use of the composite standard reference section method is so powerful, because it constitutes a method that includes the opportunity for continuous correction and refinement. There are now numerous algorithms available for sorting and standardizing the various types of data now being assembled in digital data bases. Sadler et al. (2014) provided a useful summary.

Figure 8.35A provides an example of the problems that may arise with the plotting of raw chronostratigraphic data points. Because of ecological selection, selective preservation, or incomplete sampling, the indicated correlations of taxa between sample points may include crossing correlations. First-appearance datums may appear too high in some sections because of these problems, whereas last-appearance datums might be too low because of caving in the subsurface, or because of reworking. By contrast, unless borehole caving is a problem, such data points as dated ash beds can be regarded as fixed points that may be used as "nailed" datums (Sadler et al.'s 2014 term; see Fig. 8.36), around which bioevents may be adjusted. Corrections to local taxon ranges may involve expansion to fit the composite standard ("jacked" apart in Fig. 8.36) or reductions, where corrections from other data, including fixed or "nailed" datums are

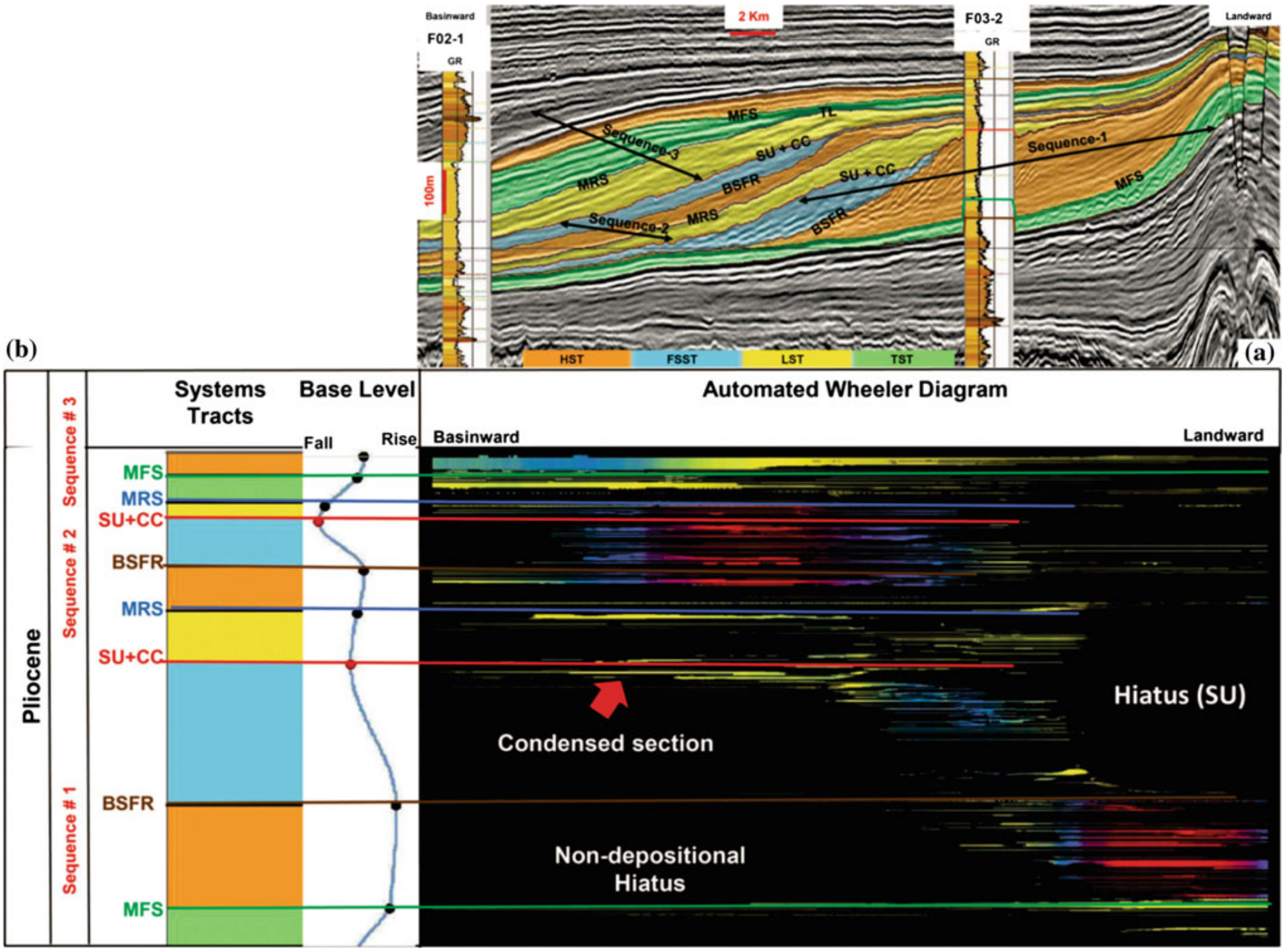


Fig. 8.33 **a** Seismic transect through two wells with overlain systems-tract interpretation of a Pliocene deltaic unit in the North Sea. **b** Automated Wheeler diagram of the studied interval, with sequence and systems-tract interpretation at left. The Y-axis of the diagram represents relative geological time. The colour-coded lines are autotracked events, and the colours represent relative thickness within each systems tract. Note that *Sequence 1* shows a low rate of sedimentation in the basinward direction. In seismic Wheeler diagrams, such condensed sections show up as hiatuses. *TL* transgressive lag; *BSFR* basal surface of forced regression; *MFS* maximum flooding surface; *MRS* maximum regressive surface; *SU* subaerial unconformity; *CC* correlative conformity (Qayyum et al. 2015, Fig. 5)

present ("clamped: Fig. 8.36"). Figure 8.35c shows the result of a fully automated correlation exercise that has adjusted and corrected the raw chronostratigraphic data to provide a best-fit solution. It may be compared with Fig. 8.35b, which represents a lithostratigraphic correlation guided by older, conventional biostratigraphy.

An insight into the accuracy and precision that is now available for the chronostratigraphic calibration of the distant geologic past was provided by Sadler et al. (2009), who reported on the use of a global graptolite data base for the Ordovician-Silurian interval comprising 17,861 locally observed range-end events for 1983 taxa, and 131 local observations of 57 other events (23 dated events and 34 marker beds) in 446 sections worldwide. This paper describes the details of how data points are ordered, culled, corrected, and calibrated to generate a time scale. The resolving power of the resulting scale is mostly in the 10^4- to 10^5-year time range (Figs. 8.37 and 8.38), which is at least an order of magnitude greater precision than that obtainable by conventional biostratigraphically-based methods for this time interval (Fig. 8.23). To repeat a caution made elsewhere in this book, the availability of such a precise scale does not automatically mean that any graptolite-bearing Ordovician-Silurian section may be dated with a comparable precision. The application of the scale, in practice, depends on the locally available suite of datable materials.

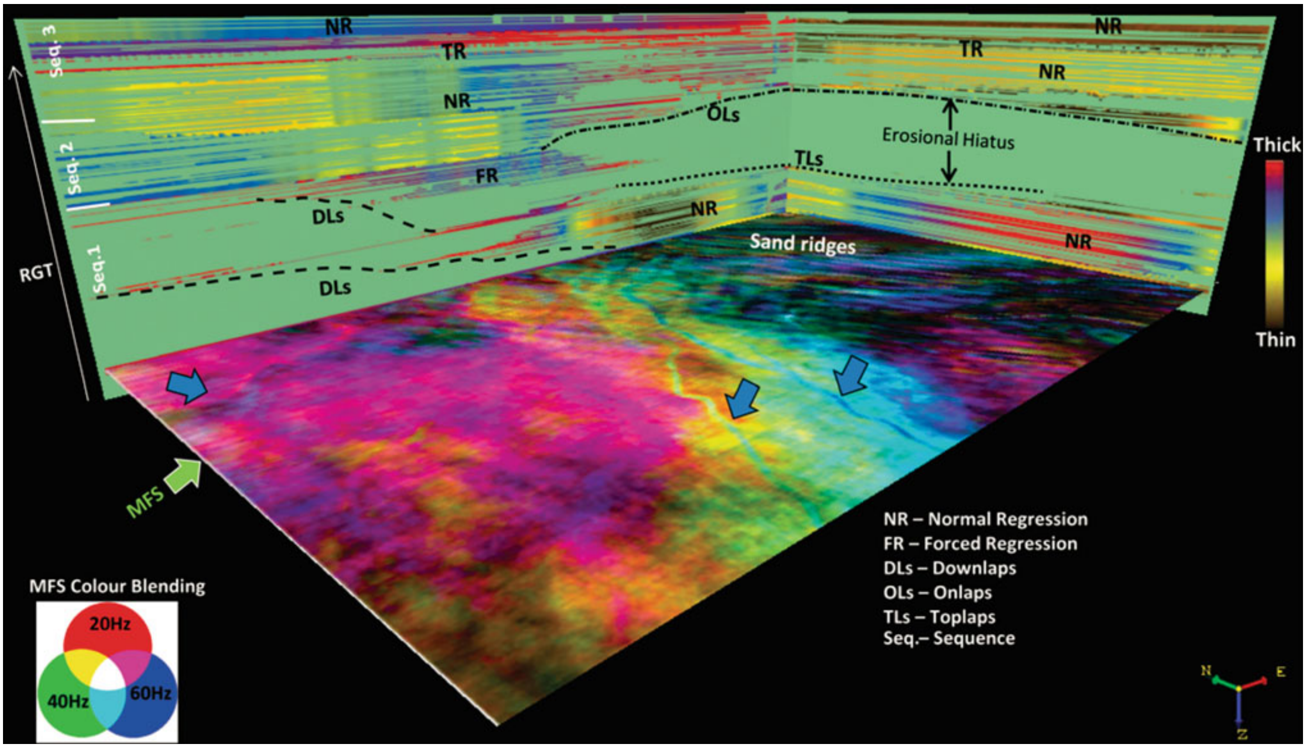


Fig. 8.34 4-D Wheeler diagram for the Pliocene interval shown in Fig. 8.31. The three-dimensional space (two horizontal dimensions plus relative time in the vertical dimension) is filled with information from the 4th dimension, systems tracts thickness in this case. The bottom slice is a colour-blended spectral decomposition attribute slice for a particular reflection event (in this case, a MFS, maximum flooding surface). Along the surface, several geomorphological features are identifiable—NE- to SW-direction flowing deep water channels (*blue arrows*) and NW-SE oriented elongated features that are interpreted as sand ridges comparable to those existing in the North Sea at the present day (Qayyum et al. 2015, Fig. 6)

8.11 High-Resolution Event Stratigraphy, Cyclostratigraphy and Astrochronology

Cyclostratigraphy and astrochronology are amongst the most active areas of stratigraphic research at the time of writing. While there are many success stories, including the development of reliable astrochronological time scales, with associated GSSPs, for much of the Cenozoic, and many individual studies of "floating" scales for parts of the older Phanerozoic (Hilgen et al. 2015), most of the successes relate to studies of deep-marine and lacustrine successions, where it could be expected that orbital control may act essentially undisturbed over millions of years within environments where autogenic influences are weak and other allogenic controls are longer-term and readily recognized. The cautions expressed by Miall and Miall (2004) should continue to provide guidance for researchers in this field. Amongst these are the following issues, which relate to all current research into high-resolution stratigraphic definitions and correlation, whether concerned with cyclostratigraphy or not:

The continuity of the stratigraphic record: The discussion in this chapter has focused on the issue of sedimentation rates and the ubiquity of "missing" time in the stratigraphic record. Hilgen et al. (2015) asserted that when an integrated approach is used to build a high-resolution time scale it can be demonstrated that many successions are complete at the Milankovitch time scale (10^4–10^5 years), although it is conceded that not all cycles, especially those of short period, may be recorded. It is conceivable that in some settings orbital forcing may be the dominant allogenic mechanism at orbital time scales, overwhelming or at least modifying autogenic processes, such as the control of fluvial style through a climatic control on fluvial runoff and sediment supply. In such cases, even the distribution of hiatuses in the record might illustrate orbital control. A case study of the Coniacian-Santonian (Upper Cretaceous) interval in the Western Interior of the United States (Locklair and Sageman 2008; Sageman et al. 2014) provides an excellent example of the use of multiple chronostratigraphic criteria in the establishment of more accurately dated stage boundaries and biozones, and the documentation of a 400-ka cyclicity in the Upper Cretaceous of the Western Interior Basin. They

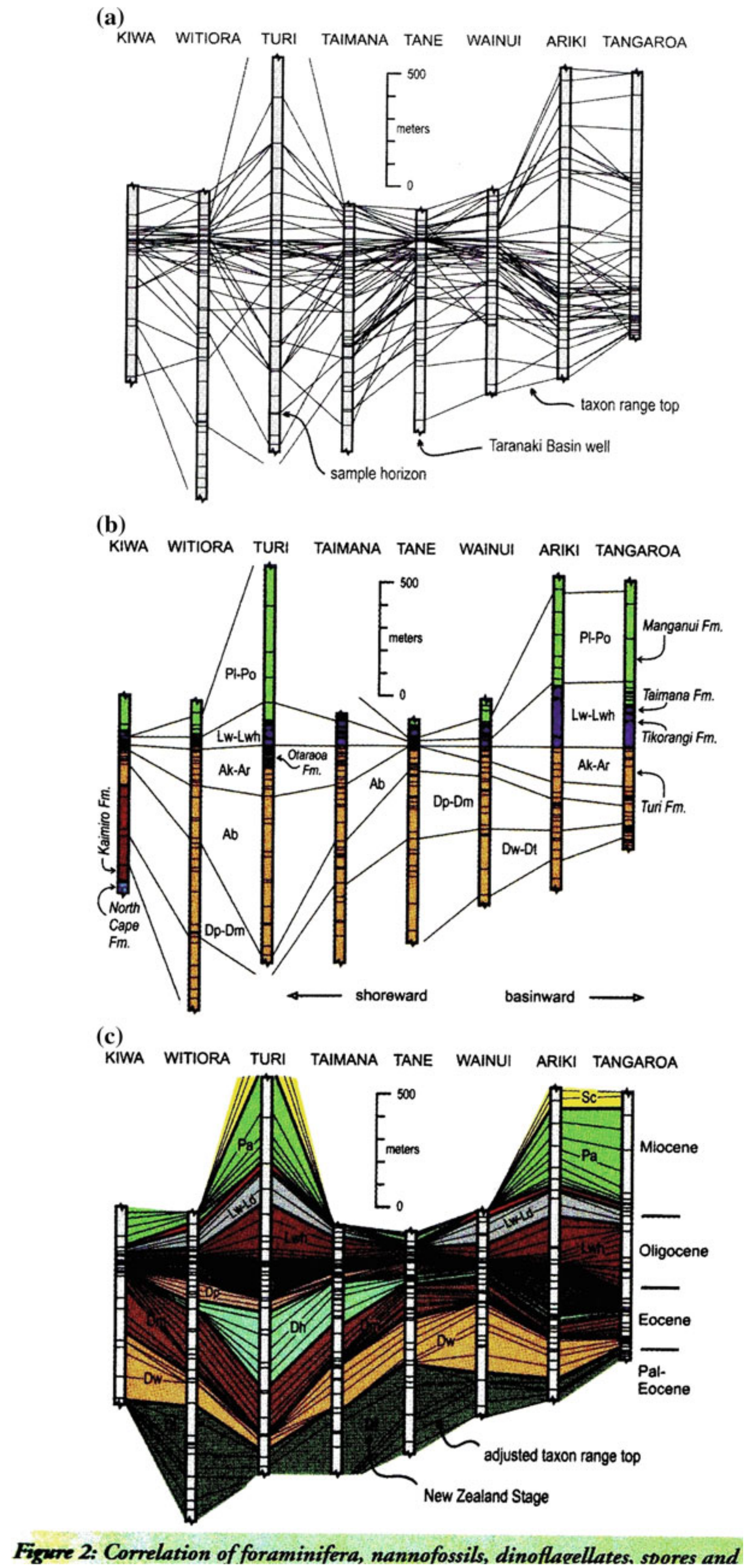


Fig. 8.35 Correlation of foraminifera, nannofossils, dinoflagellates, spores and pollen from 8 wells in New Zealand's Taranaki Basin. **a** Raw correlation of range tops of the 87 most reliable of 351 taxa. Range bases were potentially compromised by borehole caving. **b** Lithostratigraphy and traditional biostratigraphic correlation. **c** Outcome of automated correlation to a fully-resolved, composite, scaled time-line by minimal adjustment of observed ranges and insertion of missing taxa (Sadler et al. 2014, Fig. 2, p. 6)

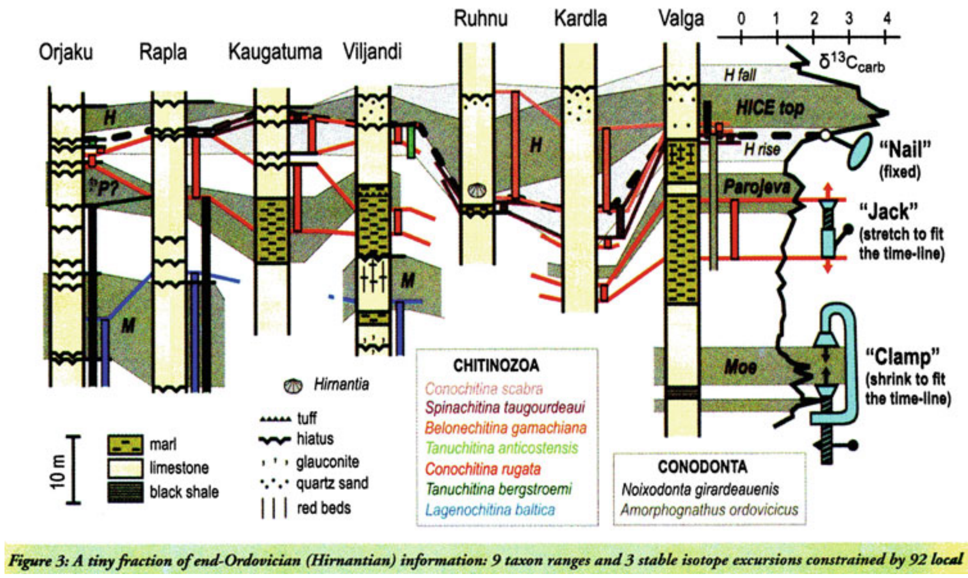


Fig. 8.36 A sample of end-Ordovician (Hirnantian) information: 9 taxon ranges and 3 stable isotope excursions constrained by 92 local event observations from 7 Estonian cores (see Sadler et al. 2014 for references). To align all cores with one sequence of events, some observed event pairs may be jacked farther apart (e.g. taxon range ends); others may be clamped closer together (e.g. uncertainty intervals on parts of stable isotope excursions); and some must be left in-place—the nailed horizons of steepest onset (*thick dashed line*) of the Hirnantian Isotopic Carbon Excursion (HICE) (Sadler et al. 2014, Fig. 3, p. 8)

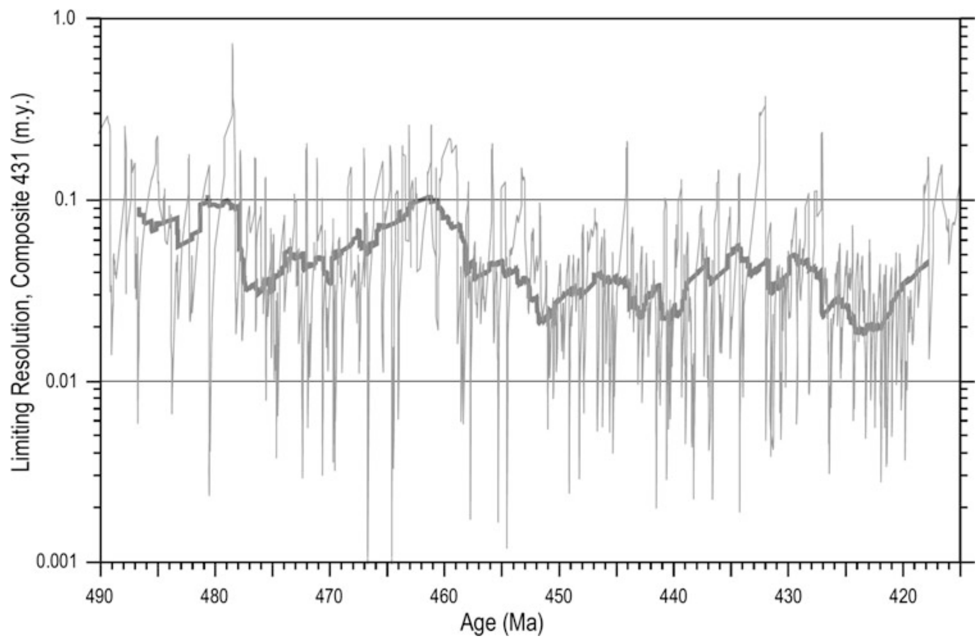


Fig. 8.37 Variation of potential resolving power as a function of age in an Ordovician-Silurian time scale generated by the computer-based optimization process described by Sadler et al. (2009). Differences in interpolated age were determined for all 3904 pairs of adjacent events. These highly variable data are summarized by 10-point (*thin gray line*) and 200-point moving averages (*thick gray line*), plotted at the center point of the moving window (Sadler et al. 2009, Fig. 8, p. 900)

commented that "The use of accurate radioisotope data sets to determine how time is distributed in the strata of interest becomes ever more challenging as the level of temporal resolution increases" (Sageman et al. 2014, p. 966).

Tuning-induced Milankovitch spectra: "The potential for Milankovitch frequencies to be introduced into records through astronomical tuning is well known and is a serious drawback" (Hilgen et al. 2015). Another issue is that autogenic and other allogenic processes can generate a cyclicity that may mimic an orbital cycle thickness spectrum (Algeo and Wilkinson 1988). The use of various statistical tests and a careful attention to the real cyclicity in actual stratigraphic data should alleviate this problem.

Potential error in the assignment of numerical ages to orbital successions: Until relatively recently, the ability of radiogenic dating systems to provide sufficiently accurate age determinations was a major stumbling block in the research on orbital control. As noted in Sect. 7.8.2, it is now

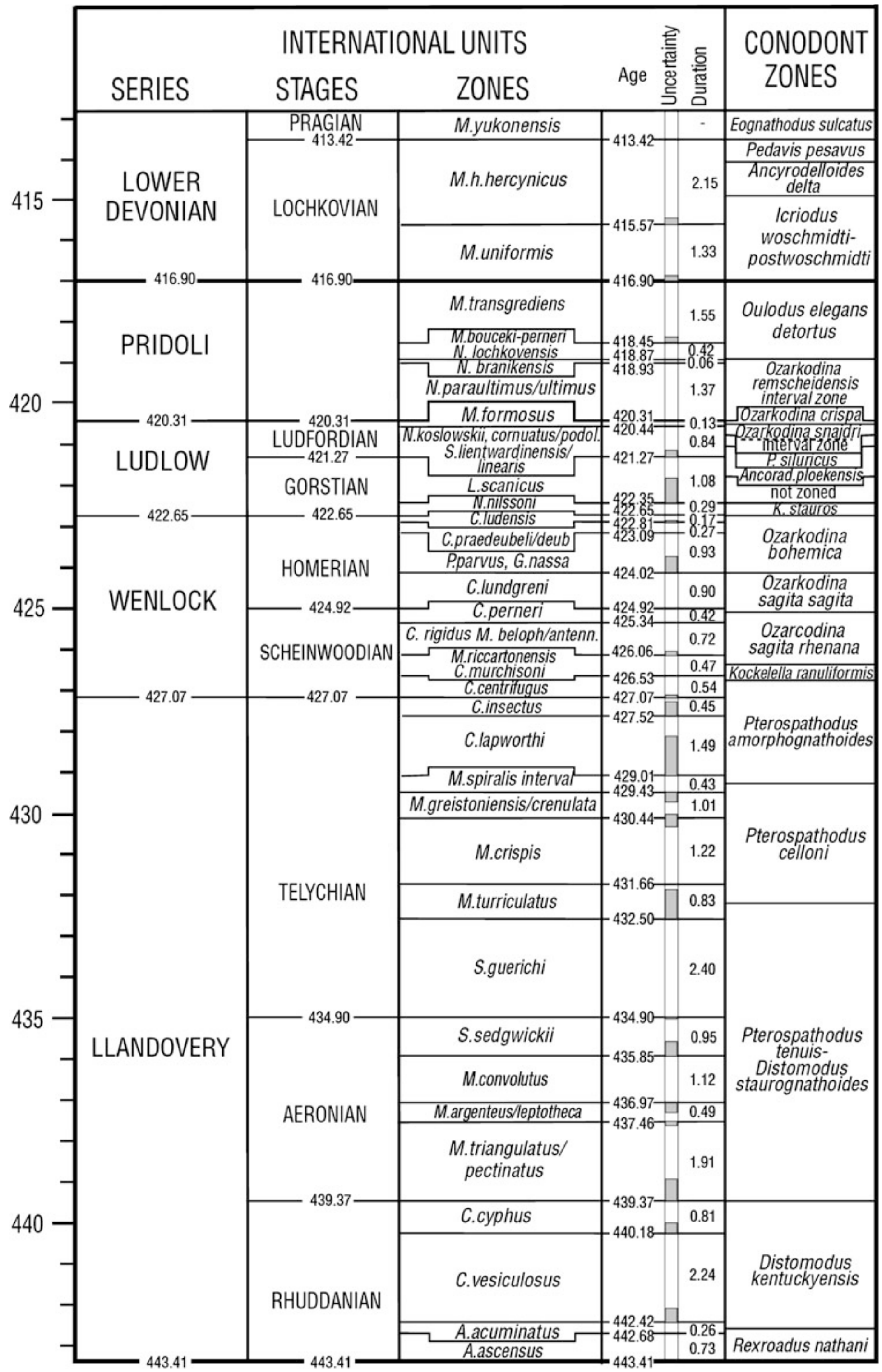


Fig. 8.38 An Ordovician-Silurian time scale developed by the automated processing of a chronostratigraphic data base consisting primarily of global graptolite occurrences. *Grey* intervals in the "uncertainty" *column* show the quantified potential error associated with each zone boundary (Sadler et al. 2009, Fig. 9, p. 901)

possible, under some circumstances, to develop numerical ages with uncertainties of ±0.1 % (e.g., 100,000 years at 100 Ma). This is at the scale of the long eccentricity cycle (405 ka) for Mesozoic rocks, which means that the extension of an astrochronological scale back into the Mesozoic may be possible. Systematic uncertainties in numerical dating, such as possible errors in a decay constant, are not a concern in the calculation of orbital frequencies and relative timing for floating sections, so long as the same systematics are used for all relevant age determinations. However, such potential error will still impact the development of a global time scale so long as these imprecisions remain of an order

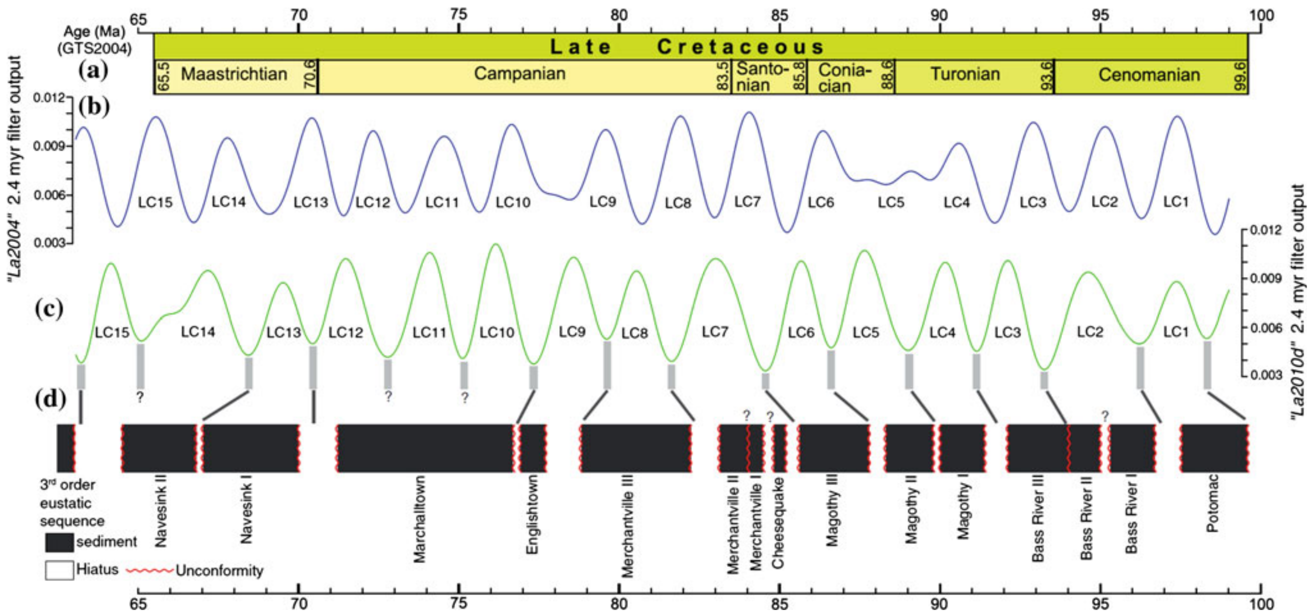


Fig. 8.39 Comparison of the Late Cretaceous (~64 to ~99 Ma) third-order eustatic sequences of New Jersey (Kominz et al. 2008; Browning et al. 2008) with ~2.4 million years orbital eccentricity cycles (Boulila et al. 2011, Fig. 8, p. 104)

of magnitude comparable to that of orbital frequencies. Current work to develop a High-Resolution Event Stratigraphy (HiRES) is discussed below.

The stability of astronomical frequencies through geologic time. The retrodiction of astronomical frequencies back through geologic time is itself an outcome of the careful, integrated stratigraphic studies emphasized in modern research (Hilgen et al. 2015). The most recent astronomical solutions of planetary behaviour suggest that eccentricity cycles have remained stable for the last 50–55 million years, with the 405 ka cycle unchanged for at least 250 million years. It is the 405-ka cycle that guides tuning for the early Cenozoic, and the floating scales of the Mesozoic and Paleozoic.

Many papers have been published in recent years offering cyclostratigraphic interpretations of local stratigraphic successions. It is common practice to show the sections in the time domain, which makes correlation to a calculated astrochronological scale straightforward. However, caution is to be recommended, because this practice may hide irregularities in the succession caused, for example, by autogenic processes. Time series analysis of sections in the thickness domain cannot be used to explore orbital control where there are significant autogenic effects on lithofacies and unit thicknesses. A recent cyclostratigraphic interpretation of the so-called "third-order" sequences of the New Jersey continental margin is a case in point (Boulila et al. 2011; e.g., Fig. 8.39 of this book). A time-depth plot for the five wells drilled through the Oligocene-Miocene succession on the continental slope (ODP Leg 150) reveals very irregular

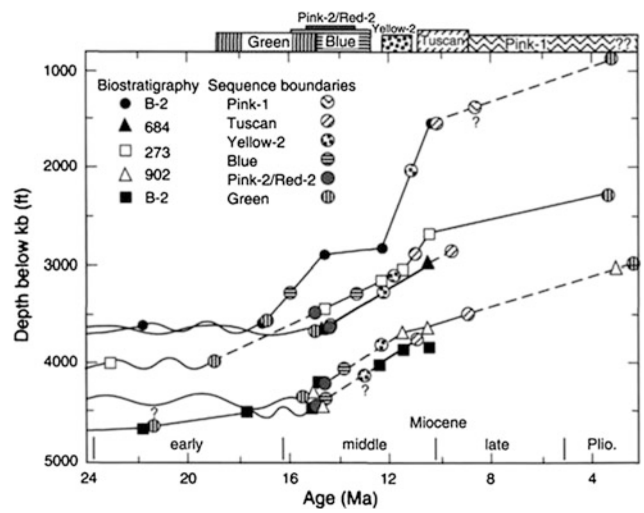


Fig. 8.40 Subsidence plots for drill holes on the New Jersey continental margin (Miller and Mountain 1994)

sedimentation rates (Miller and Mountain 1994; Fig. 8.40 of this book). Facies analyses of these deposits (Browning et al. 2008) indicates that they were deposited under a range of coastal, deltaic and shelf environments where autogenic redistribution of clastic sediment by wave, tide and other processes is ubiquitous (Fig. 8.41). Sequence analysis based strictly on empirical seismic, facies and biostratigraphic interpretations, indicates that, both in the thickness and time domains, sequence boundaries are quite irregularly spaced and there is no obvious cyclicity in the lithofacies successions (Kominz et al. 2008). Yet Boulila et al. (2011, Figs. 4, 6)

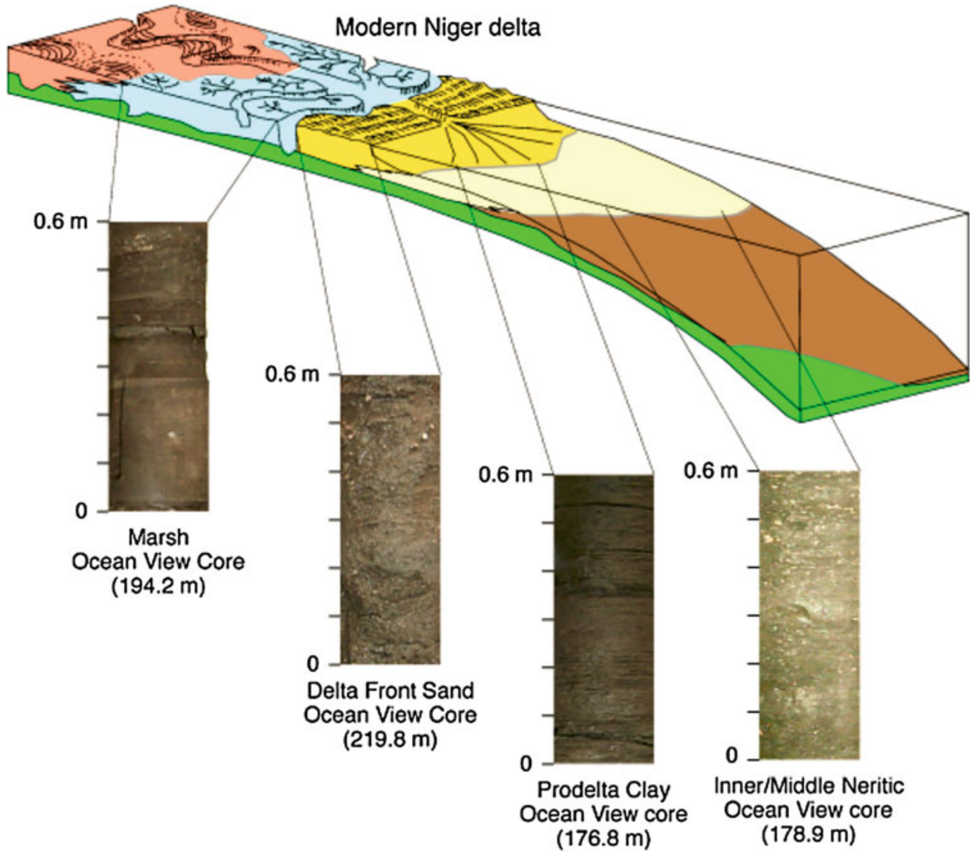


Fig. 8.41 A depositional model for the Niger delta, used as an illustration of the depositional environments and autogenic processes that, it is interpreted, were active on the New Jersey continental shelf during the deposition of the Early Cretaceous and Paleogene (from Browning et al. 2008, Fig. 7, p. 235)

show correlations to a calculated obliquity sequence characterized by 1.2-Ma cycles, or by 2.4-Ma cyclicity (Fig. 8.39). The sequence record and the obliquity record for the Oligocene-Miocene record show the same "number" of sequence boundaries for the 5–34 Ma time period, but there is not the same exact "match" for the Late Cretaceous cycles shown in Fig. 8.39, and otherwise there is nothing about the stratigraphy or the sedimentology of the succession that would suggest cyclostratigraphic control.

A more convincing example of cyclostratigraphic analysis is that of the Green River Formation, by Aswasereelert et al. (2013). Long identified as an example of an orbitally-forced stratigraphic succession (Bradley 1929), this recent study used the ages of six tephra layers interbedded with the approximately 350 m of section to generate a thickness-to-time transformation. Ages of the tephras were obtained with maximum errors of ±0.21 million years, and provided a model of modest, smooth changes in sedimentation rate. Detailed stratigraphic analysis confirmed the importance of the 100-ka astronomical cycle in sedimentological forcing that generated the distinctive layering in this well-known formation.

Where the evidence of autogenic activity, or of tectonic influence acting within a similar time scale to that of cyclostratigraphy (10^4–10^5-a) is strong, it is clearly incumbent on proponents of cyclostratigraphic control (especially for hanging sections representing the distant geological past) to do more than provide statistical "proof" of their reality, such as from amplitude spectra of time series studies. Stratigraphic sections should be shown in the depth domain, and a detailed facies analysis performed. Statistical analysis cannot take account of changes in facies or sedimentation rate, the presence of cryptic hiatuses, etc., without the use of special methods. The facies successions should be clearly cyclic, with regularity of facies and of unit thicknesses. Bailey (2009) discussed these and other problems, pointing out the difficulty of designing sufficiently rigorous statistical and other tests for the detection of orbital control. Meyers (2012) discussed the issue of "red noise" in stratigraphic sections, proposing statistical tests to evaluate the suitability of given data sets for cyclostratigraphic analysis. As he pointed out, it is possible for "noise to look like signal." Even random variation can generate "cycles" (e.g., Hiscott 1981).

The current "best practices" for chronostratigraphic analysis make use of the techniques of High-Resolution Event Stratigraphy, or HiRES. "The cornerstone of HiRES is the integration of every available piece of stratigraphic information into a single set of data that can be cross-correlated and internally calibrated" (Cramer et al. 2015, p. 138). Originally conceived by Kauffman (1986, 1988), the guiding principal is that there are many features of a sedimentary section, beyond biostratigraphy, that may be used to develop tools for correlation and dating.

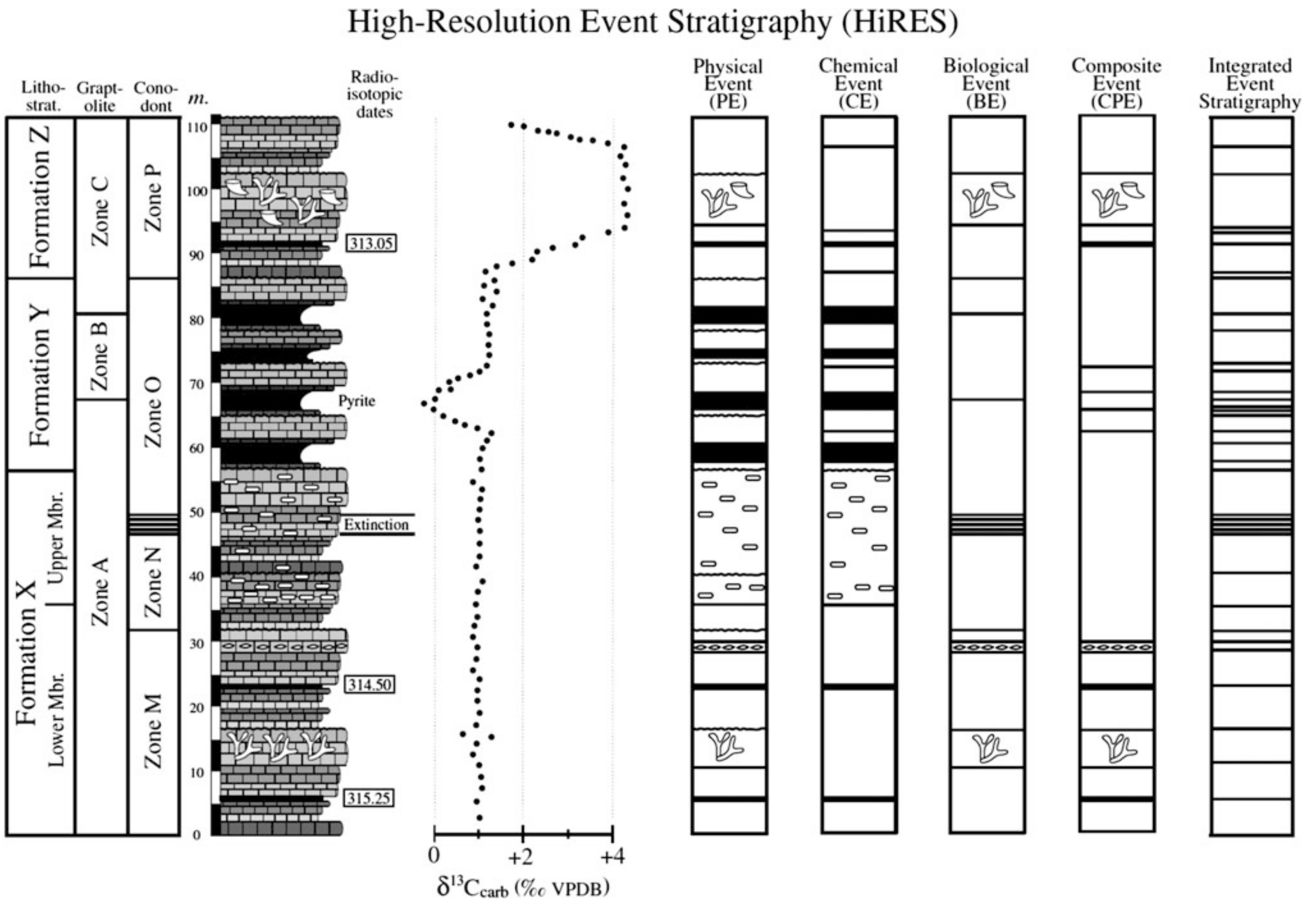


Fig. 8.42 Demonstration of High-Resolution Event Stratigraphy (HiRES) concepts and methods by using a hypothetical stratigraphic section and data (modified from Kauffman 1988). Lithostratigraphic nomenclature, biostratigraphy, lithostratigraphy, biotic events, radioisotopic age determinations, and stable carbon isotope stratigraphy shown at the *left*. The *right five columns* illustrate the principles of HiRES in which all stratigraphic information is included and a series of 'events' is delimited within the section. All of the chronostratigraphically useful horizons are combined into the integrated event stratigraphy at the far right. In principle, the lithostratigraphic names and biozones at the far left provide a total of 12 discreet horizons for correlation while the integrated event stratigraphy at the far right provides many more potential discreet horizons for correlation and an improved chronostratigraphic resolution (Cramer et al. 2015, Fig. 2, p. 139)

Stratigraphic events, such as storm beds, tephras, and flooding events, may have limited regional extents, but when used in combination across multiple stratigraphic sections and integrated with chemostratigraphic, magnetostratigraphic and other indicators, they may permit highly detailed stratigraphic syntheses to be developed. Figure 8.42 illustrates the principals involved in the development of an "integrated event stratigraphy." The application of this methodology is not necessarily straightforward. Individual events may be diachronous to a greater or lesser degree, particularly first and last occurrence taxon data, reflecting environmental control and migration patterns. For example, for HiRES work in the Paleozoic record, it remains a question whether conodonts or graptolites provide the most chronostratigraphically reliable information (Cramer, 2015). Other events, such as storm beds may be very confined in their distribution. Chemostratigraphic signatures vary in their diachroneity. Cramer et al. (2015, pp. 148–149) suggested that given the long residence time of strontium and the magnitude of the Sr reservoir in the marine environment, the $^{87}Sr/^{86}Sr$ composition of ocean waters should be quite stable over long time scales, whereas the shorter residence time of ^{13}C makes $\delta^{13}C$ a higher-precision chronostratigraphic tool, but one with an imprecision in the 10^{3-4}-year range reflecting a mixing time of a few thousand years.

Cramer et al. (2015, p. 144) suggested that the process of establishing and refining a HiRES chronostratigraphic record could be clarified by the use of three terms:

Geochronometry: refers to the numerical dating of stratigraphic events by the use of radioisotpes.

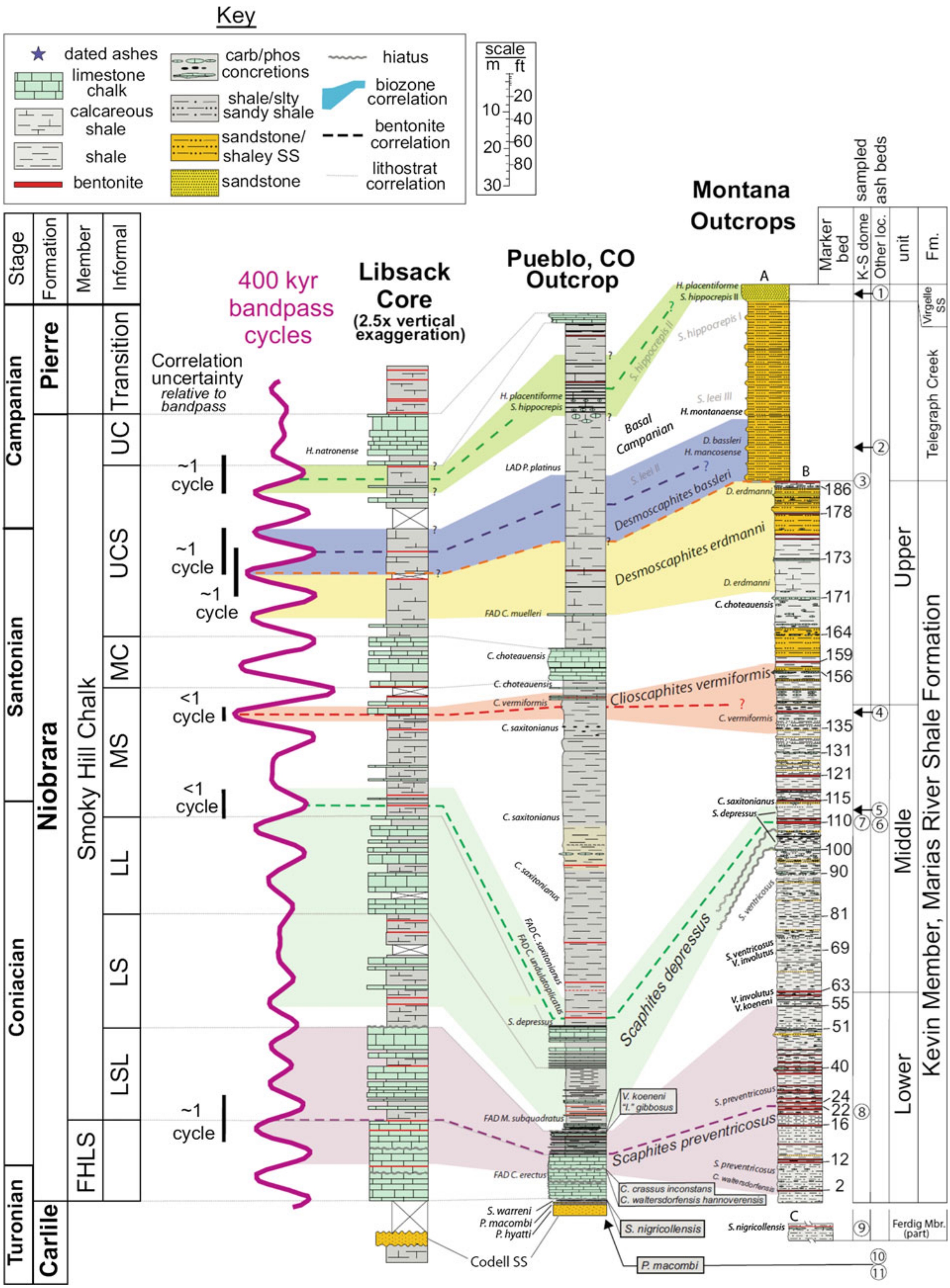


Fig. 8.43 Lithostratigraphic and biostratigraphic correlation of Coniacian-Campanian sections from Colorado to Montana, showing the 40-ka cycle record derived by time-series analysis (Sageman et al. 2014, Fig. 2, p. 959)

Geochronology: is the synthetic art of reconciling all available geochronologic and chronostratigraphic data to provide temporal calibration of the stratigraphic record.

Chronostratigraphy refers to the documentation, testing and calibration of a regional to global framework of age-dated stratigraphy.

The use of these three terms should help to illuminate what exactly is being done in each specific research endeavour. Thus, for example, a discussion of the potential error in correlation, in stratigraphic interval (expressed in metres) of a GSSP is an exercise in chronostratigraphy. The numerical calibration of a specific section is an exercise in geochronology. The laboratory processing of a sample and assignment of an age and range of error is geochronometry. In this last case, consideration of the specifics of precision and accuracy and the difference between them may become significant.

Locklair and Sageman (2008) and Sageman et al. (2014) reported on a study to investigate the cyclostratigraphy of the Niobrara Formation (Santonian-Coniacian) and laterally equivalent units in the Western Interior Basin of the United States. The chalk-marl cycles of the Niobrara were digitized using microscanner resistivity data from drill core. The 85-m core was divided into eight segments, corresponding to the lithologically-defined members of the formation. Ages were assigned using the available time scale for this unit, which is characterized by one of the best established chronostratigraphic records in the Phanerozoic time scale. The depth-to-time conversion and the analysis for orbital cyclostratigraphy were carried out using a succession of statistical methods. An essential step is a technique termed evolutive harmonic analysis (Locklair and Sageman 2008, Fig. 5), which is designed to take into account gradual changes in average sedimentation rate reflecting allogenic forcing at a time scale longer than that of orbital forcing. Calculated rates vary between 0.0075 and 0.0235 m/ka with an average of about 0.07 m/ka, which corresponds to SRS-9 and is a typical accumulation rate for orbital cycles (Miall 2015). The cyclostratigraphic analysis, carried out over successive segments of the core, suggested that sedimentation of this section at this locality was continuous at the 10^5-year scale, a conclusion supported by biostratigraphic analysis and bentonite correlations. Tuning to the temporally stable 400-year eccentricity period revealed obliquity and precessional frequencies in the record. The later study (Sageman et al. 2014) extended the cyclic analysis to other cores and to a series of outcrop sections in New Mexico, Utah and Montana (Fig. 8.43), in which the cyclostratigraphic analysis was combined with new radioisotope data with the objective of refining laboratory methods, recalibrating decay constants and developing more precise correlations between methods in order to increase the accuracy and precision of the Coniacian-Santonian time scale. The possible presence of hiatuses in the sampled sections was recognized to be a potential problem. Breaks with a length equivalent to a whole cycle or multiple of whole cycles may not be detected by spectral analysis (Meyers and Sageman 2004). The duration of several gaps that were suggested by biostratigraphic zonation were within the potential error of radioisotopic calibrations ($\sim 10^5$ years), which means that they could not be ruled out in the cyclostratigraphic analysis and require further study by means of regional correlations and additional data. This means that correlation to specific cycles in the 400-ka record could be in error by one or more cycles, but the results, nevertheless, represent a substantial increase in the accuracy and precision of this part of the Cretaceous time scale, and constitute a substantial contribution in the project to extend an astrochronological time scale back through the Mesozoic.

8.12 Conclusions

Two hundred years ago, William Smith gave us the first complete geological map (Smith 1815), and started us on the road to an understanding of Earth's geologic history. Lyell (1830–1833) gave us the necessary tools for interpretation, based on the principle of uniformitarianism, and Holmes, beginning a little more than one hundred years ago, began the development of the modern geological time scale (culminating in his first book: Holmes 1913). Barrell (1917) was the first to attempt to synthesize these critical developments, but most of his ideas were forgotten or ignored for decades. The development of the formal principles of stratigraphy, the evolution of sedimentology as a mature discipline, the stimulus provided by seismic stratigraphy, all have been necessary developments in the evolution of the modern synthesis that constitutes the science described in this book.

So where have we arrived at today, and what may we predict as possible future developments, and outcomes from the application of this science?

Analysis of depositional and erosional processes over the full range of time scales provides insights into long-term geological preservation. At time scales of days to months (10^{-1}–10^{-6} years), preservation of individual lithofacies units is essentially random, reflecting autogenic processes, such as diurnal changes in current speed and tidal activity. Packages of strata that survive long enough are subject to the next cycle of preservational processes, such as autogenic channel switching, the "100-year flood", or storm activity at the 10^0–10^3-year time scale. At the 10^4–10^5-year time scale, so-called "high-frequency" geological processes come into play, including orbital forcing of climate and sea level, and local tectonic episodicity. Ultimately, all remaining stratigraphic accumulations are subject to the long-term (10^6–10^7-year) geological (largely tectonic) controls on basin accommodation (Miall 2014b).

An important insight emerging from this analysis has critical implications for the application of uniformitarianist principles. Geological processes interpreted from successions accumulated over the post-glacial period, such as those of the Mississippi and Rhine-Meuse deltas (descriptions and analyses of which comprise substantial contributions to sedimentological literature on fluvial and deltaic systems) can only be used as analogs for interpretations of geological processes up to the 10^4-year time scale. The geological record contains many examples of coastal fluvial-deltaic successions spanning millions of years, but a 10^6–10^7-year record cannot be interpreted simply by "scaling-up" an analysis carried out on a 10^4–10^5-year time scale. Firstly, coastal succession such as those on present-day continental margins could be largely eliminated by subaerial erosion during the next glacial cycle of lowered sea-level, as the geological preservation machine begins to operate over the next longer-time scale. Secondly, the time-scales implied for sedimentary processes would be wrong. For example, sequence models for fluvial systems, which relate channel stacking behaviour to rates of sedimentary accommodation, are largely based on measurements of rates of sedimentation and channel switching in modern rivers and in post-glacial alluvial valley-fills, at time scales no greater than 10^3 years. Applications of these models to the ancient record deal mostly with so-called "third-order" sequences (durations in the 10^6-year range) for which calculated accumulation rates are one to three orders of magnitude slower than those on which the sequence models are based (Miall 2014a). Colombera et al. (2015) confirmed, by a detailed study of twenty ancient fluvial systems, that there is no relationship between channel stacking pattern and aggradation rate. It is suggested that the observed changes in channel-stacking patterns that have been observed in the rock record are the product of longer-term processess, such as tectonically-controlled changes in paleoslope or sediment supply (Miall 2014a).

Modern stratigraphic techniques are at the very core of current methods of petroleum exploration and development. Figure 8.44 is an excellent example of a continuing major thrust in the petroleum industry, the development of ever more sophisticated techniques of seismic data acquisition, processing and visualization. The image shown here is from an advertisement appearing in "*AAPG Explorer*", the monthly news magazine of the American Association of Petroleum Geologists. It shows an example of the type of seismic imagery now being developed in the highly competitive field of seismic exploration. It is from an area of the world that has received considerable attention from the industry in recent years because geophysicists have developed techniques for "seeing" through the thick layers of evaporites that occur near the bottom of the sedimentary layer on the floor of the Gulf of Mexico. The so-called

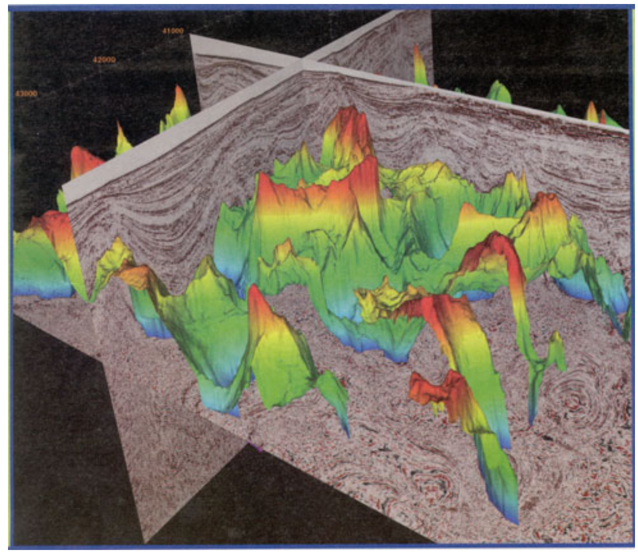


Fig. 8.44 An image generate from three-dimensional seismic data showing the upper surface of a salt horizon in the Gulf Coast, intersected by vertical and horizontal 2-D sections (Petroleum Geo-Services, Houston)

"sub-salt play" has been the hottest area of exploration in North America for several years, and is finding increasing application in other comparable basinal settings worldwide, such as the deep Atlantic Ocean, offshore from Brazil and Angola. Other examples of advanced seismic techniques are illustrated and discussed in Chap. 6. The increasingly precise information now obtainable from seismic data, together with the modern techniques of directional drilling, and geosteering, backed up by sequence-stratigraphic mapping and detailed chronostratigraphic control, have substantially improved the odds of successful drilling in frontier areas. On a smaller scale, such detail is also an essential component of projects to efficiently exploit heavy oil using in situ methods. Issues such as shale distribution and bed length, and reservoir cap integrity, are key to the successful use of the steam-assisted gravity drainage (SAG-D) method for oil extraction in the Alberta Oil Sands.

Fresh water is a critical natural resource. About one quarter of the world's supply is stored in the ground (most of the rest is in major ice caps), and its health is very much a concern of sedimentary geologists. Groundwater movement depends on the porosity and permeability architecture of the rocks (mostly sediments) through which water moves. In some deep basins, groundwater bodies at depth contain enough heat to offer considerable potential for geothermal power generation. Hydrogeology involves many of the same stratigraphic approaches utilized by petroleum geologists. The tracking and treatment of pollutants involves adaptations of traditional geological methods of exploration and remote sensing, including down-hole petrophysics, high-resolution seismic exploration and ground-penetrating radar.

One of the lines of evidence that modern climate scientists point to as an indication of the anthropogenic influence on climate is the supposed rapidity with which global warming has occurred (essentially all of which has taken place since about 1850) compared with the supposedly much slower rates of change that can be observed in the geological record. In fact, earth scientists have not been able to either prove or disprove this assertion because the accuracy and precision of the geological time scale for deep time has not permitted refinements in the dating of geological events down to the 10^2-year time scale. The development of the astrochronological time scale is getting is closer, with a time scale in a 10^{4-5}-year accuracy range, but this gap is unlikely ever to be completely closed. However, refinements in the paleoclimatic reconstructions from the stratigraphic record, in terms of the scope, type, and rate of past climate change, should be able to provide much better comparisons, and analogues for testing climate models and understanding Earth's behaviour under different climatic conditions than have been available in the recent past.

High-resolution stratigraphic studies are increasingly pointing to a much more complex climatic history during the Cretaceous than the simple, long-term "greenhouse" that has long been assumed. Studies in both the American and Canadian portions of the Western Interior Basin, some of which are referred to elsewhere in this book, are providing ever more convincing evidence for what Miller et al. (2005) referred to as "cold snaps", in the isotopic record, in the recognition of cyclostratigraphic signatures, and in the record of erosion surfaces that can be traced for hundreds, if not thousands of kilometres, indicating likely glacioeustatic control on sedimentation.

In a more general sense, as the well-known sedimentologist Harvey Blatt said in 1982: "Sediments and sedimentary rocks are the only source of knowledge about conditions on the Earth's surface before the invention of written language a few thousand years ago." Historical geology depends largely on the study of the stratigraphic record. It is from the rocks that we know about the evolution of life, the plate-tectonic development of the earth's crust, and ancient climate changes. Continued detailed study, and the development of new techniques, can therefore be expected in the future.

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