

Chapter 1

The Limits of Paleontological Resolution

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1. INTRODUCTION

When used by stratigraphers and paleontologists, the term "resolution" typically denotes *stratigraphic resolution* as determined by the finest-scale units or surfaces that can be recognized vertically, traced laterally, and correlated using approaches such as biostratigraphy or sequence stratigraphy. However, the term "resolution" can also denote *depositional resolution* of the physical records (e.g., fossils, grains, diagenetic precipitates, etc.) contained within individual strata. Due to temporal (e.g., Walker and Bambach, 1971; Kidwell and Bosence, 1991) and spatial mixing (e.g., Flessa, 1998), depositional resolution of records contained within individual strata may be much coarser than the stratigraphic resolution of depositional events that produced those strata. Moreover, an individual stratum is made predominately of fossils and sedimentary grains that predate its deposition, but may also include fossils, sedimentary structures, and diagenetic overprints that post-date its deposition. There are two distinct resolution concepts: *stratigraphic resolution* among strata and within-stratum *depositional resolution*.

The relevance of the two concepts depends on the goals of a study. If the task is to correlate units, reconstruct depositional histories of sedimentary basins, or develop a sequence-stratigraphic framework, we are concerned primarily with the stratigraphic resolution determined by the spacing of correlative depositional events and the duration of diastems separating those events (Fig. 1). In some cases, very fine levels of stratigraphic resolution can be achieved laterally by correlating highly resolved records such as varves (e.g., Nederbragt and Thurow, 2001), tree rings (e.g., Lageard *et al.*, 1999), or trace-fossil horizons (e.g., Kowalewski and Demko, 1997). A comparably high resolution can be achieved vertically, within single sections, by time-series analyses of continuous cyclic deposits such as tidal deposits (e.g., Miller and Eriksson, 1997).

However, potentially high stratigraphic resolution *among* strata does not

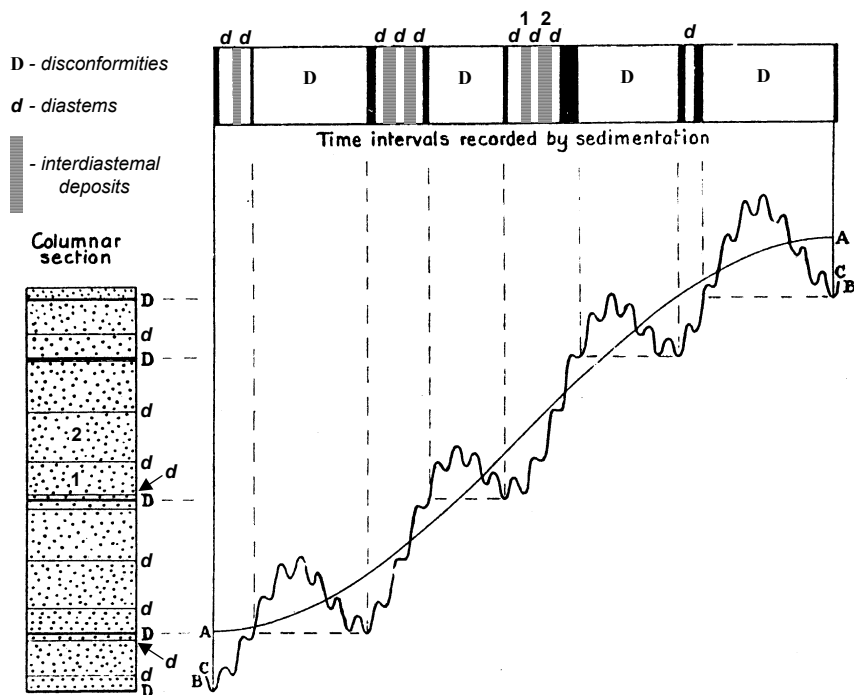


Figure 1. Joseph Barrell's (1917) model for the temporal dynamics of the sedimentary record. Depositional events are separated by diastems (d). Sets of events form higher-order packages bounded by disconformities (D) and controlled by diastrophic oscillations. Conceptually, the model is strikingly close to the approach of sequence stratigraphy developed many decades later (Vail and Mitchum, 1977; Vail *et al.*, 1977; Mitchum and Vail, 1977). Strata 1-2 represent interdiastemal deposits and correspond to strata 1 and 2 shown on Figure 2. Unlike the intervals suggested by Barrell's figure, typical diastems represent much longer time intervals than the depositional events they separate. Modified after Barrell (1917, fig. 5).

necessarily imply a comparably high depositional resolution *within* strata. In an example shown here (Fig. 2), the time span of paleontological records contained in Stratum 2 exceeds the duration of the diastems that separate neighboring strata. A fossil from Stratum 2 is not necessarily younger than Stratum 1: the stratigraphic resolution of depositional events can be finer than the resolution of the physical records contained within strata. Thus, if the research objectives involve integrating paleontological data, analyzing isotope ratios, or measuring any parameter from physical materials extracted from within strata, depositional resolution of records needs to be evaluated. Such evaluation will be particularly fruitful when done in the context of the duration of diastems separating that stratum from adjacent units.

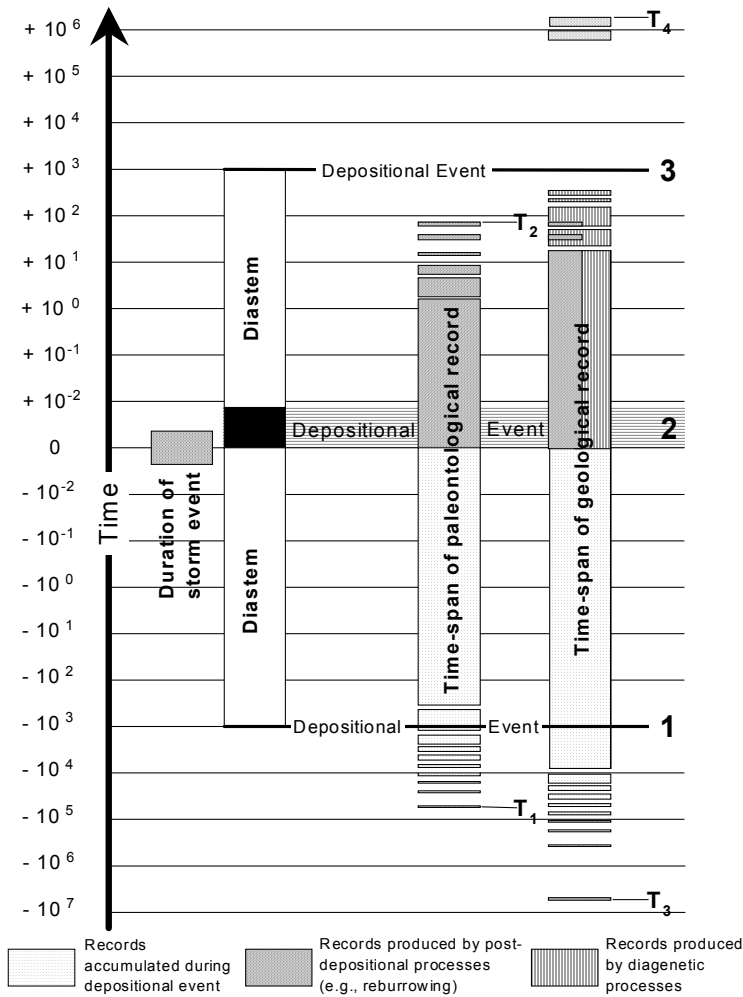


Figure 2. Depositional resolution of a single event (stratum "2" on Figure 1) exemplified by a storm bed. In this hypothetical example, both the paleontological and geological records have time-spans that exceed the duration of the diastems (marked as "d" on Figure 1) separating stratum 2 from the two neighboring depositional events. Thus, depositional resolution of a stratum is much poorer than the stratigraphic resolution of the same sedimentary record. Single depositional events correspond to interdiastemal deposits on Figure 1. Because the time is presented on a logarithmic scale, the lines representing events 1 and 3 are not to scale.

The studies compiled in this volume deal primarily with the stratigraphic resolution and illustrate powerful approaches used to improve the precision and accuracy of stratigraphic correlation. The aim of such studies (e.g., Kauffman *et al.*, 1991; Sageman *et al.*, 1997) is to maximize resolution of stratigraphic correlation by careful integration of paleontological and stratigraphic data. In contrast, our paper deals with the finest stratigraphic

scale: the internal resolution of single depositional events and their adjacent diastems. Using data amassed in recent years, primarily from modern depositional environments, we examine both depositional resolution of paleontological records contained within single strata as well as temporal characteristics of diastems that separate consecutive depositional events. The comparison of temporal characteristics of diastems with the depositional resolution of paleontological records allows us to integrate knowledge about both stratigraphic and depositional resolution into a single analysis. The two metrics of resolution considered jointly provide a useful conceptual insight into the temporal limits of paleontological and geological data.

We focus here on data and interpretations from marine nearshore and shelf environments where relatively frequent disturbance events (hurricanes, storms, pulses of sediment input from coastal settings, etc.) create the conditions that produce distinct bedding, providing the potential for recognizing and interpreting numerous short-term events. As noted by Miall (1990, p. 9): "...such events are typically responsible for deposition of disproportionately large volumes of sediment in sedimentary basins". In North America, for example, they comprise most of the marine Paleozoic sections in the Appalachians and on the craton, large amounts of Mesozoic age marine deposits of the Cordillera, much of the nearshore marine Mesozoic of the craton, and all of the Cretaceous and Cenozoic sedimentation of the Atlantic and Gulf Coastal Plain. Most paleontological studies of benthic faunas derive from deposits representing such settings.

Although basinal settings with less episodic sediment accumulation are not rare, rates of sediment accumulation in basins are commonly relatively low. In such cases, bioturbation processes mix sediment particles (including fossils) of different ages. Thus, the sediment, although possibly accumulated relatively continuously, will no longer preserve the exact superposed position of every grain. This post-depositional mixing makes any bioturbated sediment sample temporally mixed, just as if it had been reworked and redeposited in a short-term event. Martin (1999, Chapters 4, 5) discusses at length the features of "bioturbation" and "stratigraphic disorder" produced by bioturbation. *Only* laminated basinal sediments can carry a reliable record of depositional resolution at the finest scale, and these settings are relatively uncommon, being generally restricted to anoxic basins. In some settings, such anoxic basins may undergo repeated colonization by benthic fauna (e.g., Röhl *et al.*, 2001; Harries, pers. comm., 2001) and may provide higher resolution than what we consider here to be the typical marine fossil record. Barring such exceptions, the concepts discussed below relate to the most common and frequently studied stratigraphic records.

2. DEPOSITIONAL RESOLUTION OF PALEONTOLOGICAL RECORDS

2.1 Time Averaging and Temporal Mixing

It has long been recognized (e.g., Schäfer, 1956; Walker and Bambach, 1971) that fossils may both pre-date (via reworking and bioturbation) and post-date (via post-depositional reburrowing) the stratum that contains them (Fig. 2). Thus, unlike live-collected organisms, fossils found together within a single stratum need not be contemporaneous with one another, but may typically represent mixed remains of organisms that lived at different times and never interacted with one another. That is, paleontological records tend to undergo temporal mixing (e.g., Walker and Bambach, 1971; Peterson, 1977; Wilson, 1988; Goodfriend, 1989; Kidwell and Bosence, 1991; Behrensmeyer, 1991; Flessa, 1993; Kidwell and Behrensmeyer, 1993; Martin, 1993, 1999; Martin *et al.*, 1995, 1996; Wehmiller *et al.*, 1995; Kowalewski, 1996a; Kidwell, 1998).

Kidwell and Bosence (1991; see also Kidwell and Flessa, 1996) classified paleontological records into four overlapping classes of temporal mixing: ecological census, within-habitat time averaging, environmental condensation, and biostratigraphic condensation. This classification reflects a prevailing point of view (e.g., Kidwell and Bosence, 1991; Kowalewski, 1996a; Martin, 1999) that paleontological records vary along a continuum of time averaging from days to millions of years. It also implies that all records are time-averaged -- indeed, all records must be mixed at some scale as perfect synchronicity is infinitely unlikely (Kowalewski, 1996a). However, from the perspective of depositional and stratigraphic resolution, it seems useful to distinguish "ordinary" (time-averaged) records that dominate sedimentary strata from unusual and easily discernible extremes of snapshots, condensation, and *remanié*. Such "ordinary" strata do not contain any obvious relic fossils and occur within successions of beds separated by regular diastems rather than disconformities. That is, the term time averaging denotes here ubiquitous records that contain no obvious warning signs of mixing or condensation, but still may have a relatively low depositional resolution. Thus, our definition differs from that of many recent studies (e.g., Kidwell and Bosence, 1991; Kowalewski, 1996a; Kidwell and Flessa, 1996; Kidwell, 1998) in that we restrict the concept of time averaging to interdiastemal units and exclude the extreme cases of condensation and *remanié*. We use the term "temporal mixing" to denote all types of records and understand time averaging as a special (inter-diastemal) case of temporal mixing.

Our definition returns to the original definition of time averaging of

Walker and Bambach (1971) who proposed the term to denote subtle mixing that affect unsuspecting-looking deposits, and not obvious cases of culling such as dinosaur teeth in Tertiary river beds (e.g., Argast *et al.*, 1987). Thus, time averaging is a subtle temporal mixing. Accordingly, paleontological records are categorized here into three major classes of resolution: (1) snapshots ("ecological census" of Kidwell and Bosence, 1991) that contain fossils that are all contemporaneous with one another; (2) time-averaged records ("within-habitat time averaging") that contain fossils mixed over time intervals notably exceeding the life span of organisms, typically hundreds to thousands of years (see below), but include no signs of substantial temporal mixing associated with condensation or reworking of much older fossils into much younger deposits; and (3) condensed records and *remanié* ("environmental condensation" and "biostratigraphic condensation" *sensu* Kidwell and Bosence, 1991) that include mixtures of fossils culled over longer time scales, typically tens of thousands to millions of years. For more details see Section 2.3 below.

Three aspects of temporal mixing need to be considered when evaluating temporal depositional resolution of a stratum: (1) the duration of temporal mixing (Section 2.2); (2) the internal temporal structure (Section 2.3); and (3) the completeness of the temporally mixed deposit (Section 2.4).

2.2 Duration of Temporal Mixing

The duration of temporal mixing (i.e., the time span represented by fossils contained in a single sample) is the key determinant of depositional resolution of paleontological records contained within individual strata. The shorter the time span of temporal mixing of a given stratum, the finer the depositional resolution of that stratum.

The most common way to measure time averaging is the age range between the youngest and oldest fossil sampled from a stratum (e.g., Flessa and Kowalewski, 1994). The shell half-life (amount of time it takes to destroy 50% of shells; e.g., Meldahl *et al.*, 1997) and the standard deviation of dated specimens (Kowalewski *et al.*, 1998) have also been used. Regardless of the metric used, temporal mixing can be assessed from various data including actuopaleontological, paleontological, and computer-based approaches. The current estimates come primarily from research in modern and subfossil depositional systems where direct quantitative estimates can be obtained by absolute dating of individual shells. The indirect methods based on faunal differences, shell survival experiments, or resampling methods have also been employed but are much less reliable (see Flessa, 1993) and vary much more in their estimates of temporal mixing (Peterson, 1976; Cadée, 1984; Carthew and Bosence, 1986; Staff *et al.*, 1986; West *et al.*,

1990; Kidwell and Bosence, 1991; see Flessa, 1993). Consequently, we focus our discussion here primarily on estimates derived by direct dating of individual specimens and use other lines of evidence only as supplemental sources.

The dating projects conducted to estimate temporal mixing in marine bioclastic deposits (Table 1) are all restricted by the range of radiocarbon dating (the last 40,000 years or so) and necessarily target the youngest fossil record (the latest Pleistocene and Holocene). Except for foraminifers, the estimates in Table 1 were derived by dating individual specimens collected, in most cases, from single sites or single strata. These specimens were collected either from active depositional surfaces with live fauna (mixing estimated by the oldest dated individual) or from single subfossil beds (mixing estimated by the age range between oldest and youngest fossil). Both approaches yield estimates of incipient mixing, prior to any serious temporal culling. They are, therefore, expected to be a good analogue for interdiastemal time averaging, and not condensed records or *remanié*.

The estimates show that regardless of the type of depositional environment (supratidal, intertidal, nearshore subtidal, or offshore shelf) or analyzed taxa (mollusks, brachiopods, or foraminifers), temporal mixing is always present. The variation among the estimates barely exceeds one order of magnitude, with values ranging from a few hundred to several thousand years, suggesting that time averaging of marine shelly fauna varies in a narrow range relative to the overall range that is possible for temporal mixing of fossils (Fig. 3). It is also noteworthy that dating of terrestrial and lacustrine gastropod accumulations yielded strikingly comparable estimates of temporal mixing: hundreds to thousands of years (Cohen, 1989; Goodfriend, 1987, 1989; Goodfriend and Gould, 1996; Goodfriend and Ellis, 2000).

In addition, many studies with other research goals (not included in Table 1) provided multiple dated specimens from single marine sites or surfaces (e.g., Bjorlykke *et al.*, 1978; Wilson, 1979, 1988; MacIntyre *et al.*, 1978; Nelson *et al.*, 1988). These studies yielded comparable estimates (see Flessa, 1993), but were generally on the higher end, reaching as much as 30,000 years. This is at least partly because many of those studies deliberately targeted older materials (for example, MacIntyre *et al.*, 1978, specifically dated relic oysters). Higher estimates were also obtained for bivalve shells collected from modern beaches of the eastern United States (Wehmiller *et al.*, 1995). In essentially all sites analyzed by Wehmiller *et al.*, temporal mixing exceeded 10,000 years: about 60% of shells dated by Wehmiller and his colleagues were Pleistocene in age and some were perhaps as old as 500 to 700 kyr. These shells were derived from

Table 1. Estimates of the duration of temporal mixing in marine bioclastic accumulations in Late Quaternary deposits and/or present-day depositional environments.

Reference	Type of study ¹	Environment /Deposit	Organisms	Temporal mixing ² (n)	Age structure
Flessa <i>et al.</i> , 1993	Radiocarbon	Tidal flats	Bivalves	3200 ³ (17)	Right-skew
	Radiocarbon	Tidal flats	Bivalves	1500 ³ (13)	Right-skew
Flessa and Kowalewski, 1994	Literature	Nearshore	Mollusks	1200 ^{3,4} (63)	Right-skew
	Literature	Shelf	Mollusks	9200 ^{3,4} (129)	Right-skew
	Literature	Fossil beds	Mollusks	800 ^{3,4} (35)	Right-skew
Martin <i>et al.</i> , 1996	Literature	Beach ridge	Mollusks	1400 ^{3,4} (49)	Right-skew
	Radiocarbon	Tidal flats	Bivalves	1700 ³ (2)	Not known
	Radiocarbon	Tidal flats	Bivalves	2100 ³ (4)	Not known
	Radiocarbon	Tidal flats	Bivalves	800 ³ (2)	Not known
	Radiocarbon	Tidal flats	Forams	2000 ^{3,5} (1)	Not known
Meldahl <i>et al.</i> , 1997	Radiocarbon	Tidal flats	Forams	1300 ^{3,5} (1)	Not known
	Radiocarbon	Fan delta	Bivalves	1000 ³ (24)	Right-skew
	Radiocarbon	Fan delta	Bivalves	1100 ³ (24)	Right-skew
Kowalewski <i>et al.</i> , 1998	Radiocarbon	Pocket bay	Bivalves	500 ^{3,6} (24)	Right-skew
	Amino acids	Beach ridge	Bivalves	300 ^{3,6} (20)	Uniform
	Amino acids	Beach ridge	Bivalves	200 ^{3,6} (20)	Uniform
	Amino acids	Beach ridge	Bivalves	1100 ^{3,6} (20)	Right-skew
	Amino acids	Beach ridge	Bivalves	800 ^{3,6} (18)	Uniform
	Amino acids	Beach ridge	Bivalves	800 ^{3,6} (21)	Uniform
	Amino acids	Beach ridge	Bivalves	800 ^{3,6} (19)	Uniform
	Amino acids	Beach ridge	Bivalves	600 ^{3,6} (7)	Not known
	Amino acids	Beach ridge	Bivalves	1200 ^{3,6} (19)	Uniform
	Amino acids	Beach ridge	Bivalves	600 ^{3,6} (19)	Uniform
Carroll <i>et al.</i> , 2000	Amino acids	Inner shelf	Brachiopods	400 ^{3,6} (19)	Uniform
	Amino acids	Inner shelf	Brachiopods	530 ^{3,6} (20)	Uniform
	Amino acids	Inner shelf	Brachiopods	2000 ^{3,6} (21)	Right-skew
	Amino acids	Inner shelf	Brachiopods	3100 ^{3,6} (22)	Right-skew

¹Studies based on uncalibrated or partly calibrated amino-acid methods (e.g., Powell and Davies, 1990; Wehmiller *et al.*, 1995) are not included here because they do not provide estimates that can be expressed in years. Nevertheless, these studies also suggest the levels of temporal mixing on the scale of hundreds to thousands of years.

²All estimates in years rounded to the nearest 100. Number of dated specimens provided in parenthesis.

³Temporal mixing measured as the age range defined by the difference in age between the youngest and oldest dated specimens in a sample. For active depositional settings that included living fauna, the range was estimated by the oldest dated specimen.

⁴Median values of temporal mixing³ for sites compiled from the radiocarbon literature estimates (see Flessa and Kowalewski, 1994, for details).

⁵Estimates based on ¹⁴C dates of multiple tests of foraminifers (see Martin *et al.*, 1995, 1996).

⁶Estimates exclude shells that are outside of the calibration range (i.e., values underestimate the amount of temporal mixing).

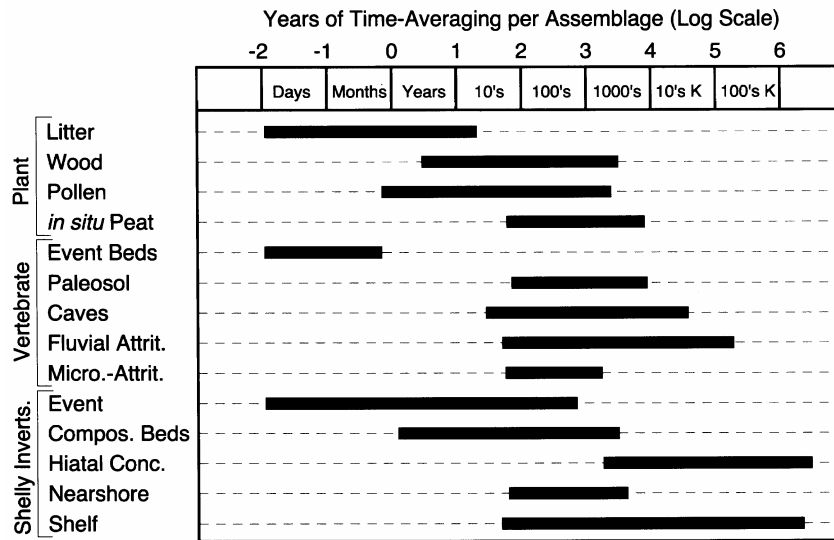


Figure 3. Estimates of temporal mixing for modern and fossil assemblages from terrestrial and marine depositional systems. Reproduced from Behrensmeier *et al.* (2000, fig. 3) with the permission of the Paleontological Society.

Pleistocene sediments that commonly crop out in the shoreface and inner shelf of the region. This exceptionally high mixing is due to the combination of the rapid, post-glacial sea-level rise and the fact that Holocene sediment cover is thin in the region. Thus, the study provides an analogy for *remanié* rather than interdiastemal time averaging.

Admittedly, considerable risks are involved in extrapolating modern rate estimates into the older record (e.g., Gould, 1965, 1987). However, it should be stressed that the resolution of subfossil and modern accumulations cannot be improved, but only worsened by subsequent geological processes. Diagenetic processes, erosional unroofing, and other processes that may affect surficial deposits before they become fossiliferous strata cannot unmix already mixed bioclasts. They can only mix them further. The more serious problem is that many modern depositional surfaces represent settings where sediment supply is still limited following the end-glaciation sea-level rise. Such settings characterized by unusually low sedimentation rates may be more prone to temporal mixing than typical records. However, studies that targeted areas with high sedimentation rates (e.g., Meldahl *et al.*, 1997) -- providing the best analog for interdiastemal deposits -- yielded estimates comparable with those obtained in other studies. This reinforces the validity of the actuopaleontological estimates of temporal mixing.

Mixing can also be inferred using taphonomic, sedimentological and

stratigraphic evidence (e.g., Brett and Baird, 1993; Johnson, 1993; Kidwell, 1993b; Rogers, 1993). Such approaches cannot employ direct dating methods and therefore provide much less precise estimates of temporal mixing. Nevertheless, these studies in the older fossil record suggest scales of temporal mixing (see Kidwell and Behrensmeier, 1993; Behrensmeier and Kidwell, 1993; Fig. 3) comparable to those implied by dating projects in the Holocene. Computer models of taphonomic processes (Cutler and Flessa, 1991; Miller and Cummins, 1990, 1993; Powell, 1992; Kowalewski and Misniakiewicz, 1993; Behrensmeier and Chapman, 1993; Cutler, 1993; Sadler, 1993; Cutler and Behrensmeier, 1996; Olszewski, 1999) provide supplementary insights that seem consistent with the estimates of Table 1.

A summary of estimates of depositional resolution was provided by Behrensmeier and Kidwell (1993; see also Martin, 1999) who compiled actualistic, paleontological, and computer-based studies and showed that temporal mixing (including snapshots, time-averaged records, and condensed records and *remanié*) ranges over at least 9 orders of magnitude of time (Fig. 3): from days (10^{-2} years) to millions of years (10^6 years). If one includes rare cases of early Paleozoic fossils reworked into modern sediments, the range of temporal mixing could be extended up to 10^8 years. Because well-biomineralized fossils such as mollusks or foraminifers are ubiquitous in the fossil record and very useful in stratigraphy, the resolution suggested by dating projects using bioclastic materials (Table 1) provides a highly relevant estimate of the duration of interdiastemal time averaging. The recent study of Carroll *et al.* (2000) (Table 1) that provides first estimates of temporal mixing for brachiopods reinforces the general validity of estimates obtained for mollusks and foraminifers and suggests that brachiopod-derived bioclasts may undergo as much age mixing as do mollusks.

Despite all caveats and uncertainties, the evidence is strong that, although temporal mixing can vary over 9 orders of magnitude, interdiastemal depositional resolution ranges typically from 100's to 1000's of years.

2.3 Internal Structure of Temporally-Mixed Strata

Temporal aspects of depositional resolution encompass not only the duration of a temporally-mixed record, but also the internal temporal structure of that record. A storm bed that mixes fossils from two short time-intervals separated by a 1000-year gap and a storm bed that mixes fossils representing a continuous 1000-year record are comparable in terms of the duration of temporal mixing, but differ dramatically in their internal temporal structure and completeness.

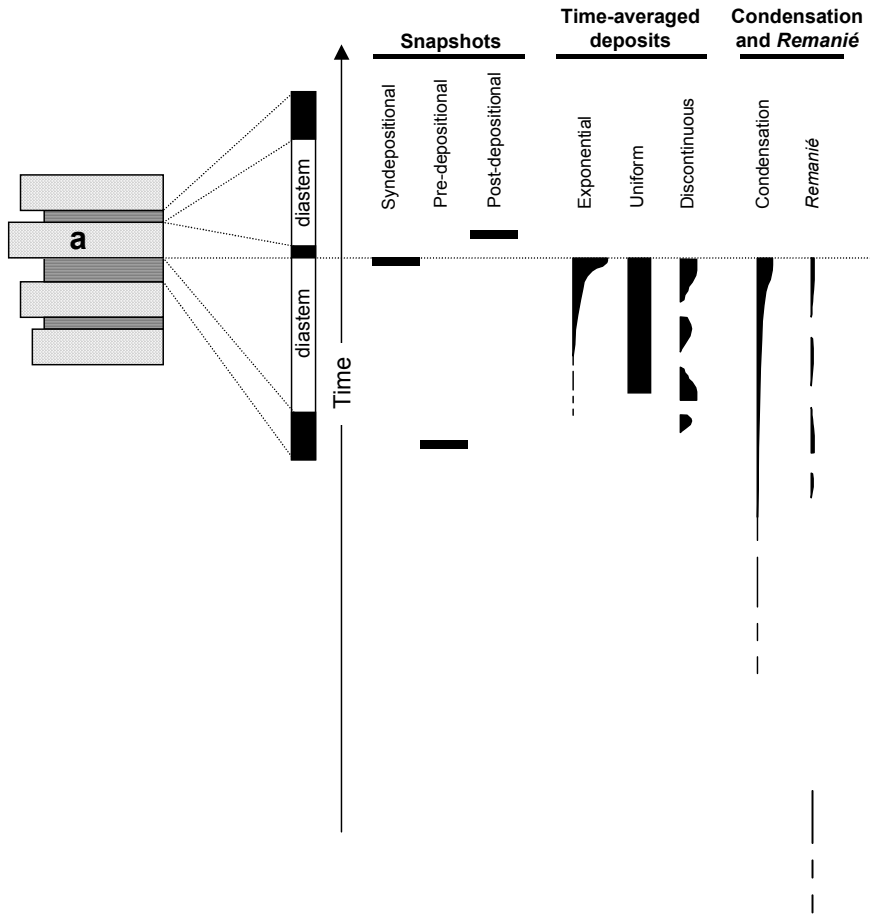


Figure 4. Temporal structure of paleontological records. Depositional resolution of records contained within a single stratum (exemplified by Bed "a") can vary greatly in terms of temporal structure. Solid shapes represent eight hypothetical examples of age structures of fossils that can be preserved in a bed. They illustrate the end-member classes of temporal mixing predicted for marine, bedded deposits. Note that even though the duration of temporal mixing in the three time-averaged records is comparable, they vary in their age structure (the depositional resolution of those records differs subtly despite the same duration of mixing.).

Eight end-member types of records are expected to occur in the fossil record (Fig. 4): three types of snapshots (pre-, syn-, and post-depositional), three types of time-averaged records (exponential, uniform, and discontinuous), condensation, and *remanié*. These types of records are not hypothetical, as most of them have been already illustrated empirically.

2.3.1 Syndepositional Snapshots

These are associated with mass-mortality events, where a bed is dominated by remains of organisms killed during the single depositional event by which the bed formed. Boyajian and Thayer (1995) described a beach deposit on the New Jersey shore that consisted almost exclusively of shells of the bivalve *Spisula* killed during a 1992 winter storm. Fenton (1966) observed similar syndepositional snapshot made of shells of *Lingula* in the Philippines. Ediacaran fossil assemblages are a likely fossil example of syndepositional snapshots (Seilacher, pers. comm. 1992; see also Seilacher, 1989). On the other hand, an obrutionary deposit of shelly organisms need not represent a snapshot because biomineralized fossils are likely to include specimens that predate notably an obrutionary event (e.g., Simões *et al.*, 1999). Syndepositional snapshots may be also occasionally observed among trace fossil assemblages made in soft substrates (e.g., Kotake, 1994; Kowalewski and Demko, 1997).

2.3.2 Pre-Depositional Snapshots

Beds where fossil assemblages pre-date the depositional events, have not yet been documented but could be formed by reworking of older snapshots during subsequent depositional events. Such temporal structures are probably rare because they can form only in areas devoid of bioclasts younger than the reworked snapshot materials ("virgin areas" *sensu* Craig and Oertel, 1966).

2.3.3 Post-Depositional Snapshots

These occur whenever colonization events post-date depositional events. Burrowing organisms can attempt to colonize substrate after its deposition and fail to do so. This is documented in the fossil record by unsuccessful attempts of colonization recorded by short-term trace fossil assemblages on top of turbidite-generated sediments (e.g., Föllmi and Grimm, 1990; Grimm and Föllmi, 1994). Body fossil assemblages incorporated after depositional events are also documented (e.g., Richard, 1972; Richards and Bambach, 1975). Such snapshots are probably much less common than syndepositional snapshots.

2.3.4 Exponential Time Averaging

This depositional mode is well documented by dating projects, which show that age-frequency distributions of dated fossils tend to be strongly

right-skewed (Table 1), approximating exponential curves (Flessa *et al.*, 1993; Flessa and Kowalewski, 1994; Martin *et al.*, 1996; Meldahl *et al.*, 1997; Olszewski, 1999; Kowalewski *et al.*, 2000). This pattern, somewhat analogous to that resulting from the decay of a radioactive isotope, reflects an exponential loss of older shells through destruction by taphonomic processes (Flessa *et al.*, 1993; Flessa and Kowalewski, 1994; Meldahl *et al.*, 1997; Martin, 1999). As suggested by dating, exponential time averaging is probably the most common type of time averaging in the marine fossil record in the nearshore and shelfal settings (Table 1).

2.3.5 Uniform Time Averaging

This style of age mixing has been documented recently in a project involving extensive amino-acid racemization dating of shells of the bivalve *Chione fluctifraga* from the Colorado River Delta (Kowalewski *et al.*, 1998). For seven out of nine samples of dated shells, age distributions were statistically indistinguishable from a uniform distribution (Table 1). Thus, some shell beds may record the optimal type of time averaging, where paleobiological data are a time-weighted average of the faunal composition from the spectrum of environments that existed during the entire interval of time. When the data from individual samples are pooled, however, the resulting structure of time averaging becomes exponential (Kowalewski *et al.*, 2000, fig. 2 therein), suggesting that the structure of time averaging may be partly dependent on sampling and analytical resolutions (see also Fürsich and Aberhan, 1990; Behrensmeyer and Hook, 1992) with exponential time averaging becoming increasingly common at coarser scales of observation.

2.3.6 Discontinuous Time Averaging

This concept was proposed by Fürsich and Aberhan (1990) who pointed out that time averaging can be either continuous with all time-averaged time intervals represented in an assemblage or discontinuous with some of the time intervals missing (see also Fig. 6 later in the text and Kidwell, 1998). The extreme case one could imagine is a deposit made by mixing two syndepositional snapshots that differ notably in age. Obviously, the continuity (i.e., completeness) of a time-averaged record is scale-dependent and therefore the same record may be continuous or discontinuous depending on the level of resolution chosen for analysis.

2.3.7 Condensation

Condensation typically occurs when sedimentation rate is so low as to

allow for a substantial temporal culling of fossils. These types of records are most often associated with major sequence boundaries and maximum flooding surfaces (see below) and include environmental and biostratigraphic condensation. The environmental condensation involves mixing of remains of organisms that lived in different environments (Fürsich, 1978). The co-occurrence of oyster shells with deeper-water faunas condensed together on present-day, sediment-starved shelves (e.g., MacIntyre *et al.*, 1978) offers an excellent modern analog of environmental condensation. In the most extreme cases stratigraphic condensation may result, as revealed by co-occurrence within single strata of index fossils from different biostratigraphic zones (e.g., Wendt, 1970; Jenkyns, 1971; Machalski and Walaszczyk, 1987; see Kidwell and Bosence, 1991, p. 181 for more details and references).

2.3.8 *Remanié*

Remanié (*sensu* Craig, 1966) are extreme cases of temporal mixing via reworking or unroofing with fossils culled over time scales often exceeding millions of years. *Remanié* can result from both abiotic and biotic mechanisms. Abiotic reworking is probably a dominant causal factor. For example, coastal exposures of the fossiliferous Miocene of Maryland contribute 6 to 17 million year old shells to the nearshore deposits forming today (Flessa, 1993). Also, biological *remanié* can form as a result of biological recycling of fossils by hermit crabs (Walker, 1994), but it is difficult to evaluate the frequency and severity of this mechanism.

2.3.9 Summary

The eight types of record can be viewed as end-members along a spectrum of possible records. Intermediates between the types as well as mixtures likely occur even within single-event fossil concentrations (*sensu* Kidwell, 1991a). For example, Simões and Kowalewski (1998) documented that even a deposit that was believed to represent a single storm bed may represent a complex mixture of snapshots and time-averaged records.

An important question is: how common are snapshots, condensation, and *remanié* relative to time-averaged records? Frequency of snapshots is difficult to evaluate for the older record where direct, high-resolution dating of the material is not possible. However, *all* dating studies in modern depositional systems (primarily from nearshore to shelfal environments) reveal substantial time averaging (Table 1) and suggest that snapshots are neither present in subfossil deposits nor are they being formed in modern depositional settings. Because old shells are always present on or just below

modern surfaces (e.g., Flessa and Kowalewski, 1994; Wehmiller *et al.*, 1995; Kowalewski *et al.*, 1998), and temporal mixing is a function of the availability of old shells in the depositional system, even catastrophic deposits (mass-mortality bone beds, storm shell beds, etc.) will typically contain notable admixtures of older materials (see Brett and Baird, 1993; Kowalewski *et al.*, 1998; Simões and Kowalewski, 1998). Thus, if a major storm hit an inner shelf, the resulting deposit, even though formed in several hours, would be made of shells that vary in age by hundreds of years. Only when mass-mortality events occur out of the natural habitat ("virgin area" *sensu* Craig and Oertel, 1966), or when standing populations are abundant enough to overwhelm older bioclastic materials (e.g., Boyajian and Thayer, 1995), depositional snapshots can occur. The frequency of snapshots may be higher in basinal settings when intermittent colonization events may punctuate anoxic conditions, but bedded, nearshore and shelfal successions of strata and bioturbated non-laminated deposits are unlikely to contain snapshot records.

In contrast to snapshots, condensed records may be relatively common in marine sedimentary successions, as indicated by the literature compilation of Kidwell (1991a). The distribution of condensed records within stratigraphic sequences is not uniform, varying depending on subsidence rates and position in the sequence. Condensed shell beds are particularly common in association with maximum flooding surfaces, onlap, and 2nd and 3rd order sequence boundaries (see Carter *et al.*, 1991; Kidwell, 1991a, b, 1993a; Holland, 1995; Kondo *et al.*, 1998). The condensed nature of records can often be inferred from sedimentary and taphonomic features (phosphorite steinkerns, abundant shark teeth, variable preservation of fossils) (Kidwell, 1991a; Brett and Baird, 1993; Kidwell and Bosence, 1991). Condensation may also be identified by anachronous or ecologically-incompatible fossils (e.g., Fürsich, 1978). *Remanié* are temporally anomalous deposits that should be easy to recognize, with the possible exception of temporal anomalies generated by biological agents (Walker, 1994). No data exist to evaluate the frequency of *remanié* through the Phanerozoic.

In summary, (1) time-averaged records (primarily of exponential type) are the most common types of interdiastemal records from nearshore and shelfal settings, (2) snapshots are rare, (3) condensation may be common around some types of sequence boundaries (but rarely in interdiastemal beds), and (4) *Remanié* are easy to recognize but their frequency in the record is not known. Table 1 provides what we believe to be a picture of typical temporal mixing within bedded successions of strata. Interdiastemal deposits are expected to be characterized by exponential time averaging on the scale of 100's to 1000's years.

2.4 Depositional Completeness

The internal structure of temporally mixed deposits determines *depositional completeness* of records provided by samples taken from those deposits. How continuous or discontinuous is temporal mixing? How temporally complete are records extracted from individual paleontological samples? Those questions cannot be answered for the older fossil record, but some insight can be gained (again) by dating the most recent materials and exploring them in a fashion analogous to estimating paleontological or stratigraphic completeness (e.g., Sadler, 1981; Allmon, 1989; Sadler and Strauss, 1990). Kowalewski *et al.* (1998) defined the temporal completeness of a sample as the percent of time-intervals, within the time-span of a sample, that are represented by the paleontological record (a definition analogous to that for temporal paleontological completeness of Allmon (1989) and McKinney (1991)). For example, at the resolution of 50 years, the completeness of a sample from Beach Ridge 2 (illustrated later in the text; Fig. 6a) is 41%. Nine out of the 22 50-year intervals separating the oldest from the youngest shell in the sample contain records.

Kowalewski *et al.* (1998) found that, at the dating resolution of 50 years, the temporal completeness of the record provided by mollusk samples collected from the beach ridges of the Colorado Delta varied from 41 to 100% and averaged 63.6%. That is, for an average sample, a time series of individually dated shells provided records for over a half of the 50-year time intervals encompassed by that time series. Almost all gaps can be attributed to small sample sizes. The observed completeness of 63.6% was very close to the highest possible completeness value that would be expected for sample sizes available in that study (~20 specimens per sample). That is, if we draw random samples of ~20 shells from a 100%-complete, uniform time-series, the expected completeness is 67.3%. Thus, the samples, when analyzed at this rather high 50-year resolution level, appear to have a continuous (= complete), temporal structure. No other analyses of this sort have been conducted to date, so we have no way of evaluating how common (or rare) continuous and discontinuous age structures are.

2.5 Spatial Resolution

Depositional resolution can also be lowered by lateral transport of fossils. Such transport may not only mix specimens from different regions, thus confusing paleoenvironmental interpretations, but may also enhance temporal mixing by contributing specimens derived from two or more source areas that differ in the age structure of bioclasts. As is the case for temporal mixing, the scale of spatial mixing is not only a function of environmental

setting but also may vary among different types of fossils depending on their size and skeletal durability. Skeletal durability and small weight both may enhance the scale and significance of pre-burial transport (Kowalewski, 1997). Numerous studies suggest, however, that marine macrofossils are typically preserved in their habitats and only a small fraction is transported any substantial distance (see Johnson, 1965; Kidwell and Bosence, 1991; Kidwell and Flessa, 1996; Anderson *et al.*, 1997; Behrensmeier *et al.*, 2000). Even in the extreme case of high-energy, shallow-water deposits forming in transgressive settings, only a small fraction of fossils undergoes any substantial transport (Flessa, 1998). Thus, for the dominant type of marine fossiliferous deposits such as shell beds, substantial lateral mixing is probably limited (see also Martin, 1999; Behrensmeier *et al.*, 2000). Moreover, even in the case of some durable microfossils such as foraminifers – which, intuitively, may appear particularly prone to spatial mixing – substantial transport is not very common, especially below wave base (see Bé and Hutson, 1977; Martin, 1999; but see Anderson *et al.*, 1987).

Of course, spatial mixing may be substantial in bioclastic concentrations formed at major unconformities, sequence boundaries and maximum flooding surfaces, where temporal mixing is more severe and depositional history of individual fossil concentrations tends to be more complex (e.g., Kidwell, 1991a). However, these generally belong to what we call condensed records and notable spatial mixing is, most likely, negligible in the case of interdiastemal, time-averaged records.

2.6 Factors Controlling Depositional Resolution

Numerous factors can affect the scale of temporal mixing (Kidwell and Bosence, 1991; Flessa and Kowalewski, 1994; Kowalewski, 1996a; Kidwell, 1998). They include (1) intrinsic factors that characterize organisms; (2) direct extrinsic factors of depositional environments; and (3) indirect extrinsic factors.

Intrinsic factors, in particular the type of skeletal material, are important because temporal mixing is largely dependent on the skeletal durability of remains that are being mixed (Kowalewski, 1997). Durable hard parts can survive multiple reworking events and a long residence time near depositional surfaces and, consequently, may undergo temporal mixing on a scale of hundreds to thousands of years (e.g., Behrensmeier, 1991; Flessa *et al.*, 1993). In contrast, fragile remains such as leaves (e.g., Burnham, 1993; Greenwood, 1991; Wing and DiMichelle, 1995) or lingulid brachiopods (e.g., Kowalewski, 1996b) do not last very long on active depositional surfaces. Thus, they are much less prone to temporal mixing and more likely to provide records with a temporal resolution of months or single years. In

fact, we can view the resolution of the fossil record as a reciprocal function of durability of fossils (Fig. 5), as determined by their morphology, mineralogy, and microstructure. The decrease in depositional resolution that typifies durable fossils is compensated by the corresponding increase in the stratigraphic and depositional completeness of their records (Fig. 5). Other intrinsic factors including population density, geographic range, and life habitat can also play an important role. For example, abundant and widespread populations of planktonic foraminifers that provide a lot of material for mixing are more prone to temporal mixing than a single endemic cohort of a deep-infaunal clam, which is less likely to be transported after death and provide few specimens for mixing in the first place.

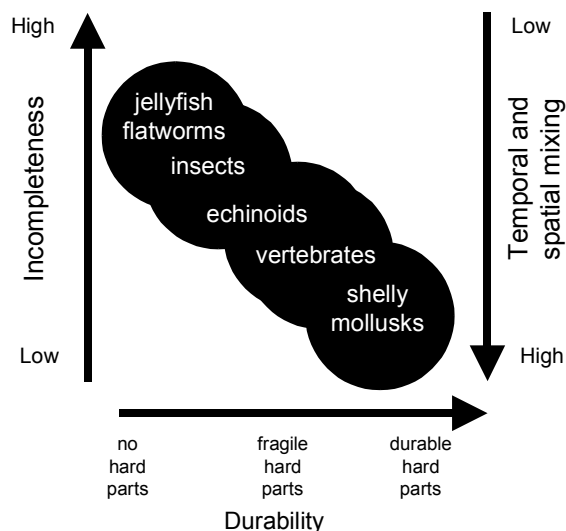


Figure 5. The Reciprocal Taphonomic Model. Increased skeletal durability (X - axis) improves the completeness of the fossil record (left Y-axis). But, organisms with durable skeletons are more prone to post-mortem temporal and spatial mixing (right Y-axis). The black circles represent typical members of a given group of organisms, and not all possible cases of skeletal durability within that group. Modified after Kowalewski, 1997, fig. 1.

Direct extrinsic factors that are important include sedimentation rate, bioturbation, and biotic and abiotic taphonomic agents. Sedimentation rate controls the potential residence time for skeletal remains present around depositional surfaces (see also Kidwell, 1991a, 1998). Decrease in net sedimentation rate correlates with increase in temporal mixing and ultimately can lead to stratigraphic condensation. Meldahl *et al.* (1997) confirmed that pattern by showing that samples of mollusks collected from modern nearshore seafloors vary in duration of temporal mixing as a

function of the local short-term accumulation rates. Bioturbation also plays an important role by mixing shells in surficial sediments and by sheltering bioclasts from harsh surficial taphonomic processes via temporary burial (e.g., Rhoads and Stanley, 1965; Clifton, 1971; Aller, 1982; Meldahl, 1987; Flessa *et al.*, 1993; Martin *et al.*, 1996; Bradshaw and Scoffin, 2001). Although bioturbation may increase degradation of bioclasts (e.g., Aller, 1982; Davies *et al.*, 1989; Walker and Goldstein, 1999), the studies of Flessa *et al.* (1993) and Bradshaw and Scoffin (2001) suggest that the positive role of bioturbators outweighs their negative effects. Taphonomic processes such as chemical dissolution, mechanical fragmentation, bioerosion, and durophagous predation control the rate of destruction of hard parts and may shorten the half-life of bioclasts. A special case is represented by hermit crabs that recycle gastropod shells and can enhance temporal mixing by preventing their final burial (see Walker, 1994).

Indirect extrinsic factors of temporal mixing include: (1) subsidence rate and tectonic setting that control direct extrinsic factors and (2) historical contingencies imposed by sea-level changes. The tectonic setting affects subsidence rate, which in turn influences accommodation space and net-accumulation rates. Tectonic setting can also affect the nature and intensity of taphonomic processes affecting skeletal remains (e.g., Kidwell, 1988; Meldahl and Cutler, 1992). Sea-level changes can also play a fundamental role by creating environments in "virgin areas" that are not contaminated by older fossils. Shells found in nearshore environments today are dominated by specimens from the last 2-3 thousand years (Flessa and Kowalewski, 1994; but see Wehmiller *et al.*, 1995) and the lack of older shells reflects the fact that, in most regions, the Holocene transgression did not reach current nearshore habitats before that time. In contrast, early Holocene or even Late Pleistocene shells are quite common in more offshore habitats. Thus, the recent sea-level changes of a given area often set limits on potential temporal mixing (see Flessa and Kowalewski, 1994 for more details).

2.7 Trends through the Phanerozoic

Because many factors controlling temporal mixing show secular trends through time, the depositional resolution of paleontological records is likely to have changed notably through the Phanerozoic. Kidwell and Brenchley (1994, 1996; see also Li and Droser, 1999; Simões *et al.*, 2000) documented an increase in thickness and taphonomic complexity of marine skeletal accumulations through the Phanerozoic. Such increase implies a parallel increase in temporal mixing (Kidwell and Brenchley, 1996; Kidwell, 1998). In addition, the increase in rates and depth of bioturbation observed through the Phanerozoic (Thayer, 1983; Ausich and Bottjer, 1982; Droser and

Bottjer, 1989, 1993; Sepkoski *et al.*, 1991) may have played an important role in increasing temporal mixing -- not only directly by enhancing temporal mixing of bioclasts (Section 2.6), but also indirectly by decreasing the frequency of *recorded* storms (Brandt and Elias, 1989; Sepkoski *et al.*, 1991) and increasing the length of diastems (see Section 3.5 below).

Support for the Phanerozoic increase in temporal mixing was provided by Kidwell (1990), who contrasted the relatively fresh appearance of brachiopods found in Early Paleozoic deposits (indicative of a limited temporal mixing) with the highly variable taphonomic signature of Neogene bivalves (indicative of a poor depositional resolution).

2.8 Inorganic versus Organic Records

Whereas we focus on biological records, the concept of depositional resolution is applicable to many physical records contained in the geological record. Temporal mixing affects sedimentary grains, diagenetic precipitates, silicates forming in magma chambers, and so on. In many cases, inorganic records are time-averaged over much longer time scales than biological records. This is largely due to the fact that silicate minerals are less prone to destruction than carbonate or organic fossils (see Kowalewski and Rimstidt, *in press*). Also, abiotic grains are not limited to the last half a billion years of the Earth's history and occur over a much larger spectrum of source areas than biological remains. Finally, fossils that are too fragmented or altered have lower informative value, and, thus, have not been evaluated for temporal mixing with such scrutiny as larger, more complete specimens. Because smaller grains tend to last longer, the temporal mixing of biocarbonates may be underestimated relative to detrital zircon or apatite, often dated in studies of provenance (e.g., Ross and Gehrels, 1998; Gehrels *et al.*, 1999). This pragmatic bias reflects the real differences between the depositional resolution of *useful* inorganic records and *useful* organic records.

The difference in the resolution between inorganic and organic records, illustrated on our conceptual diagram (Fig. 2), can be demonstrated by comparing age distributions of bioclasts and detrital inorganic grains. The best-documented examples of inorganic mixing is provided by detrital zircon grains (e.g., Ross and Gehrels, 1998; Gehrels *et al.*, 1999), for which temporal mixing commonly exceeds a billion years. The comparison of age-distributions derived for bioclasts (Fig. 6a) and zircon grains (Fig. 6b) reveals also intriguing similarities and suggests that a single observational pattern (*sensu* Rogers, 1989) underlies a temporal structure of grains contained in samples extracted from sedimentary rocks (see also

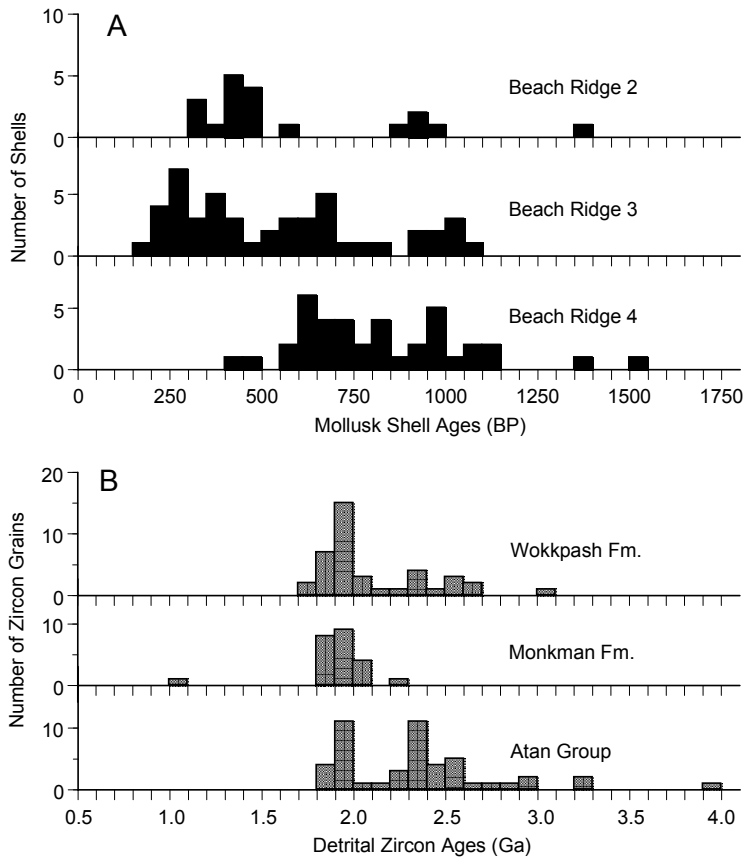


Figure 6. Similarities in age distributions of shells and detrital zircon grains. A. Ages of mollusk shells (*Chione fluctrifaga*) from the Colorado River Delta (Baja California) dated using ^{14}C -calibrated amino-acid racemization methods (data from Kowalewski *et al.*, 1998). B. Ages of individual grains of detrital zircon extracted from Paleozoic sandstone samples from British Columbia and dated using U-Pb methods (data from Ross and Gehrels, 1998).

Kowalewski and Rimstidt, in press). Despite extreme difference in the time scale (billions versus hundreds of years) and in the type of grains (ZrSiO_4 vs. CaCO_3), the temporal age distributions of those two types both display (1) time lags; (2) right skewness; and (3) multimodality. Respectively, these patterns are explainable by scale-independent and grain-independent tendencies for (1) sedimentary grains to predate depositional events; (2) older grains to be more likely to have been destroyed and/or less likely to be at the surface; and (3) source area of grains to have a high stratigraphic heterogeneity. Whereas the processes and temporal scales of the compared systems are obviously very different, the nature of the resulting records is quite comparable.

2.9 Depositional Resolution: A Summary

The previous sections can be summarized in terms of general statements regarding the depositional resolution of the paleontological record. The statements are most applicable to common marine macrofossils and to deposits separated by small-scale diastems and as such are useful in formulating generalizations regarding the limits of depositional resolution for typical fossil records found within bedded successions. The statements should not be, however, extrapolated to less common fossil groups, to extraordinary fossil deposits (*Lagerstätten*), to offshore basinal setting, or to laminated deposits.

1. Depositional resolution of fossils taken from sedimentary rocks is expected to range typically from 100's to 1000's of years.
2. Condensation, resulting in more extensive temporal mixing, should be rare in interdiastemal beds, but may be common around major disconformities, sequence boundaries, or maximum flooding surfaces.
3. Instantaneous snapshots and long-term *remanié* are both possible, but are expected to be much less common than, or easier to distinguish from, time-averaged deposits.
4. The internal structure of time averaging tends to be exponential, reflecting a cumulative loss of older shells to taphonomic processes. To some extent, however, the structure of time averaging is a function of sampling and analytical resolution.
5. Depositional completeness can be high, but data are insufficient at this point to evaluate what is the finest resolution level at which typical samples from the fossil record are complete (continuous).
6. Spatial mixing by lateral post-mortem transport may occur, but is not substantial for common marine benthic macrofossils and even microfossils such as foraminifers appear to have good spatial fidelity.
7. Factors controlling depositional resolution include intrinsic characteristics of organisms (type of skeleton, abundance, habitat, biogeography), direct extrinsic factors of depositional environments (sedimentation rates, bioturbation intensity, and abiotic and biotic taphonomic agents), and indirect taphonomic agents (subsidence rate/tectonic setting, sea-level history).
8. Secular trends in the major factors controlling depositional resolution (in particular factors such as skeletal durability and bioturbation rates) suggest that temporal mixing increased through the Phanerozoic.
9. Given similarities in temporal mixing between zircon grains and bioclasts, many statements regarding depositional resolution of paleontological records may also be applicable to abiotic records.

3. DIASTEMS AND STRATIGRAPHIC RESOLUTION

3.1 Distinguishing Diastems from Disconformities

Diastems are the separations (bedding planes) between depositional units, i.e., beds (Figs 1, 2). Diastems form when sediment accumulation is markedly episodic and intervals of non-deposition or erosion occur between intervals of sediment accumulation. Diastems are very small unconformities, not simply the pauses in sediment accumulation that make the breaks between laminae within beds.

In coining the term diastem, Joseph Barrell (1917, p. 748) made the following distinction: “Numerous breaks are now known to exist in which the beds above and below lie parallel, and, except for some change in fauna or flora, give little or no indication of the great lapse of time which occurred between their deposition. Such breaks are known as disconformities. The present argument enlarges on this conception, holding that the breaks of smaller time interval are still more numerous and may add up to equally large measures of time unrecorded by sedimentation. Such breaks have generally been too brief to give a clue by means of a faunal or floral change, but must be recognized through the physical features of the beds, often most readily because of a sudden change at the break in the character of the rhythms expressed in sedimentation. It is proposed to recognize the aggregate importance of such minor breaks by giving them a special name – ‘diastem’.”

After noting that Grabau had coined the term disconformity (Grabau, 1913, p. 821–826), Barrell (1917, p. 794-5) discussed the differences between disconformities (as they are commonly recognized) and the breaks in the record he was calling diastems: “a diastem is a break represented in other regions, often within the same formation, by a bed or series of beds. A disconformity is theoretically traceable over a broad area....the two classes of breaks, although typically distinct, must grade into each other. The assignment of a break to one or the other category must not depend on a doubtfully assigned cause, but must rest on the observable field evidence. Therefore the discrimination should rest for disconformities on breadth of occurrence and faunal or floral change, for diastems on breaks in continuity of lesser areal importance, of greater number, and not characterized by permanent faunal or floral change. The presence of diastems makes for a slow rate of accumulation of a formation, associated with a more rapid rate of accumulation of the individual beds.”

3.2 Nature of Diastems

We use the term diastem for the breaks in the continuity of sedimentation that produce bedding as seen in the field. Note that we are not discussing lamination although the breaks between individual laminae are, technically, also small diastems. Nor are we discussing diagenetic fissility in shales. For all practical purposes, the spacing between the disturbance events, which create bedding, records the finest-scale stratigraphic resolution that can be obtained in a section. We treat that spacing as the length of diastems because finer resolution is not generally possible.

Many events which generate stratification are high-energy events such as storms. The bulk of material deposited by storms in shelf settings is usually locally reworked rather than entirely new material eroded from the shoreline and transported onto the shelf (Morton, 1988). Therefore, the diastem under a storm bed represents the time for the original deposition of the sediment now reworked into the new storm-generated bed, as well as the time during which the eroding phase of the storm took place. Thus much of the time represented by a diastem may have geological representation in the depositional temporal mixing of the overlying bed (see Section 2 above).

Some features of the stratigraphic record represent at least part of the time interval (diastem) between bed-forming events. Mudstone caps on storm deposits represent whatever deposition may have occurred in the "fair weather" interval between storms as well as deposition during the interval of waning energy after the high-energy phase of the storm that formed the bulk of the bed. However, it is often difficult to separate the later "fair weather" phase from the waning energy phase in mudstone caps on most storm beds, especially if bioturbation has occurred during the "fair-weather" interval. Bioturbation during the interstorm interval can homogenize the slowly accumulating sediment — as well as the top of the underlying tempestite — so any remaining interstorm stratification and the boundary with the underlying tempestite are destroyed. This is true of most post-Early Ordovician sections (Droser and Bottjer, 1989; Sepkoski *et al.*, 1991; Droser and Bottjer, 1993). The impossibility of differentiating post-storm deposition from the fine-grained deposition of storm-resuspended sediment in bioturbated strata is clearly illustrated by Raup and Stanley (1971, fig. 11.1, p. 320 with diagram on p. 321).

Also, some scouring is usually present at most sharp bedding plane surfaces, indicating that some of the record has been eroded. If the top surface of a bed is scoured by a later event, the scouring will erode some sediment that had accumulated as part of the bed, thus "erasing" some preserved record (Goldring and Aigner, 1982). The scoured surface thus represents the time during which the now eroded material was originally

deposited and any interval of time after that deposition was complete, including the brief interval during which the scouring and erosion occurred. In fact, many somewhat smaller events may have occurred and been erased by larger, later events, before, by chance, one is left undisturbed to enter the geological record (Fig. 1; see also Sadler, 1993). The “time gap” at the scoured bedding surface represents all the time since the underlying uneroded material was deposited, including the multiple intervals of deposition and reworking that may have occurred prior to the preserved diastem and deposition of the succeeding bed (see also Seilacher, 1985).

Therefore, it is useful to think of a diastem (physically the sharp bedding plane itself) as representing all the time between bed-forming events, even though some of the preserved sediment in the finer-grained stratum in between the coarser-grained parts of two beds may have accumulated during that interval. In this instance, paleontologists need to realize that fossils found in the finer-grained deposits in between storm-generated, time-averaged shell beds lived during the diastem interval and will be more closely allied in time with the older fraction of reworked and redeposited fossils in the capping shell bed, rather than the younger fraction in the underlying shell bed (see also Sections 2.2 and 4.2).

3.3 Duration of Diastems

Although depositional events can occur in quick succession (as in tidalites – Miller and Eriksson, 1997), the depositional events recorded by most sedimentary bedding are usually separated by longer intervals. For example, the bedding planes (diastems) in a series of stacked storm deposits represent most of the time contained in the section because each depositional event (storm) was of short duration (days).

How long are the intervals in between the short intervals of deposition represented by preserved beds? Intuitively, such intervals may be expected to be brief (even several major storms can occur at one location in one season). However, it typically takes decades to centuries before storms large enough to deposit notable amounts of sediment revisit the same location (Table 2). Thorne *et al.* (1991) calculated that storms capable of depositing 10 cm thick beds occur with a frequency of approximately 200 years in areas with shelf water depths of 20 m and 2000 years for areas with 30 m water depths. This is consistent with applying the probabilistic estimates of Gretener (1967) to the data from Abbott (1996): the largest hurricane events (i.e., events expected to be more commonly preserved, in part because they rework evidence of smaller events) can only be expected to recur with high

Table 2. Estimates on spacing between preservable disturbance events and duration of diastems. All estimates expressed in years.

Type of Estimate	Min (yrs)	Mean spacing (years)	Max (yrs)	References
<i>Recent preservable disturbance events</i>				
10 cm beds in 20 m of water	N/A	200	N/A	Thorne <i>et al.</i> , 1991
10 cm beds in 30 m of water	N/A	2000	N/A	Thorne <i>et al.</i> , 1991
98% chance of 2 hurricanes crossing 80 km stretch of coast ¹	25	60	400	Gretener, 1967; Abbott, 1996
98% chance of 2 major hurricanes crossing 80 km stretch of coast ¹	57	268	4000	Gretener, 1967; Abbott, 1996
<i>Temporal spacing of storm washovers</i>				
Low marsh (calibr. accumul.)	N/A	153	N/A	Hippensteel and Martin, 1999
Low/high marsh (calibr. accum.)	N/A	316	N/A	Hippensteel and Martin, 1999
High marsh (no bioturbation)	37	102 ²	167	Hippensteel and Martin, 1999
Low marsh (notable bioturbation)	89	245 ²	445	Hippensteel and Martin, 1999
<i>Paleozoic diastems (intervals between bed forming events)</i>				
Cambrian	100	150 ²	200	Koerschner and Read, 1989
Ordovician (Martinsburg Fm.)	130	1715 ²	3300	Kreisa, 1980, 1981
L. Ordovician (Cincinnatian)	91	215	667	Holland <i>et al.</i> , 1997
Silurian	163	894 ²	1625	Bambach, 1969 (1/4 of time)

¹ Based on the mean likelihood of 6.7% (range from 1% to 16%) of a hurricane impinging on any 80 km segment of the eastern coast of the United States in any one year. For the largest hurricanes (magnitude IV and V, with winds exceeding 208 km/hr) the mean is only 1.5% (range 0.1 % to 7%) (Abbott, 1996). The interval of near certainty of recurrence (a necessary condition if a succession of strata are to be formed by such events) can be calculated by converting the probability of occurrence to the fractional annual likelihood. Gretener (1967) argued that a rare event with a probability 1/x has a 98% probability of occurring after four times x. Thus, it appears that hurricanes will occur within 60 years (4x15), but the largest events, which would be expected to be more commonly preserved, can only be expected to have recurred with high probability on a scale of 268 years (with a range of 60 to 4000 years, depending on the regional frequency of such events).

² Estimated as a midpoint of the range defined by the minimum and maximum estimates.

probability on a scale of 268 years (with a range of 60 to 4000 years, depending on the regional frequency of such events) (see Table 2 for details). These theoretical estimates match well with direct assessment of storm washover deposits in marshes along the South Carolina coast (Hippensteel and Martin, 1999). The spacing of storm washover events marked by oceanic foraminifers injected into salt marsh deposits is, on average, 153 years in a core from low marsh deposits calibrated by radiocarbon for overall sediment accumulation rate and 316 years in a

low/high marsh boundary core that also had a calibrated accumulation rate (Table 2). Two other cores, for which sediment accumulation rates were only estimated from other studies in South Carolina, had average washover spacing of 102 and 245 years (mid-points of ranges — see Table 2).

Because increased rates and depths of bioturbation may have decreased the degree of stratigraphic resolution in more recent geologic time (see Section 3.5 below and Kidwell, 1998), we compare the probable spacing between storm beds in the early and mid Paleozoic (when they should have been more frequently preserved) with the intervals between major disturbance events observed today. Numerous sections characterized by storm induced stratification are present in Lower and Mid Paleozoic rocks (Marsaglia and Klein, 1983). Several from eastern North America are well enough known to warrant estimating the average spacing of bed formation.

In southwestern Virginia the Late Ordovician age Martinsburg Formation is a 300-meter thick set of storm-generated beds (Kreisa, 1981) that more closely resembles the facies of the Reedsville Formation of west-central Pennsylvania than the flysch-like lithology of the Martinsburg in its type area. These tempestites are mostly autochthonous sediments resuspended and redeposited by large storms, as indicated by intraclasts of the underlying lithology and the similarity of the fauna in the reworked shell beds when compared to the interbedded shales (Kreisa and Bambach, 1982, Table 1).

Estimates of the time represented by the Martinsburg Formation range from 2 million to 5 million years. The section was measured in large increments (1 to 10 meter subdivisions) with centimeter-scale bed counts only done occasionally to characterize the larger subdivisions of the formation. For this reason we cannot give an exact figure for the number of individual beds in the complete formation. However, the average thickness of the beds in the formation is between 2 and 20 cm, so there are somewhere between 1,500 and 15,000 beds in the formation. Since each bed represents a storm event that lasted no more than a week, the total depositional time represented in the tempestites that comprise virtually the entire section is infinitesimally short: between 30 and 300 years. The bulk of the rest of the time is in the diastems (as well as being represented within the beds by temporal mixing of fossils and reworked sediment). Assuming no major unconformities (and none were detected in Kreisa's [1980, 1981] detailed study of the section), the median spacing of the beds must be somewhere between 130 and 3,300 years ($2,000,000/15,000$ to $5,000,000/1,500$).

The Martinsburg example above and the example from the Silurian that follows use estimates made for the entire sections and do not account for fluctuations in spacing, or variation in completeness of the section that may be associated with fourth (and higher) order sea-level fluctuations. Those effects will be noted when smaller-scale cycling is discussed below.

Calculations similar to those made on the Martinsburg Formation can be made for the 1,200 m thick Silurian section at Arisaig, Nova Scotia. In that section the bedding is also predominantly storm deposition (Bambach, 1969, 1998; Cant, 1980). The age of the Arisaig section extends from early in the Early Silurian continuously into the Early Devonian, an interval of approximately 26 Ma. Although environments vary from deep water to non-marine, there are no marked unconformities and no significant intervals of condensed or omitted section (Bambach, 1998). Bedding ranges from 3 to 30 cm in thickness (with only a few beds ranging up to a meter thick). Individual beds were not counted through the entire section, but counts of parts of the section made from detailed photographs, with scale present in each, document the range of bedding patterns in the whole section. As for the Martinsburg example above, the calculations can only be done as a range encompassing the extremes. The section contains between 4,000 and 40,000 beds. If the section represents 26 Ma, the mean spacing between bed-forming events, then, is between 650 and 6500 years. If we make a more conservative estimate that deposited sediments represent only 25% of the time -- because of possible variation in completeness of parts of the section -- then the average spacing is between 163 and 1625 years. We chose a value of 25%, which is at the higher end of the range of completeness values predicted by Wilkinson *et al.* (1991; see below), because the Arisaig section accumulated in a tectonically active, subsiding area.

Although the Cambrian was a warm interval, Milankovitch-style eustatic sea-level fluctuations can be generated under “greenhouse” conditions by a variety of forcing factors. For example, Jacobs and Sahagian (1993) calculated that several meters of sea-level change would occur just by filling known enclosed basins. Koerschner and Read (1989) document numerous 20 to 100 kyr (Milankovitch) sedimentary cycles in Upper Cambrian rocks in southwestern Virginia. These cycles average 1 to 7 m in thickness, and are recognized by coarse to fine sets of strata representing shallow-subtidal to intertidal shoaling successions. Bedding within the cycles is on the order of one to ten cm in thickness. Recent inspection of the bedding in the cycles indicates that each small cycle has 10 to 20 beds preserved. Wilkinson *et al.* (1991) argue that only 3% to 30% of the time in such meter-scale cratonic cycles is preserved by sedimentation (the rest is included in the cycle-bounding unconformity). If we assume only 10% of the time was recorded by the Cambrian cycles described by Koerschner and Read (1989), then the average temporal spacing of the beds would be 100 to 200 years if they are 20 kyr cycles, the most likely periodicity, twice that if they are 40 kyr cycles, or 500–1,000 years if they are 100 kyr cycles. Koerschner and Read discuss the variability of these cycles at length, pointing out that they are thicker and contain more elements in some settings (both relative to shoreline and

relative to third order transgressive/regressive cycles), so this bed spacing is a very generalized average.

Holland *et al.* (1997) describe bedding patterns in the storm-dominated sediments of the cratonic Upper Ordovician Kope Formation of the type Cincinnati and present a measured section divided into 40 small-scale cycles. The cycles average about 1.5 meters in thickness and contain a mean of 9.3 beds per cycle (range 3–22 beds). If one assumes only 10% completeness (again on the low side of the Wilkinson *et al.*'s, 1991, range of 3-30%) for the cycles, and if one also assumes that these cycles were produced by Milankovitch-style oscillations of sea-level with a 20 kyr periodicity (as seems likely from many evaluations of “meter-scale” cycles), then the preserved record of storm reworking had an average spacing of 215 years (range from 91 to 667, depending on the number of preserved storm-induced beds and assuming an invariant length for the cycles). Longer periodicities would increase the temporal spacing of preserved storm beds.

The above data are summarized in Table 2. It is interesting that the spacing between bed-forming events in the four Paleozoic examples all fall within the same range of temporal spacing as major bed-forming events observed today. The implication is that diastems, while highly variable in length, have a general likelihood of several centuries to as much as a few thousand years in average duration. The somewhat shorter intervals for data from the Recent and for the Cambrian example, the somewhat longer Ordovician range, and the longer Silurian range may reflect the pattern of incorporation of longer gaps in longer time intervals as originally suggested by Sadler (1981), but some of the differences are probably related to other factors that control duration of diastems themselves (see section 3.4 below).

3.4 Factors Controlling Duration of Diastems

The duration of diastems is influenced by the rate at which accommodation space develops, the frequency of major depositional events, and other factors, including water depth and position in the cycle of sea-level fluctuation.

The rate of development of accommodation space will be significant in determining the duration of diastems between discrete beds. Because the rate at which accommodation space is generated is controlled by slow-rate processes (sea-level rises and subsidence), it is highly unlikely that adequate accommodation space could develop in a matter of decades to centuries to permit closely spaced events to be preserved as discrete beds in the record. The exceptions are tectonically active settings, where subsidence can be rapid (but which seldom produces more than a meter or so of subsidence in any one event) and shoaling parasequences when considerable

accommodation space exists because sea-level rise exceeded sediment accumulation, a common short-term feature following the transgressive phase of Milankovitch-type sea-level cycles when coastal flooding traps sediment up-dip and reduces sediment supply to the shelf.

In addition, through reworking of material that was also likely to have been reworked previously in earlier small events, closely spaced large disturbance events are more likely to simply erase the record of all but the last event of a series rather than leave a stacked set of discrete beds. If relatively closely spaced disturbance events are recorded, they will usually appear as amalgamated beds, preserving a “hierarchy” of partial remnants of a series of storm events. In this instance, the largest event will be the oldest one preserved (the basal part of the amalgamated bed) and each succeeding amalgamated unit represents a later (and somewhat less deeply eroding, and so probably smaller) event. Hence diastems in sections where accommodation space was available to form discrete beds almost certainly represent considerable intervals, not simply successive storm events. This is probably why the spacing between beds in the Ordovician and Silurian examples (Section 3.3) are higher than spacing expected for the successive recurrence of major disturbance events, as observed in the Recent (Table 2). Therefore, most diastems between discrete beds deposited in shelf environments represent time intervals of greater magnitude than intervals between successive disturbance events. This suggests that the common length for many diastems is more than just a few centuries.

Climatic variability related to geographic position also can influence duration of diastems. The range of intervals between repeated storms noted in Table 2 is actually the variation observed at different locations from subtropical to cool temperate latitudes along the Gulf and Atlantic coasts of North America (Abbott, 1996). The one to two orders of magnitude difference between the most frequent and least frequent likelihood of recurrence of hurricanes suggests that a similar variability in duration of diastems could be associated with geographic setting as well. The correspondence of the theoretical spacing of major storm events with the frequency of preserved washovers in South Carolina indicates that this frequency range is a reasonable general picture. As one goes northward, the hurricane danger is replaced by severe winter storms (“nor’easters”), but very large events that will enter the geological record are still going to be less frequent events. Marsaglia and Klein (1983) have illustrated latitudinal variation in storm influence in the geological record.

Water depth is important in controlling the effect of disturbance events on the bottom. There is an order of magnitude difference in the likelihood of events capable of forming a 10 cm thick event bed between settings that differ in water depth by only 10 m (Table 2). Diastems in deeper water

settings may represent longer intervals than those in shallow-water deposits. Although the calculations would be difficult to do for an example from the remote past, the Silurian section noted above (Section 3.3) incorporates a variety of sea-level changes and environments from deep basin to shallow subtidal (Bambach, 1998). Whereas the average durations of diastems calculated for that section average all the environmental variability together, diastem spacing probably is shorter in the shallower water portions of the section and longer in the deeper water portions.

The shorter intervals for diastems calculated for the Cambrian example in Section 3.3 and Table 2 are for sediment cycles influenced by Milankovitch-style eustatic sea-level fluctuations. In this case, the spacing of diastems may be more related to the rate of sediment supply and frequency of bed-forming events rather than development of accommodation space. This is because most beds formed in the shoaling phase of each cycle, probably during and after sea level had risen and produced adequate accommodation space.

3.5 Trends through the Phanerozoic

Plate tectonics has caused geography to change over time and climates and sea level have fluctuated, but most of these changes have produced stochastic variation, not secular trends, in the sedimentary record. However, changes produced by the evolution of life may have produced some secular trends. For example, there may have been some effect on the rate of clastic sediment supply when rooted land plants became widespread in the Devonian (Algeo and Scheckler, 1998; Bambach, 1999) and a second alteration in rate of denudation may have taken place with the rise of extensive grasslands in the mid-Cenozoic (Potts and Behrensmeier, 1992). Also, Thayer (1983) argued persuasively that the depth and rate of bioturbation has increased markedly over time. Sepkoski *et al.* (1991) showed that this caused change in the preserved style of stratification. This trend has probably influenced the magnitude of preserved diastems by systematically homogenizing the smaller units into the thicker bioturbated beds common in the later Mesozoic and Cenozoic (Kidwell, 1998).

The beds described by Koerschner and Read (1989) include both hardgrounds and “flat-pebble conglomerates”, as is common in Cambrian rocks (Sepkoski, 1982; Sepkoski *et al.*, 1991). In the Cambrian, rapid submarine cementation was possible because the sediments were little bioturbated and overlying seawater was not flushed into and through the sediments. Therefore, when chemical conditions in the sediment were right, cement could precipitate close to the sediment-water interface, as it now does only below the taphonomically active zone (Sepkoski, 1982). The thin

bedding in many Cambrian rocks represents resuspended and redeposited material from small storms (Sepkoski, 1982).

Later in the Paleozoic bioturbation commonly was deep enough to homogenize the laminations from small-scale storm disturbance, “erasing” most of those smaller events (Sepkoski *et al.*, 1991). But the larger storm events did form discrete beds, commonly on a decimeter, rather than centimeter, scale (as noted above for the Ordovician and Silurian examples). Although the difference in estimated bed spacing in the Cambrian example and the later Paleozoic examples noted above could be related to differences of environment, or even of stratigraphic thickness over which the analyses are conducted, the decades to centuries Cambrian average and the centuries to millennia average for the later Paleozoic may be a function of difference in frequency of preservation of depositional units, too.

Bioturbation to meter-scale depths became widespread in the later Mesozoic and Cenozoic (Thayer, 1983). Shelf sediments of Cretaceous and Cenozoic age are often fully homogenized, with bedding only apparent as storm-concentrated shell beds (Sepkoski *et al.*, 1991). In locations such as the Atlantic Coastal Plain, distinct bedding planes are generally restricted to small unconformities in the sections. It is apparent, however, from the “ghosts” of coarse storm concentrations, that sedimentation was just as discontinuous as in the Paleozoic. Yet Paleozoic-style diastems are not commonly preserved as discrete bedding planes because of deep bioturbation. But the same temporal scale for sediment accumulation remains. The Cenozoic beds have simply lost the stratigraphic resolution present in earlier times, as suggested by Kidwell (1998).

3.6 Stratigraphic Resolution: A Summary

The previous sections can be summarized in terms of general statements regarding the stratigraphic resolution of the sedimentary record. These statements are most applicable to marine sedimentary successions separated by small-scale diastems. They should not be extrapolated to offshore basinal settings or more unusual settings, such as lacustrine varves or tidal rhythmites, where process systems operate at different temporal scales.

1. At the finest scale (bedding within a section), stratigraphic resolution is dependent on the length of time represented by diastems between beds.
2. Intervals between events that cause stratification vary widely, but several lines of evidence converge on the sense that in shelf settings diastems generally represent a few centuries to a few thousand years.
3. The general age range for the spacing between major storm events occurring at a single spot in the Recent is several centuries to a few thousand years.

4. The age range calculated for the temporal spacing between beds in the early to mid Paleozoic is generally a few centuries to a few thousand years.
5. The rate of formation of accommodation space, geographic setting in relation to climate pattern, and water depth are factors that influence the duration of diastems. When accommodation space is already present (such as after sea-level rise that "outruns" sediment accumulation, as in the transgressive phases of Milankovitch cycles) sedimentation rates and frequency of bed-forming events, rather than rates of formation of accommodation space, dominate in determining the duration of diastems.
6. Because geologic factors, such as the rate at which accommodation space forms, are critical in controlling the accumulation of sets of discrete beds, diastems are likely to be a few millennia in duration, and not just the few centuries that characterize the spacing between bed-forming events.
7. Because we can interpret the depositional mechanics of most beds, and they appear commonly to be deposited in a matter of hours to days, it is clear that the geologic record forms very episodically. Only a small fraction of geologic time is actually represented by the accumulation of sediment as it is preserved in any section. Because of diastems, at the scale of "ecological time" the geological record is lace-like, mostly gaps (diastems) with a scattered set of beds of sediment that accumulated in very short intervals of time (Barrell, 1917; Ager, 1973, 1981, 1993; Sadler, 1981; Sadler and Strauss, 1990; Anders *et al.*, 1987).

4. PALEONTOLOGICAL RESOLUTION

4.1 Limits of paleontological resolution

Our view of paleontological resolution is summarized on a schematic diagram that shows a distribution of paleontological records in the bivariate space defined by axes of depositional and stratigraphic resolution (Fig. 7). Given the compiled data (Tables 1 and 2), we argue that the overwhelming majority of records (bedded nearshore and shelfal deposits) should be characterized by the stratigraphic and depositional resolution in a 10^2 - 10^4 years range. Because the two resolutions are partly dependent, the records are expected to cluster along the thick diagonal line (Fig. 7). This makes intuitive sense. For example, fossil concentrations at major sequence boundaries and maximum flooding surfaces, where stratigraphic gaps are large, are likely to contain records with high levels of temporal mixing, but snapshots are unlikely to form in such settings. Conversely, fossil

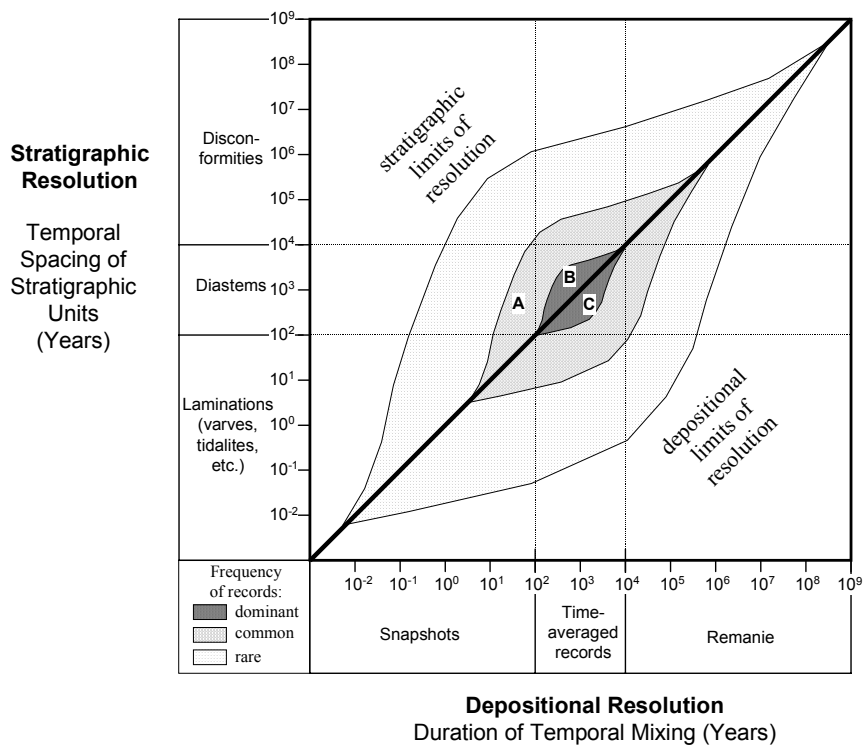


Figure 7. Temporal resolution of paleontological records. Distribution of the records is defined by their depositional resolution (x-axis) and stratigraphic resolution (y-axis). The suggested distribution of records is a rough prediction based on the data reviewed in this paper (see text and Tables 1 - 2). Letters A, B, and C mark three hypothetical examples of paleontological records.

concentrations that formed in settings typified by high-subsidence and sedimentation rates, where stratigraphic successions can be resolved at finer temporal scales, are unlikely to experience extensive temporal mixing, and snapshots are more likely to be preserved there. At the same time, the two resolutions are partly independent. For example, even within the same units, temporal mixing may vary among different types of fossils ("disharmonious time averaging" *sensu* Kowalewski, 1996a) because of intrinsic differences among organisms (e.g., differences in durability). Thus, we expect records to show some divergence from the diagonal line (Fig. 7). This spread should be highest in the region where, for both resolution types, records are common: the temporal ranges of 10^2 to 10^4 years (Tables 1-2).

We trust the diagram as a qualitative generalization, but it should not be used as a reliable quantitative estimate of the actual distribution of paleontological records in terms of their stratigraphic and depositional resolution. At this point we have limited empirical data on each type of

resolution exist (Tables 1-2). Moreover, no bivariate estimates – with both resolutions estimated concomitantly for the same records – are available.

Regardless of all uncertainties, two important generalizations can be made. First, whereas both depositional and stratigraphic resolution may potentially vary over a wide range of temporal scales, the typical (i.e., interdiastemal or within-sequence) records vary over a much narrower range, with both depositional and stratigraphic resolution ranging from hundreds to thousands of years. This means that, typically, the two types of resolution are comparable in their temporal scale and, therefore, both must be considered in determining the resolution of paleontological data. If we ignore one of the resolution types, we may misjudge the actual resolution of our data. This is illustrated on our conceptual diagram (Fig. 7), which shows that any records located to the left of, or above, the diagonal line have their resolution limit imposed by their stratigraphic resolution, whereas any records located to the right of, or below, the diagonal line are limited by their depositional resolution. Second, because some of the variables controlling depositional and stratigraphic resolution are unique (e.g., intrinsic factors of depositional resolution), the two types of resolution need not be fully dependent. In other words, a high depositional resolution of a given record does not have to imply a comparably high stratigraphic resolution, and *vice versa*. The paleontological data extracted from tidal rhythmites need not have daily resolution and correlative successions of storm beds dominated by snapshots cannot be correlated at the resolution of years, even though the records contained in individual snapshots may provide a resolution at such a fine time scale.

4.2 Paleontological Data as Records of Diastems

An important corollary of temporal mixing is that a majority of paleontological data comes from the times corresponding to stratigraphic gaps: bioclasts record organisms that lived during diastems and not during the time when the beds in which they are found were formed (Fig. 8). The extensive temporal mixing documented directly by dating (Table 1) indicates that bioclasts do not just *occasionally* predate depositional events and are not just *slightly* older, but they *often* predate depositional events and are *notably* older, lagging behind by hundreds or thousands of years (Table 1). These are the time scales that correspond to time spans of typical diastems (Table 2). Consequently, paleontological data may often provide a relatively complete record of organisms that lived during time intervals apparently missing from the stratigraphic record. In other words, *beds record depositional events, but their fossils record the preceding diastems!*

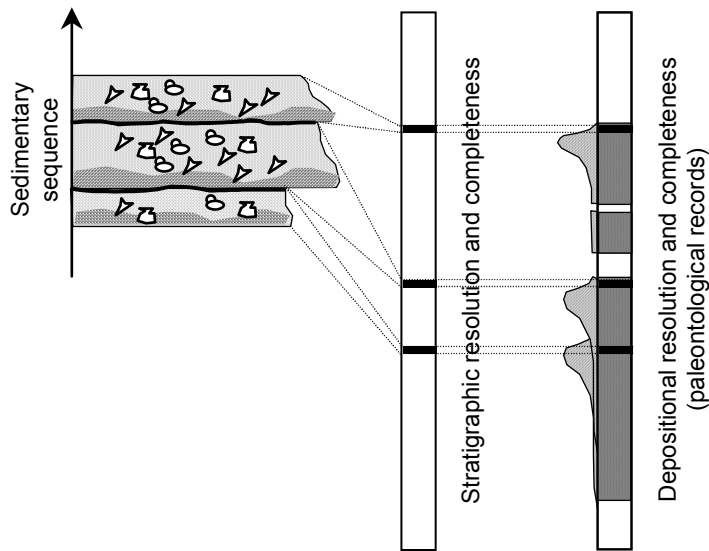


Figure 8. Temporal relationship between the timing of diastems that defined stratigraphic resolution and completeness of a succession and the timing of paleontological records that defines the depositional resolution and completeness of that record. Paleontological records lag behind depositional events and are dominated by records of organisms that lived in the time that is "missing" from the stratigraphic record. The lagging worsens temporal resolution of paleontological records, but improves their completeness.

This is good news indicating that paleontological data provide samples that are much more temporally complete and representative than is suggested by the notoriously high stratigraphic incompleteness of sedimentary successions. And although temporal mixing prevents us from making sequential reconstructions of the paleontological records (with the exception of Late Quaternary records, where high-resolution dating is possible), the average estimates of parameters obtained from fossils are probably much more representative of their true, long-term, average values than is suggested by the sporadic nature of depositional events.

4.3 Stratigraphic and Depositional Completeness

As stressed here, the term completeness, when applied to successions of fossiliferous rocks, cannot only denote stratigraphic completeness (the dominant usage of the term), but also depositional completeness. *Stratigraphic completeness* can be defined as the proportion of the total amount of time represented by a stratigraphic section that is recorded by depositional events, whereas *depositional completeness* can be defined as the proportion of the total amount of time represented by a stratigraphic section that is recorded by physical records such as fossils (see Section 2.4 above).

As argued in section 4.2, due to temporal mixing, fossils record diastems and provide a much more complete record than the stratigraphic units in which they are preserved. Depositional completeness of paleontological records may be much higher than the stratigraphic completeness of the successions that contain these records. For example, Behrensmeier (1982) postulated a credible hypothetical alluvial succession with 53% depositional paleontological completeness, but only 27% sedimentary completeness. Mixing processes can even lead to overcompleteness with fossils documenting more time-intervals than fall into the time span of a stratigraphic section. Overcompleteness is primarily a microstratigraphic phenomenon observed at very fine resolution levels (Kowalewski, 1996a).

As with stratigraphic completeness (Sadler, 1981), depositional completeness depends on the scale of observation and becomes increasingly incomplete over longer time intervals. Also, longer stratigraphic sections, are likely to include substantial intervals barren of fossils, and consequently, one may expect that, at coarser time scales, stratigraphic completeness should improve relative to depositional completeness.

4.4 Trends through the Phanerozoic

As discussed in sections 2.7 and 3.5, both depositional and stratigraphic resolution may have changed notably through time. The two secular trends have not been controlled by exactly the same suite of factors and, thus, need not have varied necessarily in perfect concert. Nevertheless, the existing data suggest that the duration of diastems and the scale of temporal mixing both have increased through the Phanerozoic. Paleontological resolution, both in its depositional and stratigraphic aspects, has decreased through time.

5. CONCLUSIONS

Numerous researchers have reviewed both temporal mixing (depositional resolution) of fossiliferous deposits (e.g., Wilson, 1988; Kidwell and Bosence, 1991; Kowalewski, 1996a; Kidwell, 1998; Martin, 1999), as well as stratigraphic resolution of sedimentary successions (e.g., Sadler, 1981; Schindel, 1982; Martin, 1999). However, to our knowledge, no explicit attempt to combine these two concepts of paleontological resolution into a single analysis has been made previously. The joint consideration of the two aspects of resolution presented here suggests the following generalizations:

1. Depositional and stratigraphic resolution may both potentially vary over a wide range of temporal scales, but the typical, interdiastemal records vary in a much narrower range from hundreds to thousands of years.

Thus, the two types of resolution are comparable in scale and must be considered jointly when evaluating the resolution of a given fossil record.

2. Depositional and stratigraphic resolution are partly dependent (as they share some controlling factors), and thus, are expected to often correlate with one another: records poorly resolved stratigraphically (separated by long diastems) tend to display high levels of temporal mixing. However, this covariation is not total: depositional and stratigraphic resolutions are partly independent (i.e., some controlling factors are unique) and both may place limits on the resolution of paleontological data.
3. Because bioclasts often predate depositional events by hundreds or thousands of years (i.e., over time scales comparable to those that typify diastems), paleontological data may often provide complete paleontological records for time intervals apparently missing from the record (i.e., beds record depositional events, but their fossils record the preceding diastems). Consequently, paleontological completeness often may be higher than stratigraphic completeness, and the average estimates of parameters obtained from fossils may be more representative of their true long-term, average values than is suggested by the sporadic nature of depositional events.
4. Despite some differences in underlying secular factors, the existing data suggest that depositional and stratigraphic resolution both have decreased through the Phanerozoic.

We hope that our preliminary generalizations regarding the combined limits of depositional and stratigraphic resolution, the causative factors underlying these limits, and their secular trends, will offer useful guidelines for all those geoscientists that use data from the fossil record in their research. It is clear to us that a twofold consideration of both aspects of paleontological resolution should provide a better conceptual tool for evaluating resolution limits inherent to the fossil record, and consequently, should yield a more realistic picture of the temporal nature of paleontological data.

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