Series

PALEOSCENE 16. Sequence Stratigraphy and Chronostratigraphy: Problems of Definition and Precision in Correlation, and Their Implications for Global Eustasy

Andrew D. Miall
Department of Geology
University of Toronto
Toronto, ON M5S 3B1

ABSTRACT

Sequence stratigraphy, as proposed by the Exxon school, represents a new paradigm in geology, whereby sequences are regarded as eustatic in origin, and are therefore to be considered superior, as chronostratigraphic indicators, to all other recorders of stratigraphic age. Such an approach is built on circular reasoning and may result in a sequence framework consisting of a poorly correlated assortment of regional events with little or no global significance.

Sequence correlation beyond the physical tracing that can be accomplished within an individual basin depends on the use of conventional chronostratigraphic indicators, primarily biostratigraphy.

Biostratigraphic correlation is characterized by imprecisions reflecting the rates of evolution and fossil preservation. Global correlation and dating of biozones is hampered by faunal/floral provincialism and errors inherent in numerical (*e.g.*, radiometric) dating. At present, the best available chronostratigraphic dating methods contain potential errors of up to a few million years. This is equal to or greater than the event spacing of the "third-order cycles", which constitute the main subdivisions of Exxon's global cycle chart. Therefore, sequence frameworks in different basins cannot be reliably distinguished on the basis of chronostratigraphic evidence. Much research indicates the importance of regional tectonic processes in the generation of stratigraphic sequences. For this reason, the test of global synchroneity remains central to a resolution of the tectonic-*versus*-eustatic debate for these cycles, and this currently constitutes one of the most vigorous and exciting areas of stratigraphic research.

RÉSUMÉ

La notion de stratigraphie séquentielle telle que proposée par l'école de pensée de Exxon constitue un paradigme nouveau en géologie. Selon ce nouveau paradigme, les séquences présentent un caractère eustatique à l'origine et par conséquent, doivent être considérées comme des marqueurs stratigraphiques d'une classe supérieure à tous les autres marqueurs chronostratigraphiques. Une telle approche repose sur un raisonnement tautologique qui pourrait donner lieu à un arrangement des séquences constituées d'événements régionaux mal corrélés et ayant peu ou pas de valeur à l'échelle planétaire.

Une corrélation séquentielle qui dépasse la simple reconnaissance de caractères physiques à l'intérieur d'un bassin particulier dépend de l'utilisation de marqueurs chronostratigraphiques conventionnels, principalement biostratigraphiques.

La corrélation biostratigraphique comporte des imprécisions provenant de la variabilité des taux d'évolution et de préservation des fossiles. L'existence de provincialismes fauniques ou floraux ainsi que d'erreurs inhérentes aux datations chiffrées (c-.à-d. radiométriques) nuisent aux corrélations à l'échelle planétaire ainsi qu'aux datations de biozones. Les meilleures méthodes actuelles de datation comportent des erreurs possibles de quelques millions d'années. Cela équivaut à des écarts qui équivalent ou qui sont plus grands que ceux des « cycles de troisième ordre de grandeur », lesquels constituent les principales subdivisions du diagramme des cycles planétaires de l'école de Exxon. Par conséquent, on ne peut différencier de manière fiable les arrangements séquentiels de différents bassins, en se basant sur des critères chronostratigraphiques. De nombreuses recherches montrent l'importance des mécanismes tectoniques régionaux dans l'élaboration des séquences stratigraphiques. En conséquence, voilà pourquoi le test de synchronisme planétaire est encore d'une importance vitale dans la détermination du caractère tectonique ou esutatique de ces cycles. Et présentement cela constitue l'un des champs de recherche des plus dynamiques et des plus excitants en stratigraphie.

INTRODUCTION

Sequence stratigraphy encompasses two distinct, and quite different conceptual models, both originating with the new methods of analyzing regional seismic-reflection data that were proposed by Vail *et al.* (1977). As noted by Carter *et al.* (1991, p. 42,60):

> One model relates to presumed sea-level behaviour through time; the other model relates to the stratigraphic record produced during a single sea-level cycle. Though the two models are interrelated they are logically distinct, and we believe that it is important to test them separately. ... Our studies lead us to have considerable confidence in the correctness and power of the Exxon sequence-stratigraphic model as applied to sea-level controlled, cyclothemic sequences. ... At the same time, we suspect that the Exxon 'Global' sea-level curve, in general, represents a patchwork through time of many different local relative sea-level curves.

The main purpose of this paper is to examine the stratigraphic basis for the global eustasy model. The work of P.R. Vail and his colleagues and co-workers is examined in detail, because their work has been so widely quoted and their global cycle chart is evolving toward the status of a stratigraphic standard, which gives it a particular prominence and importance. Sequence stratigraphy as a framework for regional and local stratigraphic-sedimentologic studies (*e.g.*, Vail, 1987; Wilgus *et al.*, 1988) is not discussed in this paper.

The global cycle model represents a new paradigm in geology. It has been proposed that stratigraphic sequences are superior as chronostratigraphic indicators to all other forms of stratigraphic data, because they were generated by synchronous global eustatic processes. According to this view, they therefore comprise the ideal basis for a superior standard of geological time. While considerable use is made of biostratigraphic and other conventional data for the dating and correlating of sequences, the new paradigm explicitly subordinates these data to the sequence framework, thereby downplaying the efforts of more than 200 years of stratigraphic research to develop and refine a geological time scale based primarily on painstaking biostratigraphic research (*e.g.*, see Harland *et al.*, 1990). It is on the basis of the new paradigm that the global cycle chart of Vail *et al.* (1977) and its subsequent revised version (Haq *et al.*, 1987, 1988b: the "Vail curve" or the "Exxon global cycle chart") was built. The main theoretical basis for the paradigm is the supposition that global stratigraphic architecture is controlled primarily by eustatic sea-level changes with an episodicity in the range of 1-10 m.y. (the so-called third-order cycles).

It is commonly forgotten that the basic premise of the paradigm remains unproven. There is no convincing, independent evidence that a suite of globally correlatable eustatic cycles on this scale exists. The critical test of the Exxon chart is, therefore, to demonstrate that successions of cycles of precisely similar age do indeed exist in many tectonically independent basins around the world (Miller and Kent, 1987; Gradstein *et al.*, 1988; Miall, 1992). The chronostratigraphic accuracy and precision of the chart and of the field sections on which it is based are, therefore, of critical importance. This requires independent studies of sequence stratigraphies in tectonically unrelated basins. Unfortunately, this is often not what is done. While biostratigraphers continue to refine the stratigraphic framework in individual basins, many sequence studies begin by using the Exxon chart as a template for stratigraphic correlation (*e.g.*, Olsson, 1988; Baum and Vail, 1988; most of the papers in Ross and Haman, 1987). Successful correlations are then presented as confirmation that the cycle chart is correct (*e.g.*, Baum and Vail, 1988), and excellent local evidence may even be distorted or ignored in favour of a correlation with the Exxon curve (Hancock, 1993a). The dangers of circular reasoning are obvious.

Virtually none of the events in the Exxon chart has received independent *global* confirmation by careful chronostratigraphic work. A few exceptions might include such major events as the mid-Oligocene eustatic drop related to rapid build-up of Antarctic ice (Pitman, 1978; Miller and Kent, 1987). A few specific events in the Cretaceous were discussed by Hancock (1993b), and this topic receives lengthy treatment in Hallam (1992). Most of the careful local independent studies that have been carried out (*e.g.*, Hubbard, 1988; Carter *et al.*, 1991; Underhill, 1991; Hancock, 1993a,b) indicate significant departures from the Exxon curve. How, then, is the basic premise of the Exxon chart, that globally correlatable cycles actually exist, to receive an independent test and confirmation? I suggest that existing approachs are seriously flawed.

It is the main objective of this paper to argue that current chronostratigraphic dating techniques do not permit the level of accuracy and precision in sequence correlation claimed for the global cycle charts that have been published by Peter Vail and his former Exxon colleagues and co-workers. Regional cyclicity of relative sea level on a 1-10 m.y. ("third-order") time scale can be amply demonstrated from the stratigraphic record, but we cannot yet convincingly isolate any global eustatic signal. Until this has been done it is premature to construct a "global" cycle chart.

THE GLOBAL EUSTASY PARADIGM

Peter Vail and his co-workers have made the theoretical basis for their global-eustasy model quite clear. For example, in their first major publication they stated:

> One of the greatest potential applications of the global cycle chart is its use as an instrument of geochronology. Global cycles are geochronologic units defined by a single criterion — the global change in the relative position of sea level through time. Determination of these cycles is dependent on a synthesis of data from many branches of geology. As seen on the Phanerozoic chart ..., the boundaries of the global cycles in several cases do not match the standard epoch and period boundaries, but several of the standard boundaries have been placed arbitrarily and remain controversial. Using global cycles with their natural and significant boundaries, an international system of geochronology can be developed on a rational basis. If geologists combine their efforts to prepare more accurate charts of regional cycles, and use them to improve the global chart, it can become a more accurate and meaningful standard for Phanerozoic time. (Vail *et al.*, 1977, p. 96).

This approach has been used throughout the Exxon work. For example, with reference to the Jurassic of the North Sea, Vail and Todd (1981, p. 217) stated that "several unconformities cannot be dated precisely; in these cases their ages are based on our global cycle chart, with age assignment made on the basis of a best fit with the data."

An example of this approach is given later in this same paper (p. 230) where Vail and Todd stated, "the late Pliensbachian hiatus described by Linsley and others (1979) fits the basal early Pliensbachian sequence boundary on our global cycle chart." In other words, the age assignment of the earlier workers is subordinated to the sequence framework. The Pliensbachian stage is now estimated to span approximately 7 m.y., which provides an indication of the magnitude of the revision Vail and Todd (1981) are willing to make based on their

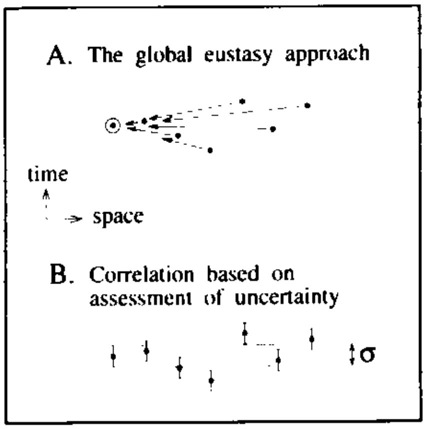


Figure 1 *Two approaches to the correlation of stratigraphic events.*

sequence analysis. Vail *et al.* (1984, p. 143) stated, "Interpretations [of stratigraphic sequences] based on lithofacies and biostratigraphy could be misleading unless they are placed within a context of detailed stratal chronostratigraphic correlations."

The context of the word "chronostratigraphic" in this reference implies correlation by tracing seismic reflections. Baum and Vail (1988, p. 322) stated that

> sequence stratigraphy offers a unifying concept to divide the rock record into chronostratigraphic units, avoids the weaknesses and incorporates the strengths of other methodologies, and provides a global framework for geochemical, geochronological, paleontological, and facies analyses.

Baum and Vail (1988) commented on the inconsistent placement of stage boundaries in the Cenozoic section of

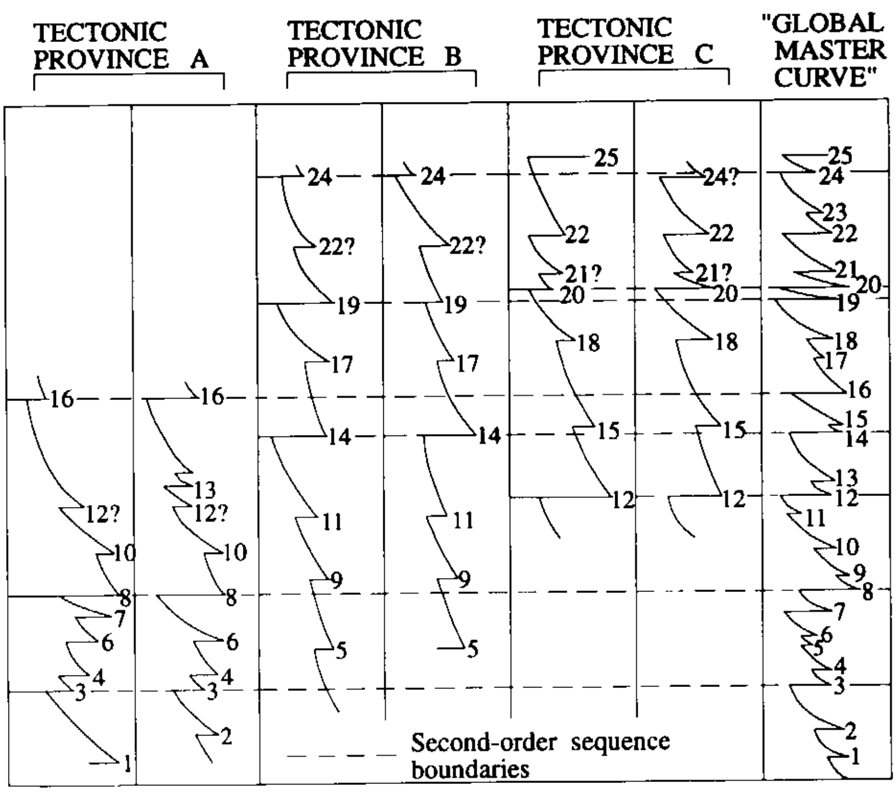


Figure 2 *The construction of a "global master curve" of stratigraphic events from local sequences of events in three separate tectonic provinces, based on the assumption that each event is globally synchronous. The "master list" of events (numbered 1 to 25) is not present in complete form in any single locality, and very few individual events may be correlated between tectonic provinces. Events indicated with question marks may or may not be correlated with those in other tectonic provinces, depending on assumptions that must be made about acceptable imprecision in chronostratigraphic correlation. The curves are drawn in this diagram to simulate the Exxon method of plotting coastal onlap. Some of the larger onlap events are labelled as second-order sequence boundaries, and may reflect regional plate-tectonic events. The other events reflect regional tectonic events related to in-plane stress, basin subsidence, etc. In the Exxon method all the events are interpreted to be eustatic (global) in origin. "Missing" events at any given locality are attributed to local tectonism, removal by erosion, etc.*

the Gulf Coast. Some are at sequence boundaries, others at other major types of surface (such as transgressive surfaces) within sequences. They recommended the use of a sequence framework for redefining the stages, and defining the stage boundaries at the correlative conformities of the sequences. This approach indicates a misunderstanding of the purpose of erecting an independent stage framework for chronostratigraphic purposes.

An example of a standard Exxon-type sequence analysis was provided by Mitchum and Uliana (1988). Their correlation of a carbonate basin-margin section in a backarc setting with the global cycle chart was done on the basis of a general positioning of the stratigraphy within the Tithonian-Valanginian interval, by comparison (not detailed correlation) of the subsurface with nearby outcrops, where ammonite zonation had been carried out. No faunal data were available from the wells used to correlate the seismic section! However, the pattern of seismic sequence boundaries was said to match the global pattern for this interval.

Vail *et al.* (1991) stated that sequences "can be used as chronostratigraphic units if the bounding unconformities are traced to the minimal hiatus at their conformable position and age dated with biostratigraphy" (p. 622), and "Sequence cycles provide the means to subdivide sedimentary strata into genetic chronostratigraphic intervals ... Sequences, systems tract, and parasequence surfaces provide a framework for correlation and mapping." (p. 659)

As is made clear by these quotes, the Exxon approach subordinates biostratigraphic and other data to the sequence framework, where conflicts arise. It fails to recognize the fundamentally independent nature of these data. The Exxon method is essentially that summarized in Figure 1A. The assumption is made that an important sea-level event in any given stratigraphic section represents a eustatic event. From the paradigm of global eustasy it then follows that a comparable pattern of sea-level events in other sections is, by definition, correlated with the original event, even when the chronostratigraphic data may not support such correlations. The application of this approach to correlation in order to construct a "global master curve" is illustrated in Figure 2. Figure

1B illustrates schematically the quantitative approach to correlation, which is to attach error bars to assigned ages, based on numerical estimates of age, calculations from sedimentation rates, *etc.* A correlation band may then be erected based on standard error expressions, such as standard deviations. The accuracy and precision of correlations can readily be assessed from such diagrams.

Miller and Kent (1987), while arguing for the need for careful chronostratigraphic correlation, point out that "the durations of the third-order cycles are at the limit of biostratigraphic resolution." They go on to state:

> We agree that in order to test the validity of the third-order cycles it is not necessary to establish that *every* [their emphasis] third-order cycle is precisely the same age on different margins. Haq and others (1987) utilized a sequence approach to recognize third-order events above known datum levels. Assuming that they observed the same patterns on different margins, their observation of the same ordinal hierarchy of events within a given time window on different margins argues against a local cause and points to eustatic control. ... However, the simple matching of third-order cycles between locations is complicated by gaps in the records, uncertainties in establishing datum planes, and the ability to discriminate between these cycles at the outcrop level.

Miller and Kent (1987) and Miall (1991a) have pointed out some of the problems and imprecisions in chronostratigraphic correlation. Ricken (1991, p. 773) stated:

> Without a precise time control the depositional mechanisms forming beds and sequences cannot be sufficiently understood. ... timing has remained an elusive problem. Too many inaccuracies are involved in resolving stratigraphic durations, including a large range of error in radiometric age determinations, poor biostratigraphic as well as magnetostratigraphic resolution, and an incompleteness of sedimentary sections. As a result, time estimates are commonly imprecise, and the range of error is often larger than the actual time span considered ...

A very similar point was made by Christie-Blick *et al.* (1988) and Gradstein *et al.* (1988). It is an examination of this subject that forms the main purpose of this paper.

The dangers inherent in simple pattern recognition, of the type alluded to by Miller and Kent (1987) are that, given the density of stratigraphic events present in the Vail curve, there is literally an "event for every occasion" (Miall, 1992). Practically any stratigraphic succession can be made to correlate with the Vail curve, even synthetic sections constructed from tables of random numbers (Miall, 1992). Dickinson (1993), in a discussion of this paper, demonstrated that the average duration of third-order cycles in the Exxon chart increases with age, and suggested that this reflects a decrease in the quality of the sequence data in older sections; in other words, the event spacing is at least in part an artefact of the data quality and the analytical methodology used to construct the chart. Haq *et al.* (1988a) referred to a procedure of "rigorous pattern matching" of sequences and systems tracts, but have nowhere described their methodology or attempted to quantify the degree of "rigour".

THE INCOMPLETENESS OF THE STRATIGRAPHIC RECORD

One of the features of the existing geological time scale that Vail *et al.* (1977) expressed concern about is that "the boundaries of the global cycles in several cases do not match the standard epoch and period boundaries." This remark reflects a historical appreciation of the almost accidental way by which many of these boundaries were determined by the methods of Oppel and D'Orbigny during the 19th and early 20th centuries (Hancock, 1977). Yet it displays an ignorance or misunderstanding of the modern approach to the calibration of the time scale. Time is continuous, whereas the events that we have historically used to document it in the geological record have commonly been prominent breaks, such as major unconformities or facies changes. The problem with using a hiatus as a chronostratigraphic boundary is that a hiatus represents missing time that is bound to be represented by a sedimentary record somewhere else (Hedberg, 1976). It is possible that entire sequences could be missing at such hiatuses. Vail would seemingly wish us to continue this approach, which carries the danger of circular reasoning in placing undue emphasis on significant "events" that are presumed to be synchronous in different areas. The modern approach to defining the chronostratigraphic record is to place boundaries within continuous successions, specifically avoiding sections that contain significant stratigraphic events, such as disconformable sequence boundaries (current practice is described by Miall, 1990, section 3.7).

It has become a geological truism that many sedimentary units accumulate as a result of short intervals of rapid sedimentation separated by long intervals of time when little or no sediment is deposited (Ager, 1981). Therefore, although time is continuous, the stratigraphic record of time is not. Time, as recorded in the stratigraphic record, is discontinuous on several time scales. Breaks in the record range from such trivial events as the nondeposition or erosion that takes place in front of an advancing bedform (a few seconds to minutes), to the nondeposition due to drying out at ebb tide (a few hours), to the summer dry periods following spring run-off events (several months), to the surfaces of erosion corresponding to sequence boundaries (tens to at least hundreds of thousands of years), to the longer breaks caused by tectonism, up to the major regional unconformities generated by orogeny (millions of years). There is a similarly wide variation in actual rates of continuous accumulation, from the rapid sandflow or grainfall accumulation of a cross-bed foreset lamina (time measured in seconds), and the dumping of graded beds from a turbidity current (time measured in hours to days), to the slow pelagic fill of an oceanic abyssal plain (undisturbed for hundreds or thousands of years, or more).

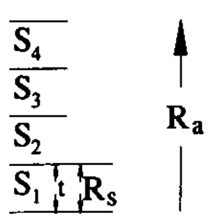
It is now widely realized that rates of sedimentation measured in modern depositional environments or the ancient record vary in inverse proportion to the time scale over which they are measured. Sadler (1981) documented this in detail, using 25,000 records of accumulation rates. His sythesis showed that measured sedimentation rates vary by 11 orders of magnitude, from 10^{-4} to 10^{7} m/ka. This huge range of values reflects the increasing number and length of intervals of nondeposition or erosion factored into the measurements as the length of the measured stratigraphic record increases. Miall (1991b) 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.*). Crowley (1984) determined by modelling experiments that as sedimentation rate decreases the number of time lines preserved decreases exponentially, and the completeness of the record of depositional events decreases linearly. Low-magnitude depositional events are progressively eliminated from the record.

Many workers, including Berggren and Van Couvering (1978), Ager (1981), Sadler (1981), McShea and Raup (1986), nsele *et al.* (1991b), and Ricken (1991) have been aware of the hierarchical nature of stratigraphic events, and the problem this poses for evaluating the correlation of events of very different time spans. Algeo (1993) proposed a method for estimating stratigraphic completeness based on preservation of magnetic reversal events. The method is most suitable for time intervals such as the Late Jurassic-Early Cretaceous, and the latest Cretaceous-present, during which periods reversal frequency was in the range of 1-5 m.y.

A simple illustration of the hierarchy of sedimentation rates, and the important consequences this has for correlation, is shown in Figure 3. Sedimentation rates used in this exercise and quoted below are based on the compilation of Miall (1991b). The total elapsed time for the succession of four sequences in this diagram is 1 m.y., based on conventional geological dating methods, such as the use of biostratigraphy. However, in modern environments where similar sedimentary successions are accumulating, such as on prograding shorelines, short-term sedimentation rates typically are much higher. Elapsed time calculated on the basis of continuous sedimentation of an individual sequence amounts to considerably less (total of 400 ka for the four sequences), indicating a significant amount of "missing" time (600 ka). This time is represented by the sedimentary breaks between the sequences. Algeo and Wilkinson (1988) concluded, following a similar discussion of sedimentation rates, that in most stratigraphic sections only about one thirtieth of elapsed time is represented by sediment.

As discussed below, a further analysis could take into account the rapid sedimentation of individual subenvironments within the shoreline (tidal channels, beaches, washover fans, *etc.*), and this would demonstrate the presence of missing time at a smaller scale, within the 100 ka represented by each sequence (*e.g.*, Swift and Thorne, 1991, fig. 16, p. 23). Thus, facies successions ("parasequences," in the Exxon terminology; *e.g.*, Van Wagoner *et al.*, 1990) that constitute the components of sequences, such as delta lobes and regressive beaches, represent 10^3-10^4 years and have sedimentation rates up to an order of magnitude higher than fifth-order sequences, in the 1-10 m/ka range.

The important point to emerge from this simple exercise is that the sedimentary breaks between supposedly continuous successions may represent significant lengths of time, much longer than is suggested by calculations of long-term sedimentation rates. This opens the possibility that the sequences that were deposited during the time span between the breaks may not actually correlate in time at all. Physical tracing of sequences by use of marker horizons, mapping of erosion surfaces and sequence boundaries, *etc.*, may confirm the existence of a regional sequence framework, but these sequences could, in principal, be markedly diachronous, and correlation between basins, where no such physical tracing is possible, should be viewed with extreme caution.



Thickness of each sequence S, given by t = 10 m
Total thickness of succession = 40 m
Average sedimentation rate R_a = 0.04 m / ka
Therefore total elapsed time for the accumulation of S_1 - S_4 = 1 m.y.

For individual sequence:
R_s = 0.1 m / ka
Elapsed time for one sequence = 100 ka
For all four sequences = 400 ka

Figure 3 *Comparison of sedimentation rates measured at two different scales. The typical sedimentation rate for accumulation at a geomorphic scale, comparable to that which can be measured for many fifth-order and some fourth-order stratigraphic sequences, is 0.1 m/ka (Miall, 1991b). Longer-term sedimentation rates, such as those estimated from geological, chronostratigraphic data, are in the order of 0.01-0.1 m/ka (Miall, 1991b). Calculations of total elapsed time using these contrasting rates indicate considerable "missing" time corresponding to nondeposition and erosion.*

Figure 4 makes the same point regarding missing time in a different way. 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. 6). The first column of Figure 4, labelled TC (for third-order cycle), illustrates an example of such a succession. Each such third-order cycle may be composed of a suite of cycles in the Milankovitch band (fourth- and fifth-order cycles; column MC in Fig. 4) which individually represent tens of years to a few hundred thousand years. Chronostratigraphic compilations for such successions commonly 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). Sedimentation rates calculated for such sequences (compiled by Miall, 1991b) confirm this, and the second column of

Figure 4 indicates a possible chronostratigraphic breakdown of the third-order cycles into component Milankovitch cycles. Each of these cycles 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.* According to the hierarchical breakdown of Miall (1991b) the four columns correspond to sediment groups 10, 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 focusses attention on a finer scale of depositional subdivision, including contained discontinuities. The evidence clearly confirms Ager's (1981) assertion that the sedimentary record consists of "more gap than record."

Devine's (1991) lithostratigraphic and chronostratigraphic model of a typical marginal-marine sequence (Fig. 5) 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, but more are present in such a succession than Devine (1991) has indicated. His chronostratigraphic diagram is redrawn in Figure 6 to emphasize sedimentary breaks, and numerous additional discontinuities have been indicated, corresponding to the types of breaks in the record introduced by switches in depositional systems, channel avulsions, storms and hurricanes, *etc.* Cartwright *et al.* (1993) made a similar point regarding the complexity of the preserved record, particularly in marginal-marine deposits, and commented on the difficulty of "forcing-through" meaningful stratigraphic correlations using seismic-reflection data.

The conclusion is that the sedimentary record is extremely fragmentary. A time scale that focusses on continuity is to be preferred over one that is built on unconformities. The modern method of refining the geological time scale uses "continuous" sections for the definition of chronostratigraphic boundaries and encompasses a method for the incorporation of missing time by defining only the base of chronostratigraphic units, not their tops. If missing time is subsequently documented in the stratigraphic record by careful chronostratigraphic observation or measurement, it is assigned to the underlying chronostratigraphic unit, thereby avoiding the need for a redefinition of the unit (Ager, 1964; McLaren, 1970; Bassett, 1985).

In the Exxon work much use is made of the term "correlative conformities," as in their original definition of a sequence as "a relatively conformable succession of genetically related strata bounded at its top and base by unconformities or their correlative conformities" (Vail *et al.*, 1977, p. 210). However, sequence boundaries are diachronous. The transgression and regression that constitute a sea-level cycle generate breaks in sedimentation at different times in different parts of a basin margin. Kidwell (1988) demonstrated that the major break in sedimentation on the open shelf occurs as a result of erosion during lowstand and sediment bypass or starvation during transgression, whereas in marginal-marine environments, the major break occurs during regression. The sequence-boundary unconformities are therefore offset by as much as a half cycle between basin-margin and basin-centre locations. Kidwell (1988) referred to this process as reciprocal sedimentation.

Given an acknowledgement of the diachronous nature of sequence boundaries, the accuracy of sequence correlation could be improved by dating of the correlative conformities in deep-marine settings, where breaks in sedimentation are likely to be at a minimum, but it is doubtful if this is commonly possible. It requires that sequences be physically traced from basin margins into deep-water environments, introducing problems of physical correlation in areas of limited data, and problems of chronostratigraphic correlation between different sedimentary environments in which zonal assemblages are likely to be of different type. As discussed below, problems of correlation across environmental and faunal-province boundaries are often significant. In view of the ubiquity of breaks in sedimentation in the stratigraphic record, it is arguable whether, in fact, the concept of the correlative conformity is realistic.

The significance of missing section and the ambiguity surrounding the correlation of unconformities is discussed further below.

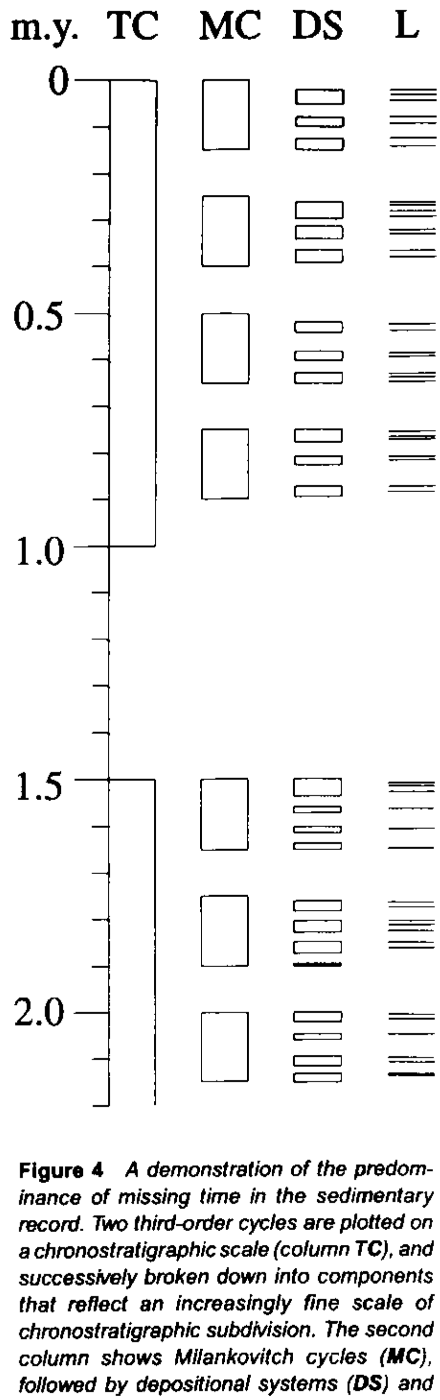


Figure 4 *A demonstration of the predominance of missing time in the sedimentary record. Two third-order cycles are plotted on a chronostratigraphic scale (column* **TC***), and successively broken down into components that reflect an increasingly fine scale of chronostratigraphic subdivision. The second column shows Milankovitch cycles (***MC***), 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 by events of shorter duration and recurrence interval (e.g., infrequent hurricanes, seasonal dynamic events, etc.).*

THE DATING AND CORRELATION OF STRATIGRAPHIC EVENTS: POTENTIAL SOURCES OF UNCERTAINTY

The dating and correlation of stratigraphic events between basins, where physical tracing-out of beds cannot be performed, involves the use of biostratigraphy and a variety of other chronostratigraphic methods. The process is a complex one, fraught with many possible sources of error. Many textbooks and review articles have dealt with various aspects of this subject, but practical reviews for the working geologist have not been developed. What follows is an attempt to break down the process into a series of discrete "steps", although in practice dating successions and erecting local and global time scales is an iterative process, and no individual stratigrapher follows the entire procedural order as set out here. The geologist is able to draw on the accumulated knowledge of the geological time scale that has (as noted earlier) been undergoing improvements for more than 200 years, but each new case study presents its own unique problems.

Standard correlation methods are discussed by Miall (1990, chapter 3) and in several standard textbooks on stratigraphy. Harland *et al.* (1990) provided what is probably the most thorough and scholarly discussion of the development of the geological time scale. Kauffman and Hazel (1977) edited a valuable collection of papers containing many different types of biostratigraphic study, and including a useful historical article

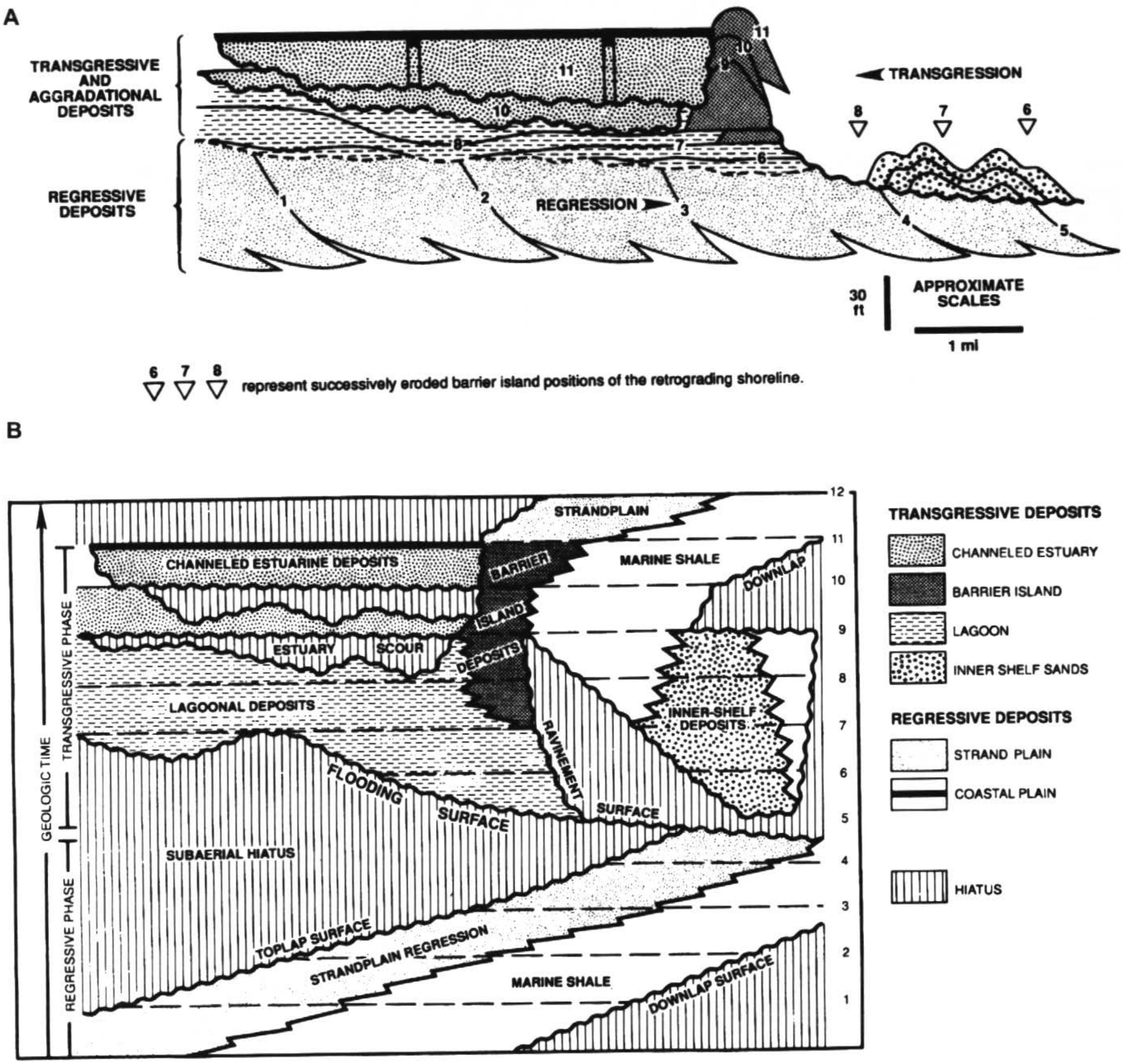


Figure 5 *Lithostratigraphic* **(A)** *and chronostratigraphic* **(B)** *model of a transgressive-regressive couplet of the Point Lookout Sandstone, northwestern New Mexico. This succession represents a sequence in the Milankovitch band, although the base-level change that controlled it may be of tectonic origin. Numbered events 1-12 are arbitrary time lines (from Devine, 1991).*

by Hancock (1977). Agterberg (1990) and Guex (1991) presented detailed descriptions of quantitative methods for correlation. Numerous books and papers have addressed the subject of biogeography and faunal provincialism. Review articles by Ludvigsen *et al.* (1986) and Smith (1988) provide useful summaries.

Six main "steps" are involved in the dating and correlation of stratigraphic events. The discussion of these steps in the following sections is elaborated from that in Miall (1991a), with the addition of many new examples. Figure 7 summarizes these steps and provides generalized estimates of the magnitude of the uncertainty associated with each aspect of the correlation and dating of the stratigraphic record. Some of these errors may be cumulative, as discussed in the subsequent paragraphs. The assignment of ages and of correlations with global frameworks is an iterative process that, in some areas, has been underway for many years. There is much feedback and cross-checking from one step to another. What follows should be viewed, therefore, as an attempt to break down the practical business of dating and correlation into more readily understandable pieces, all of which may be employed at one time or another in the unravelling of regional and global stratigraphies. The main steps are as follows:

1) Identification of sequence boundaries. Determining the position of the sequence boundary may or may not be a straightforward procedure. There are several potential sources of error and confusion, as noted below.

2) Determining the chronostratigraphic significance of unconformities. Unconformities, such as sequence boundaries, represent finite time spans which vary in duration from place to place. In any given location this time span could encompass the time span represented by several different sedimentary breaks at other locations.

3) Determination of the biostratigraphic framework. One or more fossil groups is used to assign the selected event to a biozone framework. Errors may be introduced because of the incompleteness of the fossil record.

4) Assessment of relative biostratigraphic precision. The length of time represented by biozones depends on such factors as faunal diversity and rates of evolution. It varies considerably through geological time and between different fossil groups.

5) Correlation of biozones with the global stage framework. The existing stage framework was, with notable exceptions, built from the study of macrofossils in European type sections. Correlation with this framework raises questions of environmental limitations on biozone extent, our ability to inter-

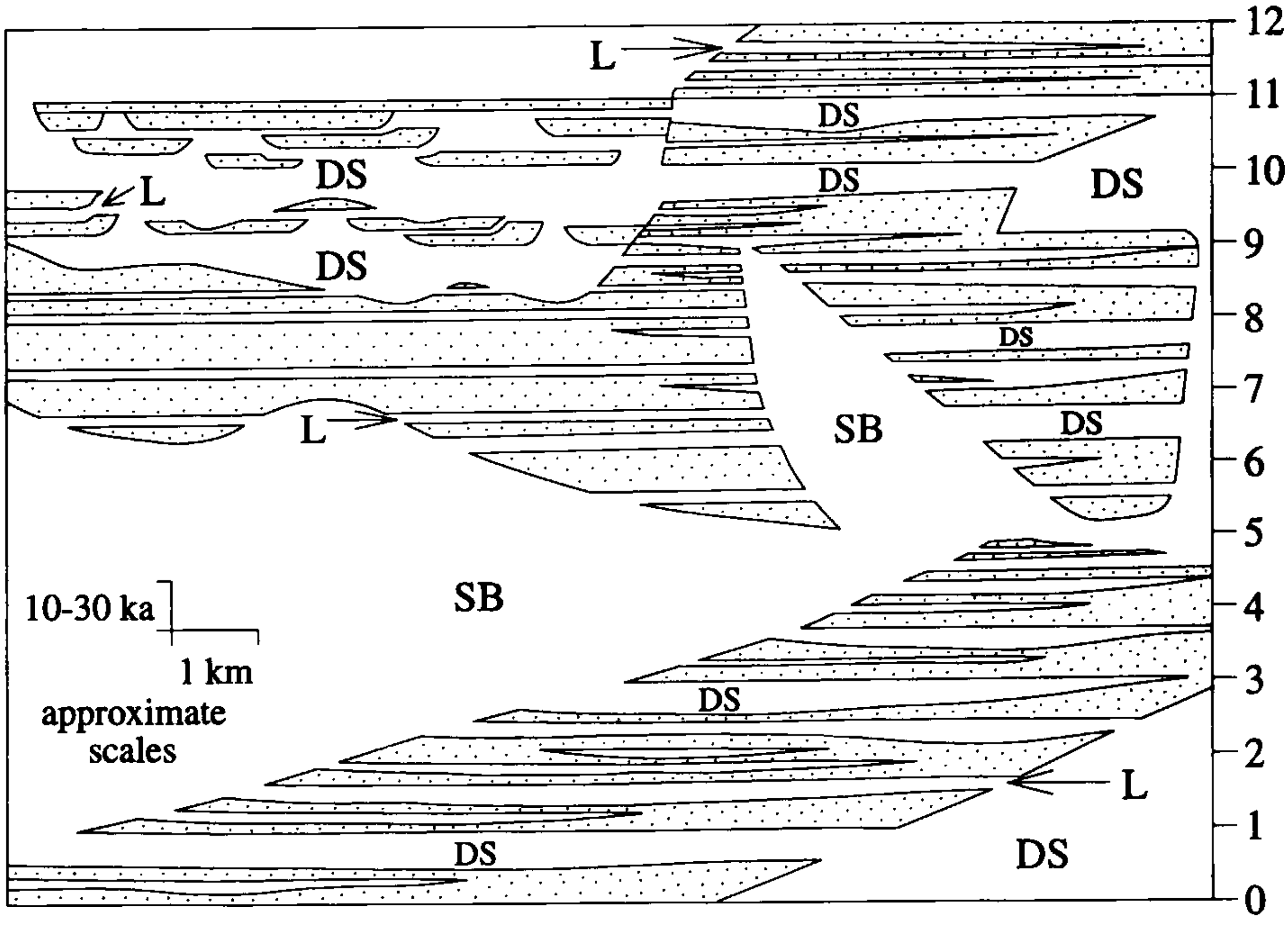


Figure 6 *A redrawing of Figure 5B to emphasize the gaps in the stratigraphic record. The larger gaps are those of Devine (1991), and represent the sequence boundary (**SB**), corresponding to the kinds of gaps shown in column MC of Figure 3. Intermediate-scale gaps are those between individual depositional systems (**DS**), and correspond to some of the time-line "events" in Devine's original model (Fig. 4A). The smallest gaps (**L**) are those between individual lithosomes. Only a few of these are labelled.*

relate zonal schemes built from different fossil groups, and problems of global faunal and floral provinciality.

6) Assignment of absolute ages. The use of radiometric and magnetostratigraphic dating methods, plus the increasing use of chemostratigraphy (oxygen and strontium isotope ratios) permits the assignment of absolute ages in years to the biostratigraphic framework. Such techniques also constitute methods of correlation in their own right, especially where fossils are sparse.

Identification of Sequence Boundaries

The first step is that a well section, seismic record, or outcrop profile is analyzed and the positions of sequence boundaries are determined from the vertical succession of lithofacies. The possible errors in this procedure include the potential for confusion between several allocyclic and autocyclic causes for the events in the stratigraphic record, and the problem of the ubiquitous gaps in the sedimentary record, as discussed in earlier sections of this paper. In a regional study of Paleogene shelf-margin deposits in the North Sea basin, Armentrout *et al.* (1993) found that correlation errors of up to 30 m could be expected when stratigraphic events, such as sequence boundaries, were traced from well to well using log markers, log-to-seismic correlations and seismic correlation loops.

Although the principles of sequence stratigraphy have by now been well documented (the following are the key Exxon papers: Vail, 1987; Van Wagoner *et al.*, 1987, 1990; Posamentier *et al.*, 1988), there are various situations where definition of the sequence boundaries may be fraught with potential error, quite apart from the relatively simple problem of within-basin correlation error noted above. These include the following five potential problems.

1. Confusion of the sequence boundary with a ravinement surface. Distinct and prominent erosion surfaces are commonly developed by wave erosion during transgression, and may easily be confused with a sequence-boundary unconformity (Demarest and Kraft, 1987). Wave-cut erosion surfaces of this type are termed ravinement surfaces. They represent the surface of equilibrium on the shelf formed in response to the local wave and current regime. "As sea-level rises the shoreface profile translates upward and landward through a process of erosional shoreface retreat. The ravinement surface cut by this process will physically rise toward the basin margin. It will also become younger in the same direction" (Nummedal and Swift, 1987). The ravinement surface is only one of several types of diastem that may be encountered in transgressive systems tracts. Others include channel scours and marine erosion surfaces. These can make

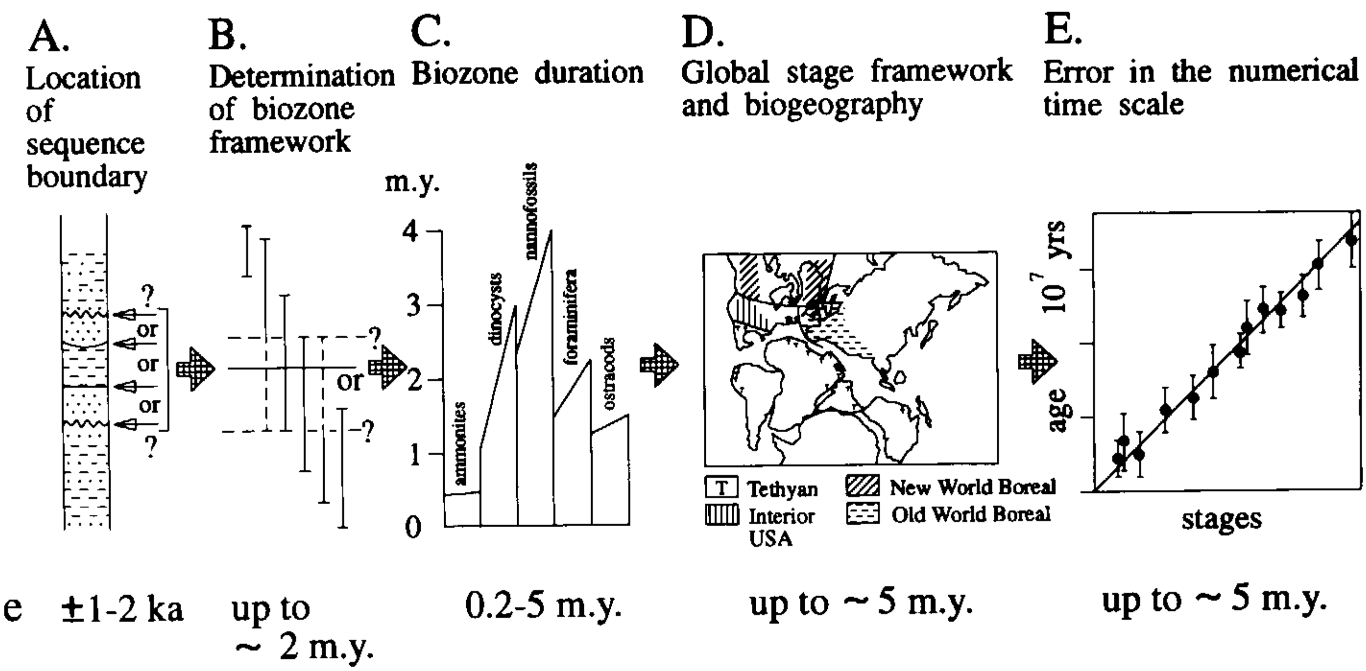


Figure 7 *Steps in the correlation and dating of stratigraphic events. e=typical range of error associated with each step.* **(A)** *In the case of the sequence framework, location of sequence boundaries may not be a simple matter, but depends on interpretation of the rock record using sequence principles.* **(B)** *Assignment of the boundary event to the biozone framework. An incomplete record of preserved taxa (almost always the case) may lead to ambiguity in the placement of biozone boundaries.* **(C)** *The precision of biozone correlation depends on biozone duration. Shown here is a simplification of Cox's (1990) summary of the duration of zones in Jurassic sediments of the North Sea Basin.* **(D)** *The building of a global stage framework is fundamental to the development of a global time scale. However, global correlation is hampered by faunal provincialism. Shown here is a simplification of the faunal provinces of Cretaceous ammonites, shown on a mid-Cretaceous plate-tectonic reconstruction. Based on Kennedy and Cobban (1977) and Kauffman (1984).* **(E)** *The assignment of numerical ages to stage boundaries and other stratigraphic events contains inherent experimental error and also the error involved in the original correlation of the datable horizon(s) to the stratigraphic event in question. Diagrams of this type are a standard feature of any discussion of the global time scale (e.g., Haq* et al.*, 1988; Harland* et al.*, 1990). The establishment of a global biostratigraphically-based sequence framework involves the accumulation of uncertainty over steps* **A** *to* **D**. *Potential error may be reduced by the application of radiometric, magnetostratigraphic or chemostratigraphic techniques which, nonetheless, contain their own inherent uncertainties (step* **E**).

the definition of sequence boundaries difficult. The ravinement surface, in particular, is commonly a major erosion surface that separates markedly different facies, but it forms within the transgressive systems tract and is, therefore, not a sequence boundary, unless the depth of erosion at the ravinement surface is such that no transgressive deposits are preserved. In the latter case, the ravinement surface is coincident with the erosion surface at the top of the underlying regressive deposits.

2. Apparent sequence boundaries formed by submarine erosion. Unconformities may be generated by marine erosion caused by deep ocean currents. These can shift in position across the sea floor as a result of changes in topography brought about by tectonism or sedimentation, resulting in diachronous breaks in sedimentation that bear no causal or temporal relation to changes in sea level. Christie-Blick *et al.* (1990) cited the case of the Western Boundary Undercurrent that flows along the continental slope of the Atlantic Ocean off the United States. This current is erosive where it impinges on the continental slope, but deposition of entrained fine clastic material takes place at the margins of the main current, and the growth of this blanket is causing the current to gradually shift up the slope. The result is onlapping of the deposits onto the slope below the current, and erosional truncation of the upslope deposits. The unconformities that define the Cenozoic sequence stratigraphy of the Blake Plateau off the eastern United States do not correlate with those on the Exxon global cycle chart, and are now interpreted to have formed as a result of submarine erosion by the meandering Gulf Stream (Schlager, 1992). Miall (1986) also suggested that the condensed sections that tend to form at times of maximum transgression (Vail, 1987) may also be confused with surfaces formed by the winnowing action of strong oceanic currents, and that they therefore may not have any significance with regard to sea level.

3. Apparent sequence boundaries formed as "drowning unconformities". Carbonate environments are very sensitive to environmental change. Schlager (1989, 1992) proposed the term "drowning unconformity" for breaks in carbonate sedimentation that could be could be caused by the following events: rapid sea-level rise, poisoning of the carbonate factory by an influx of terrigenous sediment, an oversupply of nutrients, and rapid temperature changes. The unconformities are actually intervals of slow sedimentation represented by thin condensed sections with many small hiatuses, and may be indistinguishable on the seismic record from true unconformable breaks because of limited seismic resolution. Drowning unconformities may be mistaken for sequence boundaries. Architecturally, they may be similar to lowstand unconformities, and care must be taken to interpret them correctly. Schlager (1992) stated:

> Drowning requires that the reef or platform be submerged to subphotic depths by a relative rise that exceeds the growth potential of the carbonate system. The race between sea level and platform growth goes over a short distance, the thickness of the photic zone. Holocene systems indicate that their short-term growth potential is an order of magnitude higher than the rates of long-term subsidence or of third-order sea level cycles ... This implies that drowning events must be caused by unusually rapid pulses of sea level or by environmental change that reduced the growth potential of platforms. With growth reduced, drowning may occur at normal rates of rise.

Schlager (1992) pointed to such environmental changes as the shifts in the El-Niño current, which bring about sudden rises in water temperature, beyond the tolerance of many corals. Drowning can also occur when sea-level rise invades flat bank tops, creating shallow lagoons with highly variable temperatures and salinities, plus high suspended-sediment loads due to coastal soil erosion. Oceanic anoxic events, particularly in the Cretaceous, are also known to have caused reef drowning. Schlager (1992) suggested that two Valangian third-order sequence boundaries in the Haq *et al.* (1987, 1988b) global cycle chart may actually be drowning unconformities that have been misinterpreted as lowstand events.

4. The generation of erosion surfaces during falling sea-level. Recent work has demonstrated that the component of the original Exxon sequence models covering times of falling sea level needs reevaluation (Plint, 1988; Hunt and Tucker, 1992). So-called "stranded parasequences" may form on the shelf and slope. An erosion surface may develop on the shelf beneath regressing strandplain deposits (analogous to the ravinement surface that develops during rising sea level), but this occurs during sea-level fall, and is therefore not to be confused with the sequence boundary. Plint (1988) referred to the strandplain deposits that rest on these erosion surfaces as "sharp-based" sandbodies deposited during "forced regressions". Hunt and Tucker (1992) also made the very important point that the so-called "lowstand fans" are actually deposited during falling sea level as a result of the shedding of detritus as the shelf is exposed. This phase ends at or shortly after the time when sea level reaches its lowest point. The sequence boundary should therefore be defined as occurring *above* this systems tract, not below, as in the original Exxon models.

5. Pseudo-unconformities in seismic-reflection records. It is a fundamental principle of seismic stratigraphy that seismic reflections are chronostratigraphic in character (Vail *et al.*, 1977; Cross and Lessenger, 1988). However, because of problems of resolution, seismic reflections *can* develop at diachronous facies contacts, producing what Schlager (1992) termed pseudo-unconformities. According to Schlager (1992) such reflections develop "where a rapid facies change occurs in each bed at a similar position and the seismic tool merges these points of change into one reflection. Time lines cross this reflection, thus it is not an unconformity..." He gave as an example a seismic model of the lapout of carbonate slope deposits into basinal facies in the Triassic deposits of the Dolomites. Clearly, such pseudo-unconformities are not surfaces of erosion, and must be eliminated in a sequence analysis. Schlager (1992) indicated that carbonate platforms are particularly prone to this type of seismic response because of the rapid lateral facies changes that commonly are present.

Simple errors, such as the confusion between a sequence boundary and a ravinement surface, could lead to possible errors in boundary placement of at least several metres. Given a typical sedimentation rate of 0.1 m/ka, a 10 m error is equal to 100 ka. Changing the placement of the sequence boundary from the base to the top of the "lowstand" fans could represent a considerably larger change in assigned age.

The Chronostratigraphic Meaning of Unconformities

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; it may have a complex genesis, representing amalgamation of more than one event. It may also be diachronous. For example, the transgressions and regressions that occur during the genesis of a stratigraphic sequence take a finite length of time: in the case of third-order sequences, possibly up to several million years. As noted above, Kidwell (1988) demonstrated that this results in an offset in sequence boundary unconformities by as much as one half of a cycle between basin centre and basin margin.

Unconformities actually represent amalgamations of two surfaces, the surface of truncation of older strata and the surface of transgression of younger strata. These two surfaces may vary in age considerably from location to location, as indicated by chronostratigraphic diagrams (e.g., Vail *et al.*, 1977, fig. 13, p. 78). Even if the two surfaces have been dated, this still does not provide an accurate estimate of the timing of the event or events that generated the unconformity. As shown in Figure 8A, a fall in relative sea level may have occurred at time T1, in which case no erosion or deposition took place prior to the deposition of the overlying sequence. An alternative is that sedimentation continued until time T3, followed by a rapid erosional event and transgression. Or the sea-level event may have occurred at any time T2.

A given major unconformity may represent the combined effects of two or more unrelated sea-level events, of eustatic and tectonic origin (Fig. 8B). Recognizing the occurrence of more than one event requires the location and dating of sections where the hiatus is short, as in the various possible sections B in Figure 8B. As explained by Aubry (1991, p. 6646),

> If an unconformity Y with a short hiatus on the shelves of basin A can be shown to be exactly correlative (=isochronous=synchronous) in the stratigraphic sense with an unconformity y with a short hiatus on the shelves on basin B (*i.e.*, if the two hiatuses overlap almost exactly), it is probable, although not certain, that both unconformities Y and y are correlative, in the genetic sense, with a unique event T. Overlap between hiatuses of stratigraphically correlatable unconformities in two widely separated basins fulfills a condition required but insufficient to establish global eustasy. Unconformities Y and y will become a global eustatic signal if other correlative (=synchronous) unconformities ... with short hiatus can be recognized on as many shelves as possible of widely separated basins.

Even this procedure begs the question of the expected duration of sea-level events. Given the rapid events that characterize glacioeustasy (frequency in the 10^4-10^5-year range), this is not a trivial question. Aubry's figures (Fig. 8) were drawn to illustrate actual problems that arose in attempts to assign ages to unconformities in Eocene sections. The difference between times T1 and T3 in Figure 8A is 2 m.y., which represents a significant potential range of error. It could correspond to one entire third-order sequence.

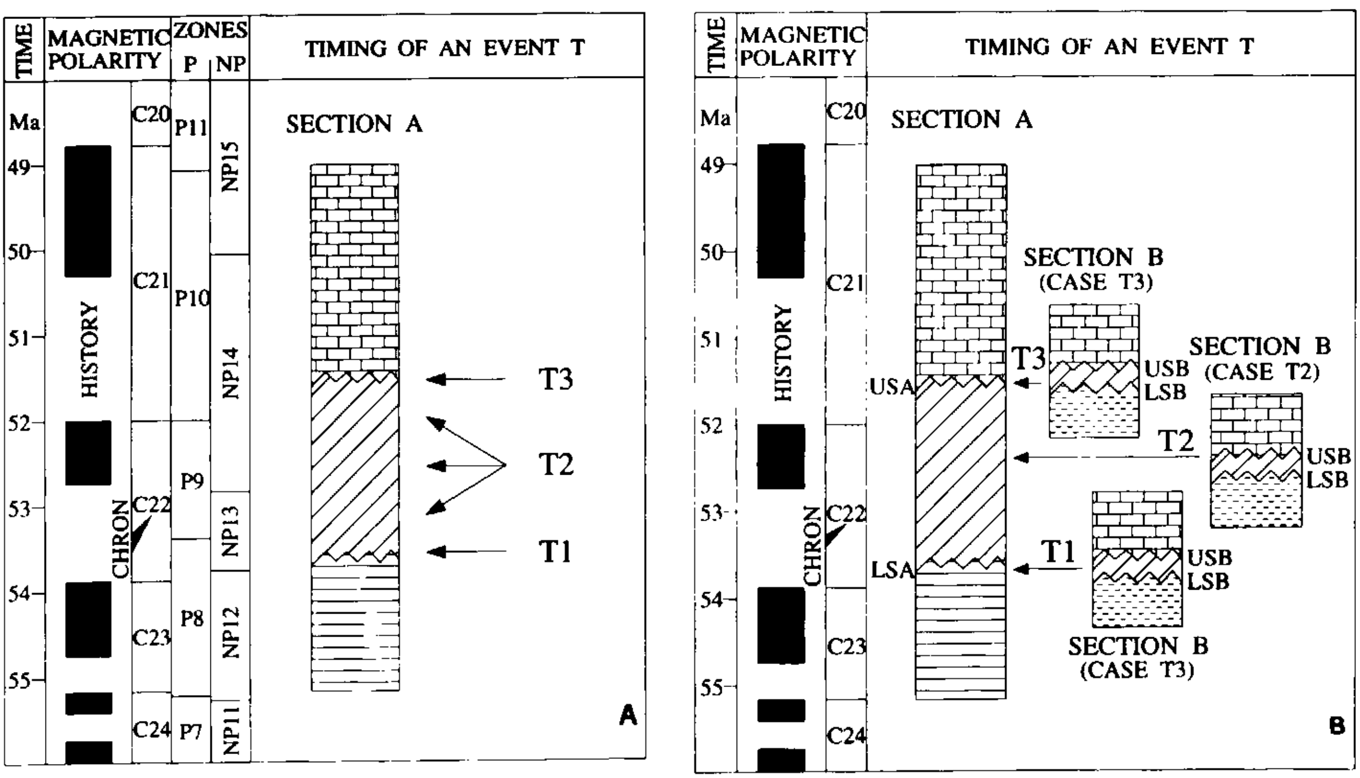


Figure 8 *The interpretation of unconformities.* **(A)** *Timing of the event which generated the unconformity. It could have been at any time T1, T2 or T3, or a longer episode which overlapped one or more of these times.* **(B)** *The generation of a single major unconformity by the amalgamation of more than one event (diagrams from Aubry, 1991).*

Theoretical studies by Pitman and Golovchenko (1988) demonstrated a phase-lag between sea-level change and the stratigraphic response, particularly in areas of slow subsidence and sea-level change, and rapid sediment supply. This was confirmed by the computer modelling experiments of Jordan and Flemings (1991), who stated that "the sequence boundary for an identical sea level history could be of different ages and the ages could differ by as much as ¼ cycle." This directly contradicts the Exxon models, based on the work of Jervey (1988), who asserted that sediment supply affects shoreline position, but not the timing of sequence boundaries. It is an important result because it indicates that sequence boundaries are inherently imprecise recorders of sea-level change. Practical examples of this were illustrated by Leckie and Krystinik (1993).

Determination of the Biostratigraphic Framework

The biostratigraphic data base for the global time scale has experienced an orders-of-magnitude expansion since micro-organisms began to take on increasing importance in subsurface petroleum exploration in the post-war years, and following the commencement of the Deep Sea Drilling Project (DSDP) in 1968. However, the main basis for the global time scale remains the classical macrofossil assemblages (*e.g.*, ammonites, graptolites) that have been in use, in many cases, since the 19th century. Supplementing macrofossil and microfossil collections from outcrops, drilling operations on land and beneath the oceans have contributed a vast biostratigraphic sample base over the last few decades, permitting the evaluation of a wide range of micro-organisms for biostratigraphic purposes in all the world's tectonic and climatic zones. The result has been a considerable improvement in the flexibility and precision of dating methods, and much incremental improvement in the global time scale. Several useful reviews of this area of research are contained in the synthesis of the first decade of DSDP edited by Warme *et al.* (1981).

As noted by Cope (1993), detailed, meticulous taxonomic work still holds the potential for much improved biostratigraphic resolution and flexibility at all levels of the geological column. In older Mesozoic and Paleozoic strata, such fossil groups as conodonts and graptolites have yielded very refined biostratigraphic zonal systems. However, this potential has yet to be fully tapped by sequence stratigraphers.

The various types of zones, and the methods for the erection of zonal schemes, are subjects dealt with in standard textbooks and reviews (*e.g.*, Miall, 1990, chapter. 3; Kauffman and Hazel, 1977), and will not be discussed here. The purpose of this section is to focus on two major problems that affect the accuracy and precision of biostratigraphic correlation.

The Problem of Incomplete Biostratigraphic Recovery.

Because of incomplete preservation, poor recovery, or environmental factors, the rocks rarely yield a complete record through time of each biozone fauna or flora. Practical, measured biostratigraphic time, as indicated by the imperfect fossil record, may be different from a hypothetical "real" time, which is recorded by invisible (hypothetical) time lines in the rock record (the "r" gaps in Fig. 9), and can rarely be perfectly defined (Murphy, 1977; Johnson, 1992).

How important are the "r" gaps shown in Figure 9? Many researchers have attempted to sidestep this problem, by treating fossil occurrences quantitatively, and applying statistical treatments to assessments of preservation and correlation (*e.g.*, Riedel, 1981; McKinney, 1986; Agterberg, 1990; Guex, 1991). However, the method of graphic correlation (discussed below), which focusses attention on the incompleteness of the fossil record, allows us to examine this question. Results presented by Edwards (1989) indicate that vertical anomalies of up to 10 m are not uncommon. Doyle (1977) illustrated in detail an attempt to correlate two wells using palynological data. Ranges of correlation error up to 30 m are apparent from his data, and result from incomplete preservation or wide sample spacing . At a sedimentation rate of 0.1 m/ka, 30 m of section is equivalent to 300 ka, more than enough to lead to miscorrelation of sequences in the Milankovitch band.

Conventional wisdom has it that pelagic organisms are the best biostratigraphic indicators because they are widely distributed by ocean currents and tend to be less environmentally sensitive. However, recent detailed studies

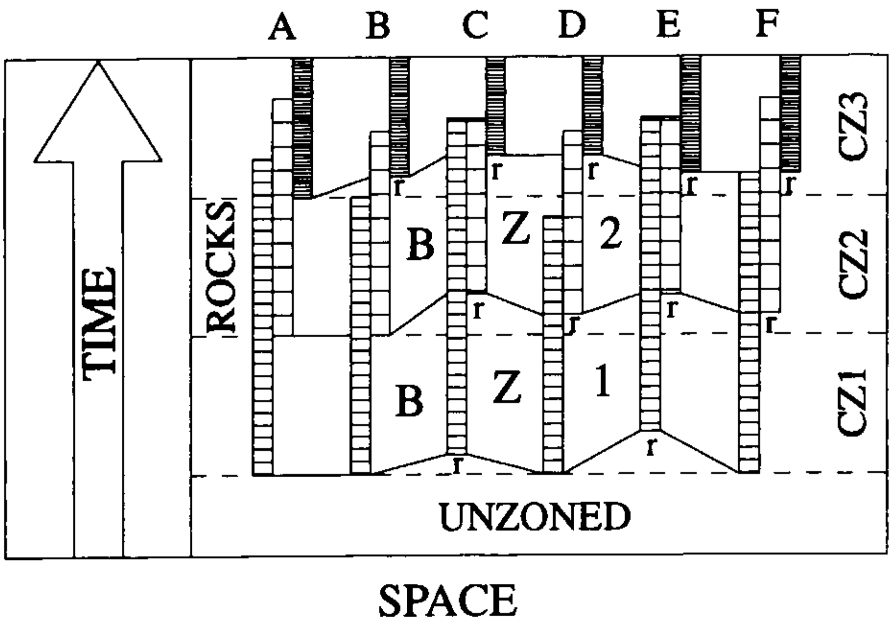


Figure 9 *Hypothetical time-rock diagram, showing the ranges of three species as recorded in six stratigraphic sections. The first-appearances of the three species in section A are used to define biozones BZ1 and BZ2, the recorded extent of which is shown by the heavy lines connecting the six sections. Dashed lines extending from section A indicate ideal chronostratigraphic time lines. In most sections these differ from the biozone boundaries by a time increment "r", resulting from failure of the fossilization process, sample spacing, or environmental factors (Johnson, 1992).*

of nektonic and planktonic forms have indicated a wide range of factors that lead to uneven distribution and preservation even of these more desirable forms. Thierstein (1981) and Roth and Bowdler (1981), in studies of Cretaceous nannoplankton, discussed a variety of mechanisms that affected distribution of these organisms. Among the most important environmental factors are changes in ocean currents, which affect water temperatures and the concentrations of oxygen and carbon dioxide and nutrients in the seas. Changes in temperature and sea level affect the position of the carbonate compensation depth in the oceans, and hence affect the rates of dissolution and preservability of calcareous forms in deep-sea sediments. Conversely, bottom-dwelling faunas, which are specifically limited in their geographical distribution because of ecological factors, may exhibit a diversity and rapid evolutionary turn over that makes them ideal as biostratigraphic indicators in specific stratigraphic settings. For example, corals have been found to be of great biostratigraphic utility in the study of reef limestones of all ages.

Diachroneity of the Biostratigraphic Record

Another common item of conventional wisdom is that evolutionary changes in faunal assemblages are dispersed so rapidly that, on geological time scales, they can essentially be regarded as instantaneous. This argument is used, in particular, to justify the interpretation of what biostratigraphers call "first-appearance datums" (FADs) as time-stratigraphic events (setting aside the problems of preservation discussed above). However, there is increasing evidence that this is not always the case. Some examples of very detailed work have demonstrated considerable diachroneity in important pelagic fossil groups.

MacLeod and Keller (1991) explored the completeness of the stratigraphic sections that span the Cretaceous-Tertiary boundary, as a basis for an examination of the various hypotheses that have been proposed to explain the dramatic global extinction occurring at that time. They used graphic correlation methods, and were able to demonstrate that many foraminiferal FADs and last-appearance datums (LADs) are diachronous. Maximum diachroneity at this time is indicated by the species *Subbotina pseudobulloides*, the FAD of which may vary by up to 250 ka between Texas and North Africa. However, it is not clear how much of this apparent diachroneity is due to preservational factors.

An even more startling example of diachroneity is that reported by Jenkins and Gamson (1993). The FAD of the Late Cenozoic foraminifera *Globorotalia truncatulinoides* differs by 600 ka between the southeast Pacific Ocean and the North Atlantic Ocean. This result is based on detailed analysis of DSDP material, and is interpreted as indicating the time taken for the organism to migrate northward from the South Pacific following its first evolutionary appearance there. As Jenkins and Gamson (1993) concluded,

> The implications are that some of the well documented evolutionary lineages in the Cenozoic may show similar patters of evolution being limited to discrete ocean water masses followed by later migration into other oceans ... If this is true, then some of these so-called 'datum planes' are diachronous.

This conclusion is of considerable importance, because the result is derived from excellent data, and can therefore be regarded as highly reliable, and deals with one of the most universally preferred fossil groups for biostratigraphic purposes, the foraminifera. It would appear to suggest a limit of up to approximately one half million years on the precision that can be expected of any biostratigraphic event.

The two cases reported here may or may not be a fair representation of the magnitude of diachroneity in general. After a great deal of study, experienced biostratigraphers commonly determine that some species are more reliable or consistent in their occurrence than others. Such forms may be termed "index fossils", and receive a prominence reflecting their usefulness in stratigraphic studies. Detailed studies may indicate that some groups are more reliable than others as biostratigraphic indicators. For example, Ziegler *et al.* (1968) demonstrated that brachiopod successions in the Welsh Paleozoic record were facies controlled and markedly diachronous, based on the use of the zonal scheme provided by graptolites as the primary indicator of relative time. Armentrout (1981) used diatom zones to demonstrate that molluscan stages are time transgressive in the Cenozoic rocks of the northwest United States. Wignall (1991) demonstrated the diachroneity of Jurassic ostracod zones.

The Value of Quantitative Biostratigraphic Methods

Much work has been carried out in attempts to apply quantitative, statistical methods to biostratigraphic data, in order to refine stratigraphic correlations and to permit these correlations to be evaluated in probabilistic terms. Excellent syntheses have been provided by Agterberg (1990) and Geux (1991). However, many problems remain, because the biostratigraphic data base does not necessarily meet some of the necessary assumptions required for statistical work. Geux (1991, p. 179), in discussing the use of multivariate methods, quoted Millendorf and Heffner (1978, p. 313), who stated:

> This approach ignores the effects of faunal gradation within an isochronous unit with respect to geographic position. Thus, if the faunal composition of such an isochronous unit changes across the study area, samples taken from distant points in the unit might be dissimilar enough not to cluster. Simply, the greater the lateral variation and the larger the distance between them, the less similar are the two isochronous samples.

Geux (1991, p. 180) himself stated:

> In one way or another, all methods based on global resemblance between fossil samples end in fixing the boundaries of statistical biofacies, and they do not make it possible to find, within a fossil assemblage, the species that are characteristic of the relative age of the deposits under study.

As Agterberg (1990, chapter 2) demonstrated, not only biofacies, but sampling methods and questions of preservation also affect the distribution of fossils. It is questionable, therefore, whether statistical methods can assist directly with solving the problem of assessing error in global correlation.

There is one important exception to this generalization, and that is a technique known as graphic correlation. The method was proposed by Shaw (1964), and has been developed by Miller (1977) and Edwards (1984, 1989). The data on foraminiferal diachroneity at the Cretaceous-Tertiary boundary quoted above from MacLeod and Keller

(1991) were obtained using the graphic correlation method. The statistical methods that have evolved for ranking, scaling and correlation (Agterberg, 1990; Gradstein *et al.*, 1990) are a form of quantified graphic correlation.

As with conventional biostratigraphy, the graphic method relies on the careful field or laboratory recording of occurrence data, and focusses on the collation and interpretation of FADs and LADs. The objective is to define the local ranges for many taxa in at least three complete sections through the succession of interest. The more sections that are used, the more nearly these ranges will correspond to the total (true) ranges of the taxa. To compare the sections, a simple graphical method is used.

One particularly complete and well-sampled section is chosen as a standard reference section. Eventually, data from several other good sections are amalgamated with it to produce a composite standard reference section. A particularly thorough paleontologic study should be carried out on the standard reference section, as this enables later sections, for example, those produced by exploration drilling, to be correlated with it rapidly and accurately.

The graphic technique is used both to amalgamate data for the production of the composite standard and for correlating the standard with new sections. Figure 10 shows a two-dimensional graph in which the thicknesses of two sections X and Y have been marked off on the corresponding axes. The FADs and LADs are marked on the sections by circles and crosses, respectively. If the taxon occurs in both sections, points can be drawn within the graph corresponding to FADs and LADs by tracing lines perpendicular to the X and Y axes until they intersect. For example, the plot for the top of fossil 7 is the coincidence of points X = 350 and Y = 355.

If all the taxa occur over their total range in both sections and if sedimentation rates are constant (but not necessarily the same) in both sections, the points on the graph fall on a straight line, called the line of correlation. In most cases, however, there will be a scatter of points. The X section is chosen as the standard reference section, and ranges will presumably be more complete there. The line of correlation is then drawn so that it falls below most of the FADs and above most of the LADs. FADs to the left of the line indicate late first appearance of the taxon in section Y. Those to the right of the line indicate late first appearance in section X. If X is the composite standard, it can be corrected by using the occurrence in section Y to determine where the taxon should have first appeared in the standard. The procedure is explained further by Miall (1990, p. 116-118).

If the average, long-term rate of sedimentation changes in one or other of the sections, the line of correlation will bend. If there is a hiatus (or a fault) in the new, untested sections (sections Y), the line will show a horizontal terrace. Obviously, the standard reference section should be chosen so as to avoid these problems as far as possible. Harper and Crowley (1985) pointed out that sedimentation rates are, in fact, never constant and that stratigraphic sections are full of gaps of varying lengths (as discussed above; see Figs. 4, 6). For this reason, they questioned the value of the graphic correlation method. However, Edwards (1985) responded that when due regard is paid to the scale of intraformational stratigraphic gaps, *versus* the (usually) much coarser scale of biostratigraphic correlation, the presence of gaps is not of critical importance. Longer gaps, of the scale that can be detected in biostratigraphic data (*e.g.*, missing biozones) will give rise to obvious hiatuses in the line of correlation, as noted previously.

The advantage of the graphic method is that once a reliable composite standard reference section has been drawn up, it enables chronostratigraphic correlation to be determined between any point within it and the correct point on any comparison section. Correlation points may simply be read off the line of correlation. The range of error arising from such correlation depends on the accuracy with which the line of correlation can be drawn. Hay and Southam (1978) recommended using linear regression techniques to determine the correlation line, but this approach assigns equal weight to all data points instead of using one standard section

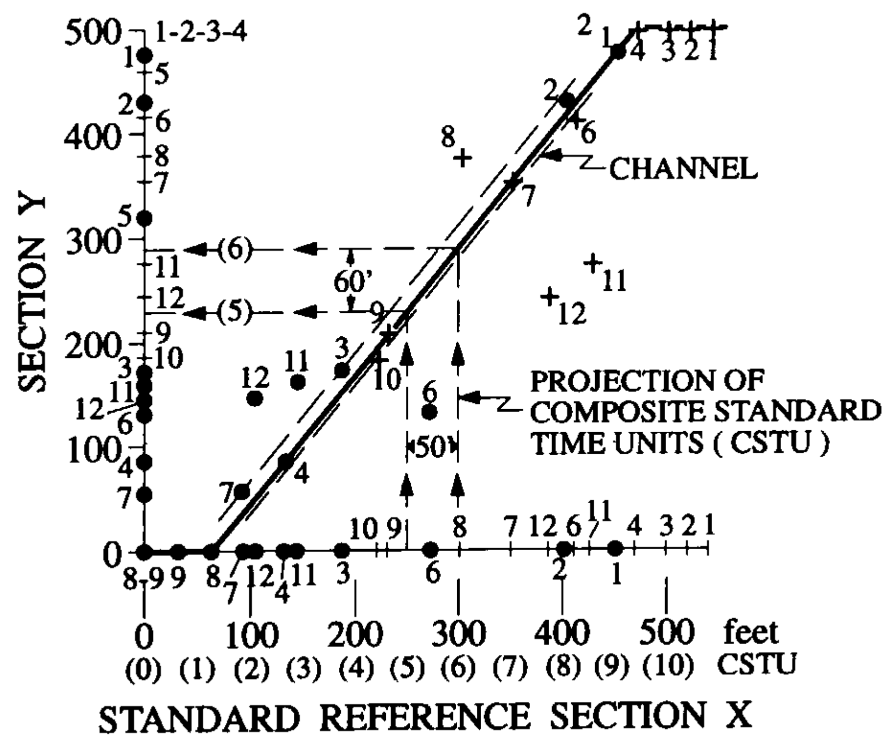


Figure 10 *Typical data plot used in the graphic correlation method. Section X is chosen as the standard reference section, and section Y is any other section to be correlated with it. FADs are shown by circles and LADs by crosses, plotted along the axis of each section. Data points within the graph indicate correlations of FADs and LADs, and are the basis for defining the line of correlation (the diagonal line). Points off the line reflect incomplete sampling or absence as a result of ecological factors. Progressive correlations of other sections to the standard enables "true" ranges of each taxon to be refined in the standard section, resulting in a detailed basis for further correlation and the erection of standard time units (Miller, 1977).*

as a basis for a continuing process of improvement. As Edwards (1984) noted, all data points do not necessarily have equal value; the judgment and experience of the biostratigrapher are essential in evaluating the input data. For this reason, statistical treatment of the data is inappropriate.

Figure 11 illustrates an example of the use of the graphic method in correlating an Upper Cretaceous succession in the Green River Basin, Wyoming, using palynological data (from Miller, 1977). The composite standard reference section has been converted from thickness into composite standard time units, by dividing it arbitrarily into units of equal thickness. As long as the rate of sedimentation in the reference section is constant, these time units will be of constant duration, although we cannot determine by this method alone what their duration is in years. Isochrons may bedrawn to connect stratigraphic sections at any selected level of the composite standard time scale. These isochrons assist in defining the architecture of the succession. For example, time unit 30 in Figure 11 is truncated, indicating the presence of an unconformity.

An important difference between the graphical method and conventional zoning schemes is that zoning methods provide little more than an ordinal level of correlation (biozones, as expressed in the rock record, have a finite thickness that commonly cannot be further subdivided), whereas the graphic method provides interval data (the ability to make graduated subdivisions of relative time). Given appropriate ties to the global time frame, the composite standard time units can be correlated to absolute ages in years, and used to make precise interpolations of the age of any given horizon (such as a sequence boundary) between fossil occurrences and tie points. The precision of these estimates is limited solely by the accuracy and precision obtainable during the correlation to the global standard. MacLeod and Keller (1991) provided excellent examples of this procedure, and their results suggest an obtainable precision of less than ±100 ka. Other examples of the use of graphic correlation are given by Scott *et al.* (1988), although no data plots are presented. In a later paper Scott *et al.* (1993) used graphic correlation methods in a study of core data to demonstrate diachroneity of some Cretaceous sequence boundaries of more than 0.5 m.y.

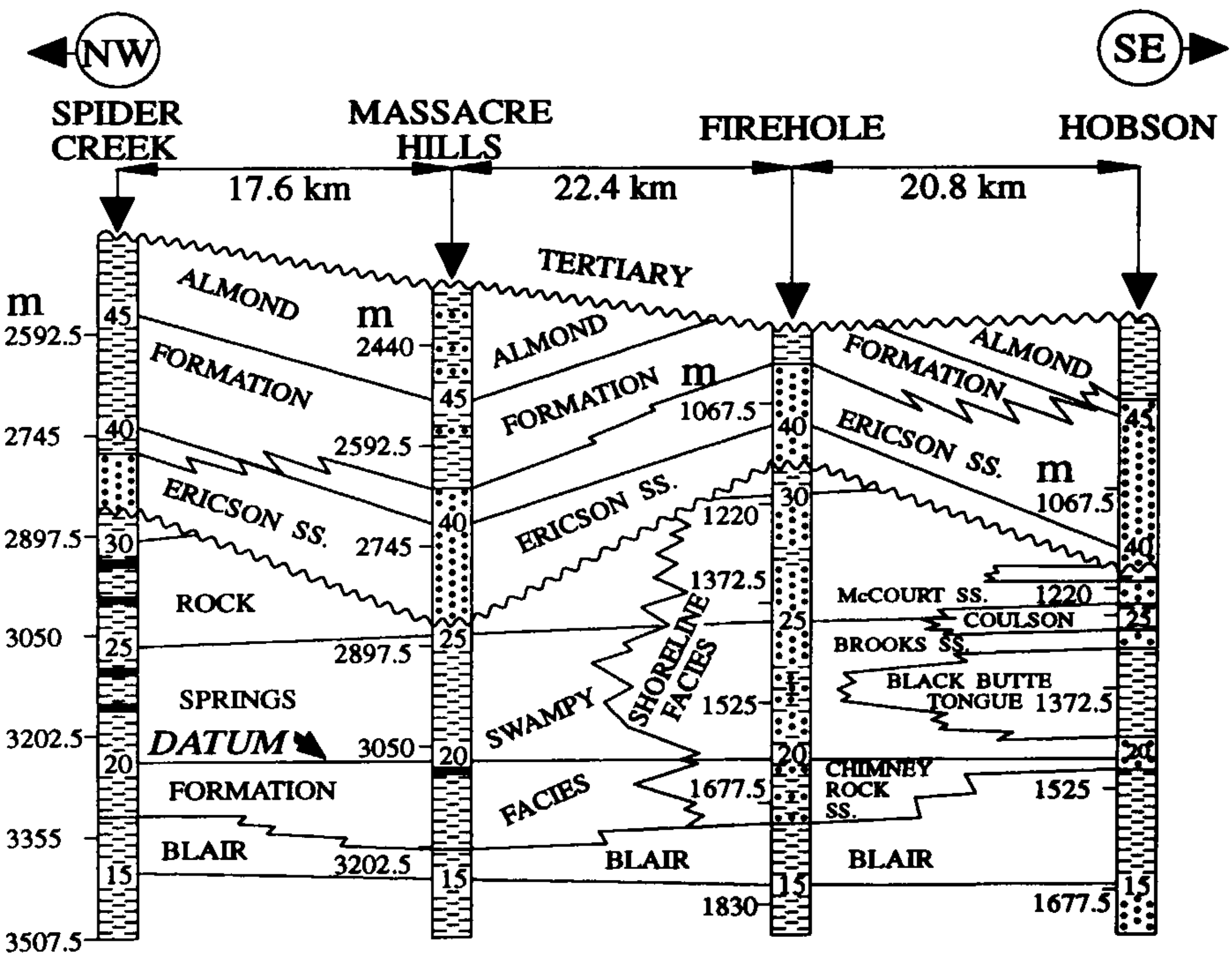


Figure 11 *An example of the correlation of four wells through Cretaceous sections in Wyoming. Figures within each log are composite standard time units derived from graphic correlation with the standard reference section. They can be used to generate correlations on an interval scale rather than the ordinal scale obtainable using conventional biostratigraphic zonations (Miller, 1977).*

Assessment of Relative Biostratigraphic Precision

The precision of biostratigraphic zonation is a reflection of the diversity and rate of evolution of the fossil group used to define the zonal scheme. This varies considerably over time and between different fossil groups. For example, Figure 7C is a simplified version of a chart provided by Cox (1990) to illustrate the time resolution of various fossil groups used in the subsurface correlation of Jurassic strata in the North Sea Basin. The best time resolution is obtained from ammonites, which have been subdivided into zones representing approximately 0.5 m.y. Hallam (1992) claimed a precision of 0.2 m.y. in exceptional cases. However, ammonites are rarely obtainable in subsurface work, and the microfossil groups that are typically used provide time resolution ranging from 1 m.y. to 4 m.y. The sloping caps to each bar in Figure 7C illustrate the varying length of biozones for each fossil group through the Jurassic. For example, dinocyst zones each represent about 1 m.y. in the Late Jurassic, but are approximately 3 m.y. long in the Early Jurassic.

Moore and Romine (1981), in a study of the contributions to stratigraphy of the DSDP project, examined the question of biostratigraphic resolution in detail. In 1975 (the latest data examined in this paper) the resolution of foraminiferal zonation, as expressed by the average duration of biozones, varied from 4 m.y. during much of the Cretaceous, to 1 m.y. during parts of the Neogene. Srinivasan and Kennett (1981) found that foraminiferal zones in the Neogene ranged from 0.4 m.y. to 2.0 m.y. They suggested:

> Experience shows that this resolution seems to have reached its practical limit. This ... is largely constrained by the evolution of important new species within distinctive and useful lineages. Further subdivision of the existing zones is of course possible when additional criteria are employed, but further subdivision of zones into shorter time-intervals does not guarantee a practical scheme for biostratigraphic subdivision; that is, such zones may not be widely applicable.

Combinations of foraminiferal zones with other micro-organisms occurring in the same sediments, such as calcareous nannofossils and radiolaria, increase biostratigraphic precision (Moore and Romine, 1981; Srinivasan and Kennett, 1981; Cope, 1993), but not necessarily by a large amount. Figure 12 shows the biostratigraphic resolution that was achievable in 1975 based on combinations of all three fossil groups. The combination of three fossil groups does increases accuracy and precision (to a 0.3-2.0 m.y. range), but, commonly, zonal boundaries of more than one group coincide in time, so that no additional precision is provided. It is not thought likely that precision is likely to further increase by very much. In fact, the system of numbered microfossil zones that was established early during the DSDP project still forms the basis for the Exxon global cycle charts of the late 1980s. As noted earlier in this paper, the analysis of different fossil groups from the same stratigraphic sections may also indicate that some groups are more facies controlled than others, and demonstrate diachronism. Cross-checking between these different groups may therefore be important in the reduction of biostratigraphic uncertainty (*e.g.*, Ziegler *et al.*, 1968; Armentrout, 1981).

It has been suggested that because sequence boundaries are dated primarily by biostratigraphic data, they should be referred to and correlated on this basis, without reference to the absolute time scale, in order to circumvent the imprecisions associated with this scale (as discussed in the next sections). However, even where no attempt is made to provide absolute ages for sequence boundaries, this discussion has shown that a built-in biostratigraphic imprecision of between approximately one half million years and (in the worst case) several million years must be accepted for the ages of sequence boundaries. A potential error in this range, as in most regional biostratigraphic frameworks, is already too great to permit the interregional correlation of sequences that are less than a few million years in duration (many third-order cycles). Biozones in the Exxon synthesis of Mesozoic-Cenozoic time have durations of 1-5 m.y. Uncertainties of this magnitude are therefore to be anticipated. Greater accuracy (to less than 1 m.y.) has certainly been attained locally, for example, by using ammonites (Hallam, 1992). Cope (1993) quoted detailed studies of British ammonites that yield a local resolution estimated at less than 200 ka, but such a level of accuracy cannot yet be extended globally for the purpose of testing the global cyclicity model.

Correlation of Biozones with the Global Stage Framework

Hedberg (1976) suggested that the

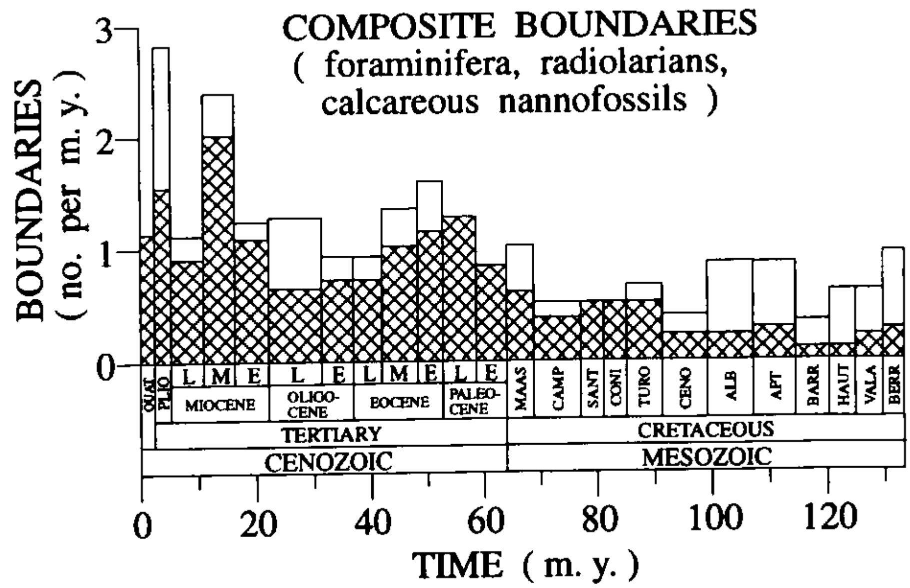


Figure 12 *Biostratigraphic resolution of marine strata based on combined zonation of foraminifera, radiolaria and calcareous nannofossils, expressed as the number of biostratigraphic boundaries per million years, averaged over individual epochs. Average resolution as it existed in 1969, at the beginning of the DSDP project, is shown by the cross-hatched columns. Improvements up to 1975 are indicated by the blank top to each column (Moore and Romine, 1981).*

stage be regarded as the basic working unit of chronostratigraphy but, as Hancock (1977) pointed out, stages were originally defined as groups of biozones, therefore stages are biostratigraphic entities. However, modern work continues to focus on the stage as the most useful, practical basis for subdividing the stratigraphic record, and for standardizing the geological time scale. This is facilitated by the gradual incorporation into the stage framework of different faunal and floral biozone systems, by the use of radiometric and magnetic methods to assign numerical ages to the stages, and by the use of stratotypes defined by "golden spikes" to establish global reference sections for unambiguous time correlation (Miall, 1990, chapter 3).

Published global time scales, such as the wall chart accompanying Harland *et al.* (1990), the Elsevier charts, and the bio- and chronostratigraphic framework accompanying the Exxon chart (Haq *et al.* (1987, 1988b) convey an impression of completeness, precision and certitude. However, an examination of the detailed evidence that is being used to build these time scales reveals numerous gaps, generalizations and inconsistencies. Difficulties in the erection of global biostratigraphic (stage) frameworks arise from the fact that most organisms are limited in their distribution by tectonic, physiographic and climatic barriers. Broad ecological differences from region to region and continent to continent require the definition of faunal and floral provinces (*e.g.*, Kennedy and Cobban, 1977; Gray and Boucot, 1979; Kauffman, 1984; Smith, 1988; Hancock, 1993a,b). Time correlation across provincial boundaries may be fraught with error or uncertainty because of the limited number of taxa that cross the province boundaries. Commonly, such correlations depend on the fact that faunal boundaries shift to and fro in response to climatic changes or plate-tectonic events, permitting faunas and floras from adjacent provinces to become interbedded. Uncertainties of the magnitude of one or more biozones are possible in this process of cross-correlation.

Hancock (1993a, p. 8) stated, "It is seldom realised by geologists at large how insecure most zonal schemes are, and how few are the regions in which any one scheme has been successfully tested." A synthesis with which he was involved (Birkelund *et al.*, 1984; see also Hancock, 1993b) noted as many as nine different possible biostratigraphic standards that could be used to define specific stage boundaries in the Cretaceous. Many are partly in conflict with one another.

Figure 13 illustrates the process of collating chronostratigraphic data from a variety of sources around the world in order to construct a global stage framework calibrated with absolute ages. During much of the Mesozoic, the presence of the wide east-west-oriented Tethyan Ocean, separation of the North and South American continents, and the broad latitudinal extent of the American continents led to considerable faunal provincialism in benthic and some pelagic fossil groups. The Tethyan,

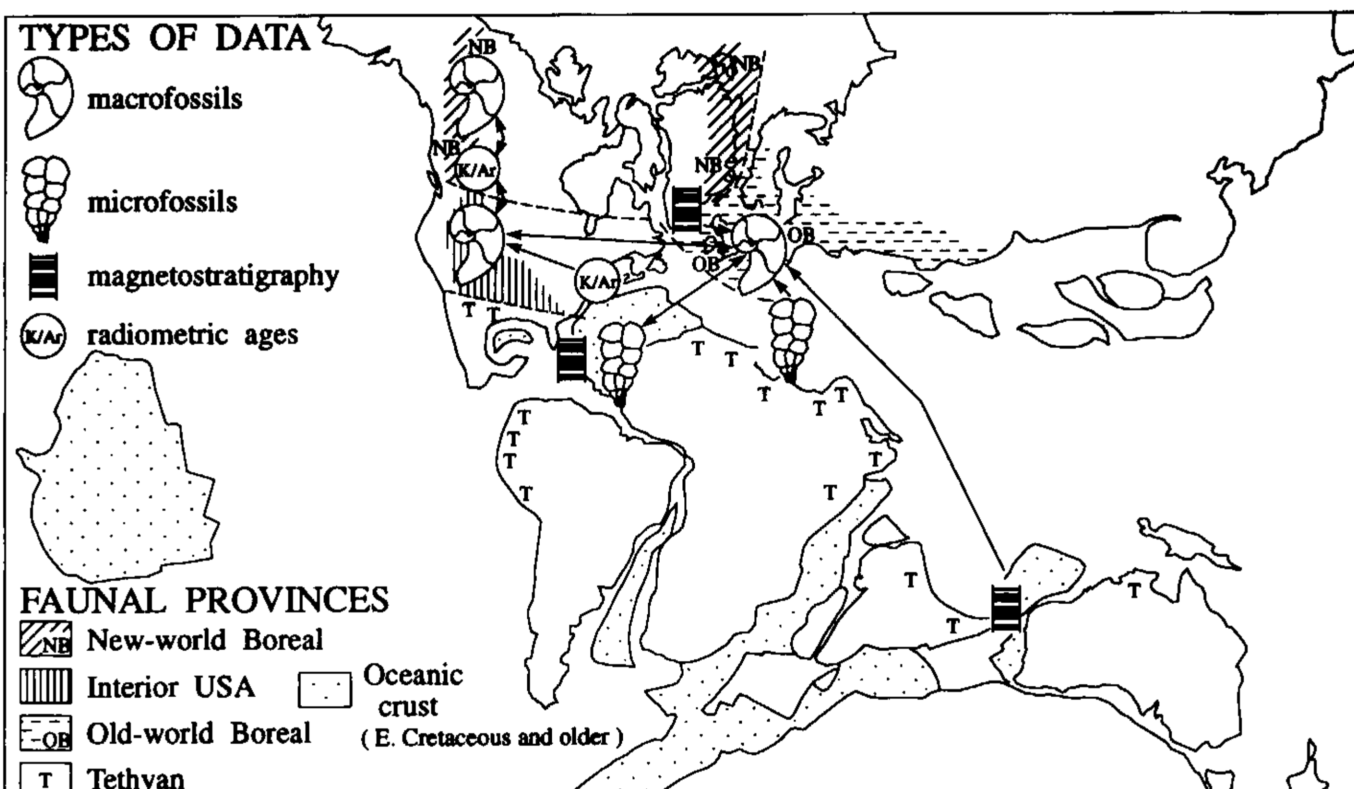


Figure 13 *The process of constructing a global time scale based on the collation of biostratigraphic, magnetostratigraphic and radiometric data. This diagram is loosely based on the construction of the Cretaceous time scale by Van Hinte (1976) but, of necessity, shows only a few of the key data points used in the compilation. Macrofossil data from the original nineteenth-century type sections in Europe comprise a critical base for the time scale. The Western Interior of North America is also a key area because of the wealth of well-studied sections there (e.g., Obradovich and Cobban, 1975). A few other data points, many representing DSDP data, are indicated. Biostratigraphic correlation is complicated by the problem of faunal provincialism. A very simplified distribution of Cretaceous ammonite faunal provinces (from Kennedy and Cobban, 1975; Kauffman, 1984) is shown.*

Boreal and other provinces indicated in Figure 13 are based on detailed work on the distribution of Cretaceous ammonites. As Hancock (1993a, p. 8) stated, "Every wide-ranging stratigrapher working on the Mesozoic meets the difficulty of correlations between boreal and tethyan realms." Faunal provincialism is also a problem with microfossils, including most of those favoured by biostratigraphers for intercontinental correlation. Theirstein (1981) and Roth and Bowdler (1981) described latitudinally controlled biogeographic distribution of Cretaceous nannoplankton. The latter authors also described neritic-oceanic biogeographic gradients.

As a single example of the magnitude of the potential for error at this stage of the analysis, Surlyk's (1990, 1991) study of the sequence stratigraphy of the Jurassic section of East Greenland may be mentioned. He derived a sea-level curve for this area, and compared it to the curves of Hallam (1988) and Haq *et al.* (1987, 1988b). In doing so, he noted "that the correlation between the Boreal and Tethyan stages across the Jurassic-Cretaceous boundary is only precise within ½ stage, rendering the eustatic ... nature of sea-level curves rather meaningless for this time interval."

An error in correlation of a biozone to the standard by as little as one zone as a result of faunal provincialism could add an error of up to 5 m.y., although this should be considered a pessimistic maximum. The degree of uncertainty varies considerably, depending on the degree of evolutionary divergence between organisms that has arisen because of long-continued climatic difference or plate separation between regions.

Assignment of Absolute Ages

An important step in the testing of regional and global correlations is to assign absolute ages to stratigraphic events using numerical methods based on radiometric, magnetostratigraphic and chemostratigraphic methods. This may be done in two main ways. First, it may be accomplished by the dating of the sequence framework itself, for example, by the radiometric analysis of interbedded volcanic horizons or glauconitic beds, or by the establishment of a magnetostratigraphic framework. Second, the biostratigraphic framework may be related to one or other of the published global time scales, making use of the accumulated evidence for the age of, say, the Campanian-Maastrichtian boundary to fix the age of local biostratigraphically dated horizons. These two approaches are not, of course, mutually exclusive, and much use may be made of local, regional and global correlation networks and data bases to achieve the best result.

The accuracy and precision of time resolution varies with the chronostratigraphic methods used and the level of the stratigraphic column. Various authors have estimated the dating precision over various intervals of geological time, and have assessed the incremental improvements in the global time scale that has been built from local, regional, and inter-regional correlation programs. Kidd and Hailwood (1993) estimated the resolution for various time slices back to the Triassic (Table 1).

Kauffman *et al.* (1991) described methods of high-resolution correlation that use biostratigraphy (graphic correlation methods), magnetostratigraphy, chemostratigraphy and the correlation of event beds. Numerous datable ash beds are present in his sections. A potential uncertainty of only ±100 ka is claimed for Cretaceous beds of the Western Interior of the United States. However, this provides only a regional framework, and it is unlikely that it could be extended to other unrelated basins with the same degree of precision.

Miller (1990) indicated that chronostratigraphic resolution of Cenozoic sections could ideally attain accuracies of ±100 ka, based on the use of modern chronostratigraphic techniques and biostratigraphic data bases, but he conceded that uncertainties of 0.5 m.y. to 2.0 m.y. are common in many actual case studies. Aubry (1991), in a detailed discussion of the Early Eocene record of sea-level change, stated that under ideal conditions, combinations of biostratigraphic (mainly microfossil) and magnetostratigraphic data should permit dating to within 0.2 m.y. to 0.3 m.y. Yet commonly, according to her, the data from specific locations are inadequate to permit the use of all available tools.

Table 1 Achievable resolution for integrated stratigraphy in marine successions.

Quaternary	<1-3 ka
Late Cenozoic	5-10 ka
Early Cenozoic	10 ka-1 m.y.
Late Cretaceous	100 ka-1 m.y.
Early Cretaceous	~10 m.y.
Jurassic	50-150 ka
Triassic	225 ka-2 m.y.

(simplified from Kidd and Hailwood, 1993)

Unfortunately there is still no universal agreement on the ages of many of the major chronostratigraphic boundaries. Many authoritative scales have been published, such as that used in the Decade of North American Geology Project (Palmer, 1983), and the synthesis of Harland *et al.* (1990). However, residual differences between these scales exist, as illustrated in Figure 14. Menning (1989) provided a thorough compilation of various numerical time scales.

Harland *et al.* (1990) indicated that the range of possible ages for stage boundaries in the Cretaceous vary by as little as ±4 m.y. for the Albian-Cenomanian boundary (the difference between the likely minimum and maximum possible ages) and as much as ± 25 m.y. for the Aptian-Barremian boundary. They assigned an overall average 2% uncertainty to the calibration of the Phanerozoic scale (± 2 m.y. at 100 Ma). These error values relate to the best available global data calibrated by several independent means, yet they reveal a residual imprecision that would not permit the dating of any given stratigraphic event, even in one of the global stratotypes, to better than ± 2 m.y. The implied precision of the Haq *et al.* (1987, 1988b) chart, and the density of event spacing, are, therefore, simply impossible, and none of the "events" shown in this chart can be relied upon as proven. It must be emphasized that this relates to the problem of *global* correlation. As noted above, much greater precision can be achieved locally, but this does not help in the testing of global cyclicity.

Summary: Uncertainties in Global Correlation

There are two related but distinct problems to be addressed in the construction of a global stratigraphic framework. On the one hand, we need to test whether similar stratigraphic events (such as sequence boundaries) and successions of events (*e.g.*, succesions of sequences) have closely similar ages in different parts of the earth, in order to test models of global causality (*e.g.*, eustasy). From this perspective, precise correlation is critical, but determination of absolute age is not, although all the Exxon publications on the global cycle chart appear to suggest that absolute age is of primary importance by the way they annotate the cycle charts. On the other hand, there is the ongoing effort to determine the precise age of stratigraphic events, leading to continuing refinements in the global time scale. In either case, the potential error, or uncertainty, involved with one or more of the "steps" described above must be acknowledged and addressed as part of a determination of the level of refinement to be expected in stratigraphic interpretation.

In the first case, tests of global synchroneity can be attempted through the use of biostratigraphic data to provide relative ages, or by very precise chronostratigraphic correlation through the use of radiometric, magnetostratigraphic or chemostratigraphic dating, or a combination of both procedures. Magnetostratigraphic and chemostratigraphic methods (particularly the use of oxygen isotope data) are becoming very precise for some Cenozoic strata, in some cases permitting precision of dating and correlation to uncertainty levels of as little as a few tens of thousands of years. This topic is beyond the scope of the present paper and is not discussed further (see Johnson *et al.*, 1988, and Kamp and Turner, 1990, for examples). For strata of Mesozoic and Paleozoic age, and for much of the older Cenozoic, radiometric dating is the most important chronostratigraphic tool. Potential error associated with this technique is summarized above, and ranges up to a few millions of years, depending on the type of data and the technique used. In many cases, imprecision arises from the fact that the material required for radiometric dating, such as a volcanic tephra, is some stratigraphic distance from the event of interest, introducing uncertainties in dating stemming from the incompleteness of the stratigraphic record and variations in sedimentation rates, of the type discussed earlier in this paper.

The establishment of global correlations based on biostratigraphic data alone involves two of the "steps" discussed above. Individual biozones have finite durations and commmonly are not subdivisible (they constitute an "ordinal" type of data). As noted above, this introduces imprecisions related to the duration of the zones, varying from approximately 0.5 m.y. to 5.0 m.y., depending on the fossil forms used, and the location and age of the rocks under

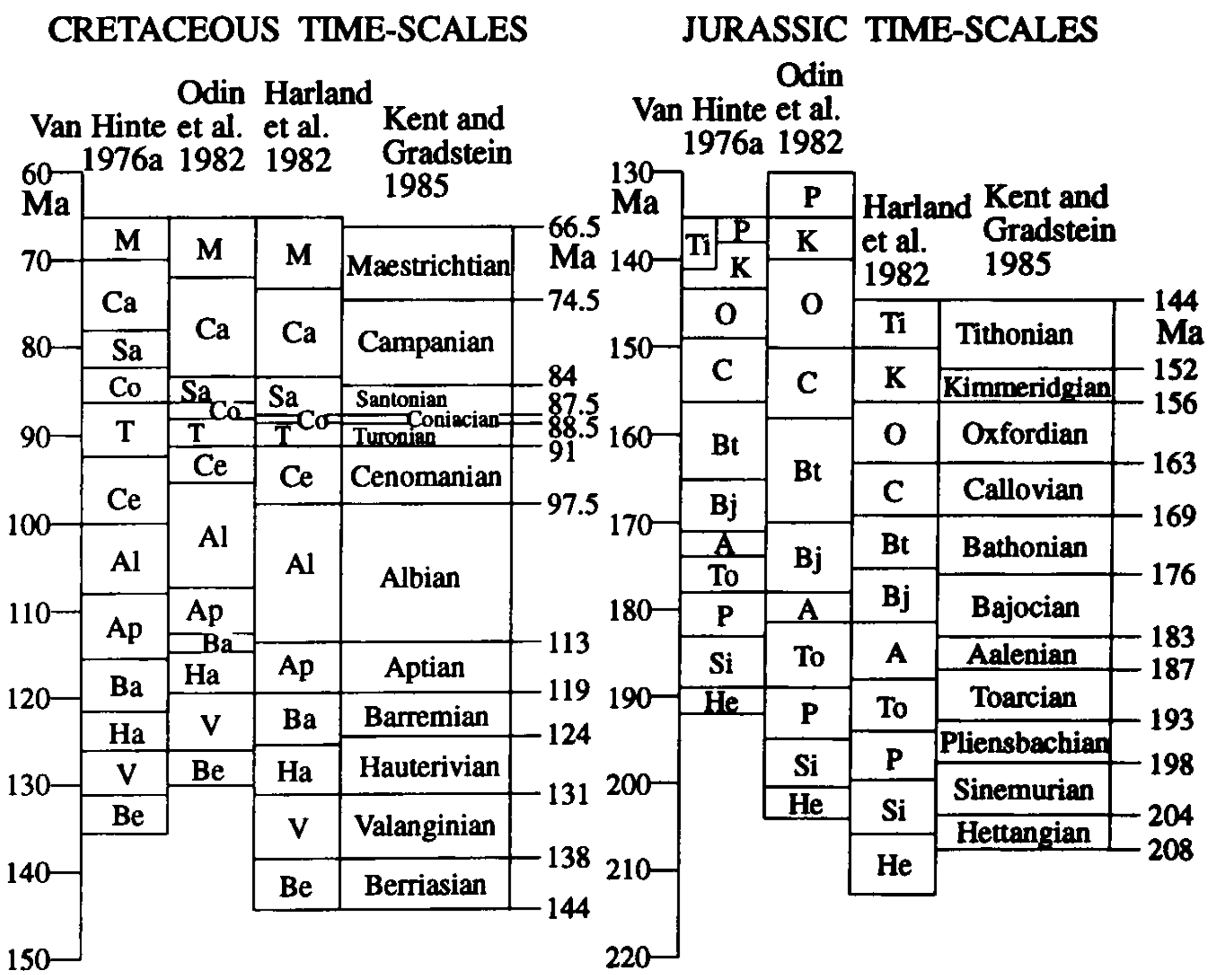


Figure 14 *A comparison of stage-boundary ages in four recent time scales (Kent and Gradstein, 1985).*

study. Biostratigraphic imprecision may be significantly reduced in some cases by the use of several zonal schemes in combination, and such combinations also serve as checks against facies control and diachroneity. The correlation of zones across environmental and faunal/floral province boundaries introduces additional uncertainty, possibly amounting to as much as a few million years, as discussed above. To a considerable extent, the two types of error, those reflecting biozone duration and interprovincial uncertainty, are additive when global correlation is attempted.

The magnitude of uncertainty in global biostratigraphic correlation may or may not be reduced by the use of chronostratigraphic methods, by assigning absolute ages to the local biozone framework. This type of cross-disciplinary work is what has led to the development and refinement of the global time scale, and research in sequence stratigraphy has the potential to add considerably to this effort and also to benefit from it. As shown by Kauffman *et al.* (1991), in some cases accuracies of ±100 ka may be achieved by very detailed work, but this type of work needs to be undertaken in many parts of the globe before tests of global synchroneity can be attempted at such a level of accuracy.

The nature of transgressive and regressive processes during a sea-level cycle may introduce an offset of up to a half-cycle in the age of the sequence-bounding unconformity between basin centre and basin margin. Theoretical studies of the formation of stratigraphic sequences also indicate that they may exhibit a variable phase lag of up to one-quarter of a sea-level cycle along depositional strike, depending on factors of subsidence rate and sediment supply. Sequence-bounding unconformities are therefore diachronous, spanning finite time intervals of up to a few million years. These factors introduce local complications into the stratigraphic record that our methods of dating and correlation are generally not yet able to resolve.

IMPLICATIONS FOR THE EXXON GLOBAL CYCLE CHART

The Exxon curves are not the first curves that have been compiled in an attempt to provide a global standard. Early work by Stille, Schuchert, Grabau and others was reviewed by Hallam (1992) who has himself been compiling and revising sea-level curves for many years. His latest book (Hallam, 1992) is an excellent compilation and updating of all his earlier work. However, it is the Exxon curves that have received so much attention, and that have appeared in global syntheses of geologic time, such as that by Harland *et al.* (1990). The Exxon work therefore needs to be examined carefully.

Potential error in the global time scale is discussed in some detail by Haq *et al.* (1988b), but the relationship between this error and the dating and correlation of sequence boundaries is not discussed. Sequence boundaries are not shown with attached error bars in the global cycle chart. Haq *et al.* (1987, 1988b) show sequence boundaries spaced 1 m.y. or less apart and, in some cases, date them to within ± 0.5 m.y., even though this is less than the stated potential age error. What this means is that in most cases, the potential dating error of any one sequence boundary encompasses the assigned age of at least the sequence above and below. Distinguishing the ages of such adjacent sequence boundaries is thus not possible on chronostratigraphic grounds. This inconsistency, plus residual disagreements between various chronostratigraphers involved in the compilation of the global cycle chart, has led to numerous errors and inconsistencies in the papers published in support of the chart. These were summarized by Miall (1991a).

The correlation and dating of stacked sequences and the use of pattern-matching techniques may reduce the potential for error, but this procedure can introduce its own problems, as discussed below with reference to Cretaceous clastic wedges in Alberta.

The practice of assigning radiometric ages to sequence boundaries, even where the absolute ages are subject to revision, is a source of considerable confusion. Baum and Vail (1988, p. 314) stated:

> Although sequence boundaries are named by a radiometric age (corresponding to the age of the sequence boundary where it becomes conformable), the sequence boundaries are dated paleontologically ... Currently there are numerous composite radiometric-time scales, all varying slightly from one another. Thus, some unnecessary confusion exists because different authors prefer different time scales. The radiometric age of a sequence boundary may vary from author to author but the paleontologic age is the same.

Comparisons between the sea-level curves published in the same book by Haq *et al.* (1988b) and Baum and Vail (1988) show that they are not the same. Both versions are clearly labelled as "eustatic," indicating that they are presenting the end product of the Exxon sequence-stratigraphic analytical methodology. This being the case, how can they be different? It is explicit in the methodology that tectonics and other complicating factors may be ignored in the *placement* (age) of sequence boundaries, although it is allowed that the *amplitude* of the sea-level deflections comprising the eustatic curve may be modified by tectonics (Vail *et al.*, 1991). Underhill (1991) has also demonstrated major inconsistencies in the Jurassic curves derived from Exxon research in the North Sea Basin. Apparent conflicts between the two curves co-authored by P. R. Vail can readily be understood as a reflection of the kinds of error or uncertainty discussed in this paper, but this is not addressed by the authors of these curves, who (as noted elsewhere) do not deal effectively with the significance of error in any of their papers.

As an example of the problems arising from chronostratigraphic imprecision, I cite here the attempt by Plint *et al.* (1992) to correlate the Cretaceous clastic pulses in the Alberta Basin, Canada, with the global cycle chart (Fig. 15). Table 2 reproduces Plint's (1991) table of possible stage ages for the mid-Cretaceous, showing the ages assigned in four recent time scales. Plint (1991) used these data as the basis for his correlation of one of the clastic pulses, the Marshybank Formation. This unit is assigned a latest Coniacian to early Santonian age on biostratigraphic grounds. Plint's table indicates that the Coniacian-Santonian boundary is between 86 Ma and 88 Ma, depending on the time scale used. The arithmetic average of these values is 86.87, and Plint (1991) is therefore confident in assigning the Marshybank clastic pulse to the 87.5 Ma eustatic event of the Exxon global cycle chart. Given the magnitudes of the errors discussed in this paper, a correlation with the 88.5 Ma event, or even the

Table 2 Boundaries and durations of the Coniacian and Santonian stages (Plint, 1991).

	Obradovitch & Cobban, 1975	Palmer, 1983	Haq *et al.*, 1988b	IUGS, 1989	Average
Campanian					
....	82	84	84	83	83.25
Santonian	(4)	(3.5)	(4)	(3)	(3.62)
....	86	87.5	88	86	86.87
Coniacian	(1)	(1)	(1)	(2)	(1.25)
....	87	88.5	89	88	88.12
Turonian					

85 Ma event on the global cycle chart, would not be unreasonable. However, as can be seen from Figure 15, this would require a realignment of many of the other clastic pulses in the Alberta Basin, none of which has been dated with any greater degree of precision. The best that can be said for this correlation exercise is that it is "permissive"; the data do not negate it as a possibility. The alternative possibility is that these clastic pulses are tectonic in origin: typical "molasse", in the sense of Van Houten (1981). Plint and his co-workers have, in fact, examined various tectonic mechanisms for the generation of sequence architectures in the Alber-

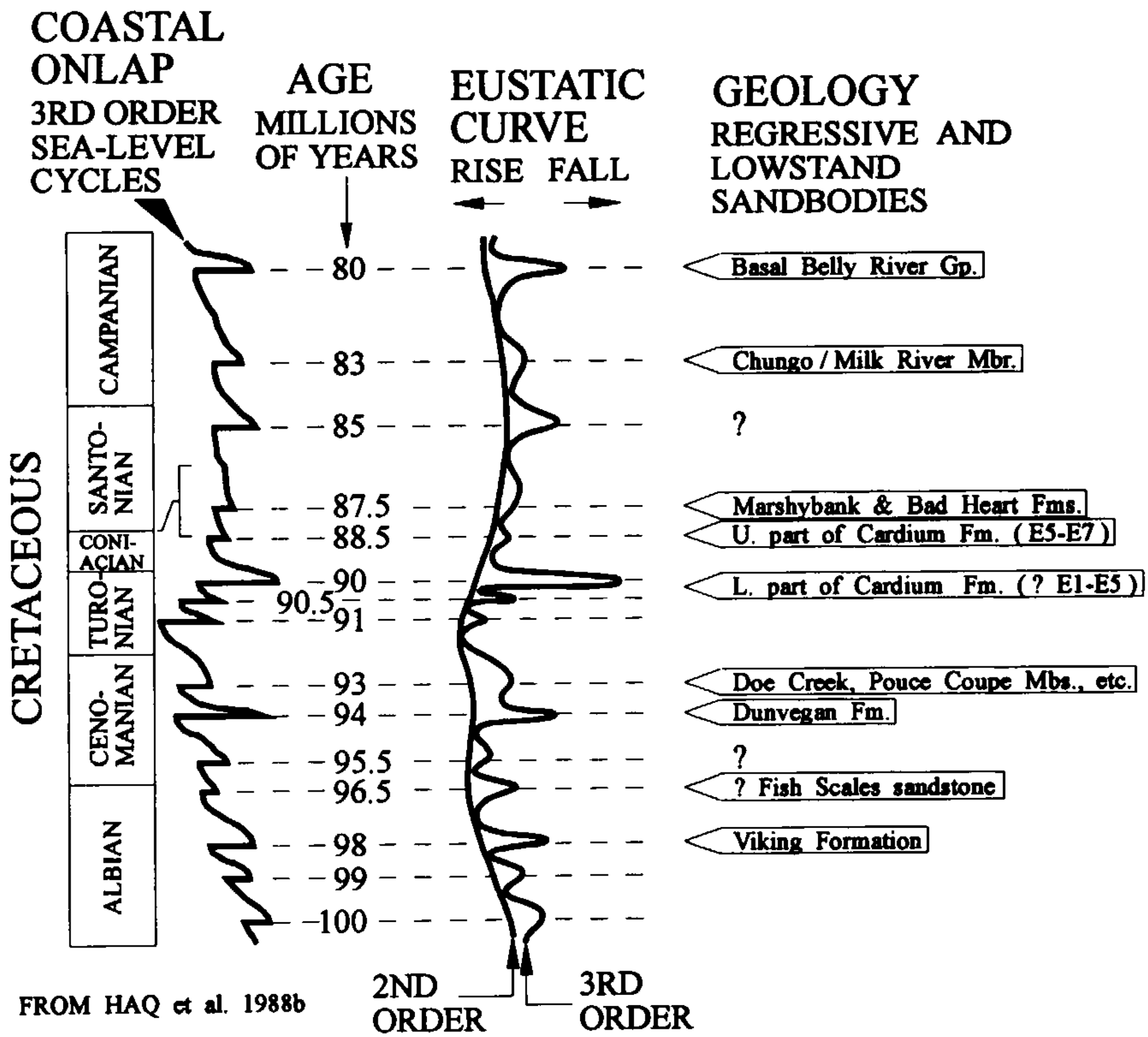


Figure 15 *The major clastic pulses in the Alberta Basin, each constituting "third-order" sandstone-dominated sequences, and their proposed correlation with the Exxon global cycle chart (Plint et al., 1992). Bracket indicates range of ages assigned to the Coniacian-Santonian boundary in various sources (Table 2).*

ta Basin (Plint *et al.*, 1993; Hart and Plint, 1993). Miall (1991a, 1992) suggested that many of the "events" in the Exxon global cycle chart are of regional tectonic origin, and the example of the Alberta clastic pulses given here is typical of the difficulties involved in assessing the alternatives.

Dixon (1993) addressed the tectonics-*versus*-eustasy question in the case of regional unconformities present in the Cretaceous succession of northwest Canada. Imprecision and uncertainty in biostratigraphic correlation with the Exxon curve exist in part because of the difficulty of precise correlation across faunal-province boundaries into the Boreal realm. Dixon (1993) demonstrated that each of the eight sequence boundaries in the succession could be correlated to two or three of the "events" in the Exxon curve, confirming Miall's (1992) suggestion that the curve contains "an event for every occasion." In several cases, however, regional evidence clearly indicates a tectonic origin for the sequence boundary. For example, a late Albian-early Cenomanian sequence boundary corresponds to a break-up unconformity preceding the sea-floor spreading that generated the Canada Basin.

Hancock (1993a,b) carried out a detailed examination of the Cretaceous part of the Exxon curve. He pointed out that the biostratigraphic framework consists of an amalgam of regional biozones, many of which do not occur together in a given location. Serious problems of Tethyan-Boreal provinciality were not addressed in the Exxon work, and Hancock (1993a) had difficulty correlating his own detailed stratigraphic synthesis with the Exxon curve using either biostratigraphic comparisons or radiometric ages. He concluded that "It is perhaps inevitable that discussion of the Exxon chart should seem to be a catalogue of complaints."

As Kauffman *et al.* (1991) showed, extremely precise dating can be carried out on a regional scale, given good biostratigraphic, magnetostratigraphic, and radiometric data. However, this is only the beginning in the effort to construct a global cycle chart, for which the establishment of global correlations is a necessary condition. I have suggested elsewhere (Miall, 1992) that without such global correlations, there is no independent proof that the paradigm of third-order global eustasy has any validity whatsoever. It is completely misleading to state, as do Posamentier and Weimer (1993, p. 737) that, on the one hand, chronostratigraphic error is a serious problem, while on the other hand arguing that the global cycle chart is most useful to stratigraphers where there is no age dating available! I respectfully submit that "They don't get it!"

CONCLUSIONS

Research into global stratigraphy and global stratigraphic controls has received an enormous impetus from the work of Peter Vail and his colleagues. The sequence-architecture model is now firmly established, and is providing a basis for much exciting research and synthesis. However, as this paper has attempted to demonstrate, the question of global synchroneity of stratigraphic events remains unresolved. It is still beyond our powers to test the global synchroneity of the "third-order" cycles (those ranging between approximately 1 m.y. and 10 m.y. in duration) that constitute the main basis of the Exxon global cycle chart because, as demonstrated in this paper, the accuracy and precision of our methods of dating and correlation are, in most cases, associated with potential uncertainties of up to a few millions of years. Much research is now demonstrating the potential for tectonic processes to develop cycles of third-order type (Macdonald, 1991; Williams and Dobb, 1993). This currently constitutes one of the most vigorous and exciting areas of stratigraphic research. Cycles of tectonic origin may have areal extents of regional or continental scope, but are very unlikely to be global. For this reason, the test of global synchroneity remains central to a resolution of the tectonic-*versus*-eustatic debate, and for the forseeable future, improvements in biostratigraphic correlation will represent our best hope for resolving this question.

ACKNOWLEDGEMENTS

I am grateful to Darrel Long for stimulating the writing of this paper as a contribution to a proposed special session at the Annual Meeting of the Geological Association of Canada. "PaleoScene" editor Godfrey Nowlan and reviewers John Armentrout and Terry Poulton provided numerous thoughtful comments that have helped me to clarify misconceptions and improve my message. Terry and John sent me copies of relevant publications, as did correspondents George Pemberton, Dale Leckie, Jake Hancock, Bob Scott and Jim Dixon. Thanks to all these individuals for sharing their ideas with me.

REFERENCES

Ager, D.V., 1964, The British Mesozoic Committee: Nature, v. 203, p. 1059.

Ager, D.V., 1981, The nature of the stratigraphical record (second edition): John Wiley, New York, 122 p.

Agterberg, F.P., 1990, Automated stratigraphic correlation: Elsevier, Amsterdam, 424 p.

Algeo, T.J., 1993, Quantifying stratigraphic completeness: a probabilistic approach using paleomagnetic data: Journal of Geology, v. 101, p. 421-433.

Algeo, T.J. and Wilkinson, B.H., 1988, Periodicity of mesoscale Phanerozoic sedimentary cycles and the role of Milankovitch orbital modulation: Journal of Geology, v. 96, p. 313-322.

Armentrout, J.M., 1981, Correlation and ages of Cenozoic chronostratigraphic units in Oregon and Washington: Geological Society of America, Special Paper 184, p. 137-148.

Armentrout, J.M., Malecek, S.J., Fearn, L.B., Sheppard, C.E., Naylor, P.H., Miles, A.W., Desmarais, R.J. and Dunay, R.E., 1993, Log-motif analysis of Paleogene depositional systems tracts, Central and Northern North Sea: defined by sequence stratigraphic analysis, *in* Parker, J.R., ed., Petroleum geology of Northwest Europe: Proceedings of the 4th conference: Geological Society, London, p. 45-57.

Aubry, M.-P., 1991, Sequence stratigraphy: eustasy or tectonic imprint: Journal of Geophysical Research, v. 96B, p. 6641-6679.

Bassett, M.G., 1985, Towards a "common language" in stratigraphy: Episodes, v. 8, p. 87-92.

Baum, G.R. and Vail, P.R., 1988, Sequence stratigraphic concepts applied to Paleogene outcrops, Gulf and Atlantic basins, *in* Wilgus, C.K., *et al.*, eds., Sea-level research: An integrated approach: Society of Economic Paleontologists and Mineralogists, Special Publication 42, p. 309-327.

Berggren, W.A. and Van Couvering, J.A., 1978, Biochronology, *in* Cohee, G.V., Glaessner, M.F. and Hedberg, H.D., eds., Contributions to the geologic time scale: American Association of Petroleum Geologists, Studies in Geology 6, p. 39-55.

Birkelund, T., Hancock, J.M., Hart. M.B., Rawson, P.F., Remane, J., Robaszynski, F., Schmid, F. and Surlyk, F., 1984, Cretaceous stage boundaries-proposals: Bulletin of the Geological Society of Denmark, v. 33, p. 3-20.

Carter, R.M., Abbott, S.T., Fulthorpe, C.S., Haywick, D.W. and Henderson, R.A., 1991, Application of global sea-level and sequence-stratigraphic models in Southern Hemisphere Neogene strata from New Zealand, *in* Macdonald, D.I.M., ed., Sedimentation, tectonics and eustasy: Sea-level changes at active margins: International Association of Sedimentologists, Special Publication 12, p. 41-65.

Cartwright, J.A., Haddock, R.C. and Pinheiro, L.M., 1993, The lateral extent of sequence boundaries, *in* Williams, G.D. and Dobb, A., eds., Tectonics and seismic sequence stratigraphy: Geological Society, Special Publication 71, p. 15-34.

Christie-Blick, N., Mountain, G.S. and Miller, K.G., 1988, Sea level history: Science, v. 241, p. 596.

Christie-Blick, N., Mountain, G.S. and Miller, K.G., 1990, Seismic stratigraphy: record of sea-level change, *in* Revelle, R., ed., Sea-level change: National Research Council, Studies in Geophysics, Washington, National Academy Press, p. 116-140.

Cope, J.C.W., 1993, High resolution biostratigraphy, *in* Hailwood, E.A. and Kidd, R.B., eds., High resolution stratigraphy: Geological Society, Special Publication 70, p. 257-265.

Cox, B.M., 1990, A review of Jurassic chronostratigraphy and age indicators for the UK, *in* Hardman, R.F.P. and Brooks, J., eds., Tectonic events responsible for Britain's oil and gas reserves: Geological Society, Special Publication 55, p. 169-190.

Cross, T.A. and Lessenger, M.A., 1988, Seismic stratigraphy: Annual Review of Earth and Planetary Sciences, v. 16, p. 319-354.

Crowley, K.D., 1984, Filtering of depositional events and the completeness of sedimentary sequences: Journal of Sedimentary Petrology, v. 54, p. 127-136.

Demarest, J.M., II and Kraft, J.C., 1987, Stratigraphic record of Quaternary sea levels: implications for more ancient strata, *in* Nummedal, D., Pilkey, O.H. and Howard, J.D., eds., Sea-level fluctuation and coastal evolution: Society of Economic Paleontologists and Mineralogists, Special Publication 41, p. 223-239.

Devine, P.E., 1991, Transgressive origin of channeled estuarine deposits in the Point Lookout Sandstone, northwestern New Mexico: a model for Upper Cretaceous, cyclic regressive parasequences of the U. S. Western Interior: American Association of Petroleum Geologists, Bulletin, v. 75, p. 1039-1063.

Dickinson, W.R., 1993, The Exxon global cycle chart: an event for every occasion? Discussion: Geology, v. 21, p. 282-283.

Dixon, J., 1993, Regional unconformities in the Cretaceous of north-west Canada: Cretaceous Research, v. 14, p. 17-38.

Doyle, J.A., 1977, Spores and pollen: the Potomac Group (Cretaceous) Angiosperm sequence, *in* Kauffman, E.G. and Hazel, J.E., eds., Concepts and methods of biostratigraphy: Dowden, Hutchinson and Ross Inc., Stroudsburg, Pennsylvania, p. 339-364.

Edwards, L.E., 1984, Insights on why graphic correlation (Shaw's method) works: Journal of Geology, v. 92, p. 583-597.

Edwards, L.E., 1985, Insights on why graphic correlation (Shaw's method) works: A reply [to discussion]: Journal of Geology, v. 93, p. 507-509.

Edwards, L.E., 1989, Supplemented graphic correlation: a powerful tool for paleontologists and nonpaleontologists: Palaios, v. 4, p. 127-143.

Einsele, G., Ricken, W. and Seilacher, A., 1991b, Cycles and events in stratigraphy — basic concepts and terms, *in* Einsele, G., Ricken, W. and Seilacher, A., eds., Cycles and events in stratigraphy: Springer-Verlag, Berlin, p. 1-19.

Geux, J., 1991, Biochronological correlations: Springer-Verlag, Berlin, 252 p.

Gradstein, F.M., Agterberg, F.P., Aubry, M.-P., Berggren, W.A., Flynn, J.J., Hewitt, R., Kent, D.V., Klitgord, K.D., Miller, K.G., Obradovitch, J. and Ogg, J. G., 1988, Sea level history: Science, v. 241, p. 599-601.

Gradstein, F.M., Agterberg, F.P., and D'lorio, M.A., 1990, Time in quantitative stratigraphy, *in* Cross, T.A., ed., Quantitative dynamic stratigraphy: Prentice Hall, Englewood Cliffs, p. 519-542.

Gray, J. and Boucot, A.J., eds., 1979, Historical biogeography, plate tectonics, and the changing environment: Oregon State University Press, Corvallis, Oregon, 500 p.

Hallam, A., 1988, A reevaluation of Jurassic eustasy in the light of new data and the revised Exxon curve, *in* Wilgus, C.K., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H.W., Ross, C.A. and Van Wagoner, J.C., eds., Sea-level research: an integrated approach: Society of Economic Paleontologists and Mineralogists, Special Publication 42, p. 261-273.

Hallam, A., 1992, Phanerozoic sea-level changes: Columbia University Press, Irvington, New York, 224 p.

Hancock, J.M., 1977, The historic development of biostratigraphic correlation, *in* Kauffman, E.G. and Hazel, J. E., eds., Concepts and methods of biostratigraphy: Dowden, Hutchinson and Ross Inc., Stroudsburg, Pennsylvania, p. 3-22.

Hancock, J.M., 1993a, Comments on the EXXON cycle chart for the Cretaceous system: Cuadernos de Geología Ibérica, n. 12, Madrid.

Hancock, J.M., 1993b, Transatlantic correlations in the Campanian-Maastrichtian stages by eustatic changes of sea-level, *in* Hailwood, E.A. and Kidd, R.B., eds., High resolution stratigraphy: Geological Society, Special Publication 70, p. 241-256.

Haq, B.U., Hardenbol, J. and Vail, P.R., 1987, Chronology of fluctuating sea levels since the Triassic (250 million years ago to present): Science, v. 235, p. 1156-1167.

Haq, B.U., Hardenbol, J. and Vail, P.R., 1988b, Mesozoic and Cenozoic chronostratigraphy and eustatic cycles, *in* Wilgus, C.K., *et al.*, eds., Sea level research — An integrated approach: Society of Economic Paleontologists and Mineralogists, Special Publication 42, p. 71-108.

Haq, B.U., Vail, P.R., Hardenbol, J. and Van Wagoner, J.C., 1988a, Sea level history: Science, v. 241, p. 596-602.

Harland, W.B., Armstrong, R.L., Cox, A.V., Craig, L.E., Smith, A.G. and Smith, D.G., 1990, A geologic time scale: Cambridge University Press, 263 p.

Harper, C.W., Jr. and Crowley, K.D., 1985, Insights on why graphic correlation (Shaw's method) works: A discussion: Journal of Geology, v. 93, p. 503-506.

Hart, B.S. and Plint, A.G., 1993, Tectonic influence on deposition in a ramp setting: Upper Cretaceous Cardium Formation, Alberta foreland basin: American Association of Petroleum Geologists Bulletin, v. 77, p. 2092-2107.

Hay, W.W. and Southam, J.R., 1978, Quantifying biostratigraphic correlation: Annual Review of Earth and Planetary Sciences, v. 6, p. 353-375.

Heckel, P.H., 1986, Sea-level curve for Pennsylvanian eustatic marine transgressive-regressive depositional cycles along midcontinent outcrop belt, North America: Geology, v. 14, p. 330-334.

Hedberg, H.D., ed., 1976, International Stratigraphic Guide: John Wiley and Sons, New York, 200 p.

Hubbard, R.J., 1988, Age and significance of sequence boundaries on Jurassic and Early Cretaceous rifted continental margins: American Association of Petroleum Geologists Bulletin, v. 72, p. 49-72.

Hunt, D. and Tucker, M.E., 1992, Stranded parasequences and the forced regressive wedge systems tract: deposition during base-level fall: Sedimentary Geology, v. 81, p. 1-9.

International Union of Geological Sciences, 1989, Global stratigraphic chart: Episodes, v. 12, part 2 (supplement).

Jenkins, D.G. and Gamson, P., 1993, The late Cenozoic *Globorotalia truncatulinoides* datum plane in the Atlantic, Pacific and Indian Oceans, *in* Hailwood, E.A., and Kidd, R.B., eds., High resolution stratigraphy: Geological Society, Special Publication 70, p. 127-130.

Jervey, M.T., 1988, Quantitative geological modeling of siliciclastic rock sequences and their seismic expression, *in* Wilgus, C.K., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H.W., Ross, C.A. and Van Wagoner, J.C., eds., Sea level research — an integrated approach: Society of Economic Paleontologists and Mineralogists, Special Publication 42, p. 47-69.

Johnson, J.G., 1992, Belief and reality in biostratigraphic zonation: Newsletters in Stratigraphy, v. 26, p. 41-48.

Johnson, N.M., Sheikh, K.A., Dawson-Saunders, E. and McCrae, L.E., 1988, The use of magnetic-reversal time lines in stratigraphic analysis: a case study in measuring variability in sedimentation rates, *in* Kleinspehn, K.and Paola, C., eds., New perspectives in basin analysis: Springer-Verlag, New York, p. 189-200.

Jordan, T.E. and Flemings, P.B., 1991, Large-scale stratigraphic architecture, eustatic variation, and unsteady tectonism: a theoretical evaluation: Journal of Geophysical Research, v. 96B, p. 6681-6699.

Kamp, P.J.J. and Turner, G.M., 1990, Pleistocene unconformity-bounded shelf sequences (Wangnui Basin, New Zealand) correlated with global isotope record: Sedimentary Geology, v. 68, p. 155-161.

Kauffman, E.G., 1984, Paleobiogeography and evolutionary response dynamic in the Cretaceous Western Interior Seaway of North America, *in* Westerman, G.E., ed., Jurassic-Cretaceous biochronology and paleogeography of North America: Geological Association of Canada, Special Paper 27, p. 273-306.

Kauffman, E.G., Elder, W.P. and Sageman, B.B., 1991, High-resolution correlation: a new tool in chronostratigraphy, *in* Einsele, G., Ricken, W. and Seilacher, A., eds., Cycles and events in stratigraphy: Springer-Verlag, Berlin, p. 795-819.

Kauffman, E.G. and Hazel, J.E., eds., 1977, Concepts and methods of biostratigraphy: Dowden, Hutchinson and Ross Inc., Stroudsburg, Pennsylvania, 658 p.

Kennedy, W.J. and Cobban, W.A., 1977, The role of ammonites in biostratigraphy, *in* Kauffman, E.G. and Hazel, J.E., eds., Concepts and methods of biostratigraphy: Dowden, Hutchinson and Ross Inc., Stroudsburg, Pennsylvania, p. 309-320.

Kidwell, S.M., 1988, Reciprocal sedimentation and noncorrelative hiatuses in marine-paralic siliciclastics: Miocene outcrop evidence: Geology, v. 16, p. 609-612.

Kidd, R.B. and Hailwood, E.A., 1993, High resolution stratigraphy in modern and ancient marine sequences: ocean sediment cores to Paleozoic outcrop, *in* Hailwood, E.A. and Kidd, R.B., eds., High resolution stratigraphy: Geological Society, Special Publication 70, p. 1-8.

Leckie, D.A. and Krystinik, L.F., 1993, Sequence stratigraphy: fact, fantasy, or work in progress (?): Canadian Society of Petroleum Geologists, Reservoir, v. 20, n. 8, p. 2-3.

Linsley, P.N., Potter, H.C., McNab, G. and Racher, D., 1979, Beatrice field, Moray Firth, North Sea (abs.): American Association of Petroleum Geologists, Bulletin, v. 63, p. 487.

Ludvigsen, R., Westrop, S.R., Pratt, B.R., Tuffnell, P.A. and Young, G.A., 1986, PaleoScene 3. Dual biostratigraphy: zones and biofacies: Geoscience Canada, v. 13, p. 139-154.

Macdonald, D.I.M., ed., 1991, Sedimentation, tectonics and eustasy: sea-level changes at active margins: International Association of Sedimentologists, Special Publication 12, 518 p.

MacLeod, N. and Keller, G., 1991, How complete are Cretaceous/Tertiary boundary sections? A chronostratigraphic estimate based on graphic correlation: Geological Society of America, Bulletin, v. 103, p. 1439-1457.

McKinney, M.L., 1986, Biostratigraphic gap analysis: Geology, v. 14, p. 36-38.

McLaren, D.J., 1970, Presidential address: Time, life and boundaries: Journal of Paleontology v. 44, p. 801-815.

McShea, D.W. and Raup, D.M., 1986, Completeness of the geological record: Journal of Geology, v. 94, p. 569-574.

Menning, M., 1989, A synopsis of numerical time scales 1917-1986: Episodes, v. 12, n. 1, p. 3-5.

Miall, A.D., 1986, Eustatic sea level changes interpreted from seismic straigraphy: a critique of the methodology with particular reference to the North Sea Jurassic record: American Association of Petroleum Geologists, Bulletin, v. 70, p. 131-137.

Miall, A.D., 1990, Principles of sedimentary basin analysis, second edition: Springer-Verlag, New York, 668 p.

Miall, A.D., 1991a, Stratigraphic sequences and their chronostratigraphic correlation: Journal of Sedimentary Petrology, v. 61, p. 497-505.

Miall, A.D., 1991b, Hierarchies of architectural units in terrigenous clastic rocks, and their relationship to sedimentation rate, *in* Miall, A.D., and Tyler, N., eds., The three-dimensional facies architecture of terrigenous clastic sediments and its implications for hydrocarbon discovery and recovery: Society of Economic Paleontologists and Mineralogists, Concepts in Sedimentology and Paleontology, v. 3, p. 6-12.

Miall, A.D., 1992, Exxon global cycle chart: an event for every occasion? Geology, v. 20, p. 787-790.

Millendorf, S.A. and Heffner, T., 1978, Fortran program for lateral tracing of time-stratigraphic units based on faunal assemblage zones: Computers and Geoscience, v. 4, p. 313-318.

Miller, F.X., 1977, The graphic correlation method in biostratigraphy, *in* Kauffman, E. G., and Hazel, J. E., eds., Concepts and methods in biostratigraphy: Dowden, Hutchinson and Ross, Inc., Stroudsburg, Pennsylvania, p. 165-186.

Miller, K.G., 1990, Recent advances in Cenozoic marine stratigraphic resolution: Palaios, v. 5, August Issue, "Online" comment.

Miller, K.G. and Kent, D.V., 1987, Testing Cenozoic eustatic changes: the critical role of stratigraphic resolution, *in* Ross, C.A. and Haman, D., eds., Timing and depositional history of eustatic sequences: constraints on seismic stratigraphy: Cushman Foundation for Foraminiferal Research, Special Publication 24, p. 51-56.

Mitchum, R.M., Jr. and Uliana, M.A., 1988, Regional seismic stratigraphic analysis of Upper Jurassic-Lower Cretaceous carbonate depositional sequences, Neuquen Basin, Argentina, *in* Bally, A.W., ed., Atlas of seismic stratigraphy: American Association of Petroleum Geologists, Studies in Geology 27, v. 2, p. 206-212.

Moore, T.C., Jr. and Romine, K., 1981, In search of biostratigraphic resolution, *in* Warme, J.E., Douglas, R.G. and Winterer, E.L., eds., The Deep Sea Drilling Project: A decade of progress: Society of Economic Paleontologists and Mineralogists, Special Publication 32, p. 317-334.

Murphy, M.A., 1977, On time-stratigraphic units: Journal of Paleontology, v. 51, p. 213-219.

Nummedal, D. and Swift, D.J.P., 1987, Transgressive stratigraphy at sequence-bounding unconformities: some principles derived from Holocene and Cretaceous examples, *in* Nummedal, D., Pilkey, O.H. and Howard, J.D., eds., Sea-level fluctuation and coastal evolution: Society of Economic Paleontologists and Mineralogists, Special Publication 41, p. 241-260.

Obradovich, J.D. and Cobban, W.A., 1975, A time-scale for the Late Cretaceous of the Western Interior of North America, *in* Caldwell, W.G.E., ed., The Cretaceous System of the Western Interior of North America: Geological Association of Canada, Special Paper 13, p. 31-54.

Olsson, R.K., 1988, Foraminiferal modeling of sea-level change in the Late Cretaceous of New Jersey, *in* Wilgus, C.K., *et al.*, eds., Sea-level research: An integrated approach: Society of Economic Paleontologists and Mineralogists, Special Publication 42, p. 289-297.

Palmer, A.R., compiler, 1983, The decade of North American Geology 1983 geologic time scale: Geology, v. 11, p. 503-504.

Pitman, W.C., III, 1978, Relationship between eustacy and stratigraphic sequences of passive margins: Geological Society of America, Bulletin, v. 89, p. 1389-1403.

Pitman, W.C., III and Golovchenko, X., 1988, Sea-level changes and their effect on the stratigraphy of Atlantic-type margins, *in* The Atlantic continental margin, United States: Geological Society of America, The geology of North America, v. I-2, p. 429-436.

Plint, A. G., 1988, Sharp-based shoreface sequences and "offshore bars" in the Cardium Formation of Alberta: their relationship to relative changes in sea level, *in* Wilgus, C.K., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H.W., Ross, C.A. and Van Wagoner, J.C., eds., Sea-level research: an integrated approach: Society of Economic Paleontologists and Mineralogists, Special Publication 42, p. 357-370.

Plint, A.G., 1991, High-frequency relative sea-level oscillations in Upper Cretaceous shelf clastics of the Alberta foreland basin: possible evidence for a glacio-eustatic control? *in* Macdonald, D.I.M., ed., Sedimentation, tectonics and eustasy: sea-level changes at active margins: International Association of Sedimentologists, Special Publication 12, p. 409-428.

Plint, A.G., Eyles, N., Eyles, C.H. and Walker, R.G., 1992, Control of sea level change, *in* Walker, R.G. and James, N.P., eds., Facies models: response to sea level change: Geological Association of Canada, p. 15-25.

Plint, A.G., Hart, B.S. and Donaldson, W.S., 1993, Lithospheric flexure as a control on stratal geometry and facies distribution in Upper Cretaceous rocks of the Alberta foreland basin: Basin Research, v. 5, p. 69-77.

Posamentier, H.W., Jervey, M.T. and Vail, P.R., 1988, Eustatic controls on clastic deposition, *in* Wilgus, C.K., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H.W., Ross, C.A. and Van Wagoner, J.C., eds., Sea level research — an integrated approach: Society of Economic Paleontologists and Mineralogists, Special Publication 42, p. 109-154.

Posamentier, H.W. and Weimer, P., 1993, Siliciclastic sequence stratigraphy and petroleum geology — where to from here? American Association of Petroleum Geologists, Bulletin, v. 77, p. 731-742.

Ramsbottom, W.H.C., 1979, Rates of transgression and regression in the Carboniferous of NW Europe: Journal of the Geological Society, v. 136, p. 147-153.

Ricken, W., 1991, Time span assessment — an overview, *in* Einsele, G., Ricken, W. and Seilacher, A., eds., Cycles and events in stratigraphy: Springer-Verlag, Berlin, p. 773-794.

Riedel, W.R., 1981, DSDP biostratigraphy in retrospect and prospect, *in* Warme, J.E., Douglas, R.G. and Winterer, E.L., eds., The Deep Sea Drilling Project: A decade of progress: Society of Economic Paleontologists and Mineralogists, Special Publication 32, p. 253-315.

Ross, C.A. and Haman, D., eds., 1987, Timing and depositional history of eustatic sequences: constraints on seismic stratigraphy: Cushman Foundation for Foraminiferal Research, Special Publication 24, 227 p.

Roth, P.H. and Bowdler, J.L., 1981, Middle Cretaceous calcareous nannoplankton biogeography and oceanography of the Atlantic Ocean, *in* Warme, J.E., Douglas, R.G. and Winterer, E.L., eds., The Deep Sea Drilling Project: A decade of progress: Society of Economic Paleontologists and Mineralogists, Special Publication 32, p. 517-546.

Sadler, P.M., 1981, Sedimentation rates and the completeness of stratigraphic sections: Journal of Geology, v. 89, p. 569-584.

Schlager, W., 1989, Drowning unconformities on carbonate platforms, *in* Crevello, P.D., Wilson, J.L., Sarg, J.F. and Read, J.F., eds., Controls on carbonate platforms and basin development: Society of Economic Paleontologists and Mineralogists, Special Publication 44, p. 15-25.

Schlager, W., 1992, Sedimentology and sequence stratigraphy of reefs and carbonate platforms: American Association of Petroleum Geologists, Continuing Education Course Notes, Series 34, 71 p.

Scott, R.W., Evetts, M.J. and Stein, J.A., 1993, Are seismic/depositional sequences time units? Testing by SHADS cores and graphic correlation: Offshore Technology Conference, Houston, Paper OTC 7110, p. 269-276.

Scott, R.W., Frost, S.H. and Shaffer, B.L., 1988, Early Cretaceous sea-level curves, Gulf Coast and southeastern Arabia, *in* Wilgus, C.K., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H.W., Ross, C.A. and Van Wagoner, J.C., eds., Sea-level research: an integrated approach: Society of Economic Paleontologists and Mineralogists, Special Publication 42, p. 275-284.

Shaw, A.B., 1964, Time in stratigraphy: McGraw-Hill, New York, 365 p.

Smith, P.L., 1988, PaleoScene 11: Paleobiogeography and plate tectonics: Geoscience Canada, v. 15, p. 261-279.

Srinivasan, M.S. and Kennett, J.P., 1981, A review of planktonic foraminiferal biostratigraphy: applications in the equatorial and South Pacific, *in* Warme, J.E., Douglas, R.G. and Winterer, E.L., eds., The Deep Sea Drilling Project: A decade of progress: Society of Economic Paleontologists and Mineralogists, Special Publication 32, p. 395-432.

Swift, D.J.P. and Thorne, J.A., 1991, Sedimentation on continental margins, I: a general model for shelf sedimentation, *in* Swift, D.J.P., Oertel, G.F., Tillman, R.W. and Thorne, J.A., eds., Shelf sand and sandstone bodies: geometry, facies and sequence stratigraphy: International Association of Sedimentologists, Special Publication 14, p. 3-31.

Surlyk, F., 1990, A Jurassic sea-level curve for East Greenland: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 78, p. 71-85.

Surlyk, F., 1991, Sequence stratigraphy of the Jurassic-lowermost Cretaceous of east Greenland: American Association of Petroleum Geologists, Bulletin, v. 75, p. 1468-1488.

Thierstein, H.R., 1981, Late Cretaceous nannoplankton and the change at the Cretaceous-Tertiary boundary, *in* Warme, J.E., Douglas, R.G. and Winterer, E.L., eds., The Deep Sea Drilling Project: A decade of progress: Society of Economic Paleontologists and Mineralogists, Special Publication 32, p. 355-394.

Underhill, J.R., 1991, Controls on Late Jurassic seismic sequences, Inner Moray Firth, UK North Sea: A critical test of a key segment of Exxon's original global cycle chart: Basin Research, v. 3, p. 79-98.

Vail, P.R., 1987, Seismic stratigraphy interpretation using sequence stratigraphy, Part 1: seismic stratigraphy interpretation procedure, *in* Bally, A.W., ed., Atlas of seismic stratigraphy: American Association of Petroleum Geologists, Studies in Geology 27, v. 1, p. 1-10.

Vail, P.R., Audemard, F., Bowman, S.A., Eisner, P.N. and Perez-Crus, C., 1991, The stratigraphic signatures of tectonics, eustasy and sedimentology — an overview, *in* Einsele, G., Ricken, W. and Seilacher, A., eds., Cycles and events in stratigraphy: Springer-Verlag, Berlin, p. 617-659.

Vail, P.R., Hardenbol, J. and Todd, R.G., 1984, Jurassic unconformities, chronostratigraphy and sea-level changes from seismic stratigraphy and biostratigraphy, *in* Schlee, J.S., ed., Interregional unconformities and hydrocarbon exploration: American Association of Petroleum Geologists, Memoir 36, p. 129-144.

Vail, P.R., Mitchum, R.M., Jr., Todd, R.G., Widmier, J.M., Thompson, S., III, Sangree, J.B., Bubb, J.N. and Hatlelid, W. G., 1977, Seismic stratigraphy and global changes of sea-level, *in* Payton, C.E., ed., Seismic stratigraphy — applications to hydrocarbon exploration: American Association of Petroleum Geologists, Memoir 26, p. 49-212.

Vail, P.R. and Todd, R.G., 1981, Northern North Sea Jurassic unconformities, chronostratigraphy and sea-level changes from seismic stratigraphy, *in* Illing, L.V. and Hobson, G.D., eds., Petroleum Geology of the continental shelf of northwest Europe: Institute of Petroleum, London, p. 216-235.

Van Hinte, J.E., 1976, A Cretaceous time scale: American Association of Petroleum Geologists Bulletin, v. 60, p. 498-516.

Van Houten, F.B., 1981, The odyssey of molasse, *in* Miall, A.D., ed., Sedimentation and tectonics in alluvial basins: Geological Association of Canada, Special Paper 23, p. 35-48.

Van Wagoner, J.C., Mitchum, R.M., Campion, K.M. and Rahmanian, V.D. 1990, Siliciclastic sequence stratigraphy in well logs, cores, and outcrops: American Association of Petroleum Geologists, Methods in Exploration, Series 7, 55 p.

Van Wagoner, J.C., Mitchum, R.M., Jr., Posamentier, H.W. and Vail, P.R., 1987, Seismic stratigraphy interpretation using sequence stratigraphy, Part 2: key definitions of sequence stratigraphy, *in* Bally, A.W., ed., Atlas of seismic stratigraphy: American Association of Petroleum Geologists, Studies in Geology 27, v. 1, p. 11-14.

Warme, J.E., Douglas, R.G. and Winterer, E.L., eds., 1981, The Deep Sea Drilling Project: A decade of progress: Society of Economic Paleontologists and Mineralogists, Special Publication 32, 564 p.

Wignall, P.B., 1991, Ostracod and foraminifera micropaleontology and its bearing on biostratigraphy: a case study from the Kimmeridgian (Late Jurassic) of north west Europe: Palaios, v. 5, p. 219-226.

Wilgus, C.K., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H.W., Ross, C.A. and Van Wagoner, J.C., eds., 1988, Sea level changes — An integrated approach: Society of Economic Paleontologists and Mineralogists, Special Publication 42, 407 p.

Williams, G.D. and Dobb, A., eds., 1993, Tectonics and seismic sequence stratigraphy: Geological Society, Special Publication 71, 226 p.

Ziegler, A.M., Cocks, L.R.M. and McKerrow, W.S., 1968, The Llandovery transgression of the Welsh borderland: Palaeontology, v. 11, p. 736-782.

Accepted, as revised, 26 May, 1994.