The Nature of the Sedimentary Record

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Summary

It has long been understood that the stratigraphic record is fragmentary. Barrell (1917) in a paper that was many years ahead of its time, was the first to clearly understood 1) the importance of accommodation, and 2) the very episodic way in which accommodation is created and removed by geological processes. He demonstrated that under typical conditions of base-level rise and fall only a fraction of geologic time is represented by accumulated sediment. This point was repeated in several influential books by Ager (1973, 1993). One of the most important, yet neglected, discoveries about the nature of the sedimentary record is the correlation between the duration of a sedimentary unit and its sedimentation rate (Sadler, 1981). Sedimentation rates range over more than eleven orders of magnitude.

It is now recognised that the durations of stratigraphic gaps, the distribution of layer thicknesses, and sedimentation rates in stratigraphic successions are fractal. The fractal model provides an elegant basis for integrating our knowledge of the processes of accommodation generation with the data on varying sedimentation rates, the scales of hiatuses, and the processes that operate over these time scales.

This paper proposes the definition of a suite of *Sedimentation Rate Scales* to encompass the range of time scales and processes that can now be recognized from modern studies of the stratigraphic record. Assignment of stratigraphic units to the appropriate scale should help to initiate a potentially rich new form of debate in which tectonic and geomorphic setting, sedimentary processes and preservation mechanisms can be evaluated against each other, leading to more complete quantitative understanding of the geological preservation machine, and a more grounded approach than earlier treatments of “stratigraphic completeness”.

The fragmentary and hierarchical nature of the stratigraphic record

It has long been understood that the stratigraphic record is fragmentary. Blackwelder (1909) recognized that the cratonic sedimentary cover of North America consists of a suite of unconformity bounded successions, later termed “layers of geology” by Levorsen (1943) and “sequences” by Sloss (1963). Barrell (1917) in a paper that was many years ahead of its time, was the first to clearly understood 1) the importance of what we now term *accommodation*, the space available for sediments to accumulate, and 2) the very episodic way in which accommodation is created and removed by geological processes. He demonstrated that under typical conditions of base-level rise and fall only a fraction of geologic time may actually be represented by accumulated sediment. This was emphasized by Ager (1973) who remarked that “the stratigraphic record is more gap than record.” In a later book, following a description of the major unconformities in the record at the Grand Canyon, he said, (1993, p. 14):

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

The description and interpretation of bedding planes and bounding surfaces has become part of the standard practice of *facies analysis*. These surfaces constitute a hierarchy of importance reflecting their duration and extent, and there have been several attempts to develop hierarchical classifications of these surfaces and the units they enclose including the classification of lithofacies units by van Wagoner et al. (1990), that for shallow-marine deposits by Nio and Yang (1991), and that for fluvial deposits by Miall (1996). At the larger scale, Vail et al. (1977) erected a hierarchical classification for stratigraphic sequences.

One of the most important, yet neglected, discoveries about the nature of the sedimentary record is the correlation between the duration of a sedimentary unit and its sedimentation rate. Sadler (1981) provided a graphic documentation of this relationship (Fig. 1). Sedimentation rates range over more than eleven orders of magnitude. What this means in practice is that, at every scale, from the individual bedset, to the scale of a basin fill, the time that can be accounted for by the accumulation of a given thickness of sediment, when measured at the appropriate time scale, accounts for a very small fraction of the total of elapsed time. To extend Ager's famous thought: there are gaps within the gaps, and the record is permeated with them, at every scale. Bailey and Smith (2010, p. 57-58) pointed out the ephemeral nature of most sedimentary processes:

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

It is now widely recognised that not only the durations of stratigraphic gaps, but also the distribution of layer thicknesses and sedimentation rates in stratigraphic successions are fractal in nature (Plotnick, 1986; Schlager, 2004; Bailey and Smith, 2005). The fractal model provides an elegant basis for integrating our knowledge of the processes of accommodation generation with the data on varying sedimentation rates and the varying scales of hiatuses and the processes that operate over these various time scales (Fig. 2). Miall (in press) explored the various autogenic and allogenic processes by which the "frozen accidents" achieve preservation. At geomorphic scales (up to 10^5 years) such autogenic processes as lateral accretion in channels and on shorefaces, and the shifting of channels across a floodplain can preserve sedimentary fragments long enough that they can become buried by successive deposits. At intermediate geological scales (10^3-10^5 years) delta lobe switching, the progradation of fans and deltas and the fill of incised valleys are significant preservation mechanisms, and at the larger scale tectonic subsidence becomes critical.

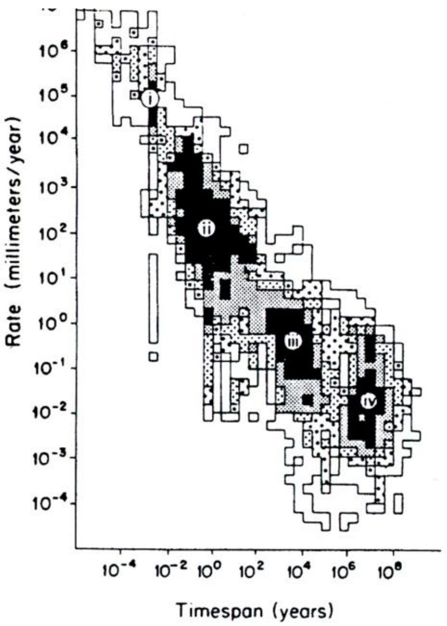

Fig. 1. The relationship between the duration of a sedimentary unit and its sedimentation rate, showing results from some 25,000 data sets (Sadler, 1981)

Miall (in press) proposed the definition of a suite of *Sedimentation Rate Scales* to encompass the range of time scales and processes that can now be recognized from modern studies of the stratigraphic record (Fig. 2; Table 1). Even our data for the Phanerozoic record merely brushes the surface of a potentially rich new form of debate in which tectonic and geomorphic setting, sedimentary processes and preservation mechanisms can be evaluated against each other, leading to more complete quantitative understanding of the geological preservation machine, and a more grounded approach than earlier treatments of "stratigraphic completeness".

Sequence stratigraphy has become the standard framework for the description and interpretation of the stratigraphic record at the regional scale (Catuneanu, 2006; Miall, 2010),

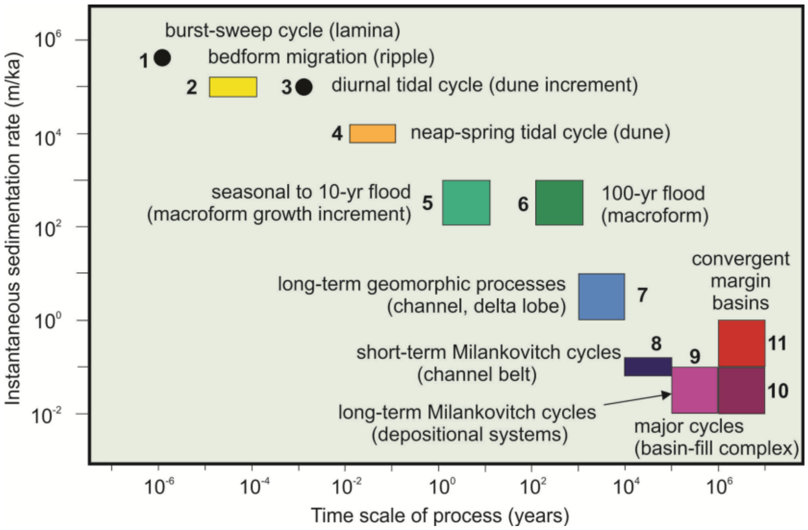

Fig. 2. Rates and durations of sedimentary processes. Numerals refer to the Sedimentation Rate Scale (Miall, in press).

and one of the central elements of sequence geology is the episodicity (or true cyclicity) of the stratigraphic record.

Fragmentary the stratigraphic record might be, but the fractal nature of the record means that it consists of intervals of succession fragments separated by larger gaps that developed at higher time scales. These larger gaps constitute the boundaries between stratigraphic sequences. Several decades of analysis have now indicated that there is a limited number of sequence types, which develop because of the occurrence of particular allogenic processes that are characterized by particular time scales, ranging from 10^4 to 10^8 years (Miall, 1995, 2010; Table 2). These natural time scales, because of their predominance, tend to lead to enhanced preservability, and it is for this reason that sequence stratigraphy "works." As can be seen in this table, a modern understanding of sequences demonstrates that the original "order" classification of Vail et al. (1977) is no longer appropriate.

Discussion

It has long been known that the sedimentary record is fragmentary. However, this has not stopped stratigraphers from making calculations about sedimentation rates and the ages of key beds, based on assumptions of continuous sedimentation and extrapolation from known horizons. For example, the study of cyclostratigraphy requires the conversion of the "depth domain" to the "time domain" using age calibration points (Strasser et al., 2006, p. 82). Based on the arguments presented here, much of this type of analysis should now be treated with considerable caution. This could be argued before on an *ad hoc* basis, but not until the advent of the fractal concept has it been possible to systematize these observations and place them into a formal framework that suggests a continuity of process over all time scales. These concepts likely hold a key to a completely new way of studying and interpreting the sedimentary record, and this requires us to go back and look at that record again, ironically, to document what is not there in greater detail: the record of missing time.

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

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

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Table 1: The hierarchy of depositional units, recurrence interval, rates of sedimentation, and preservation

SRS	**Time scale (years)**	**Inst. Sed. Rate (m/ka)**	**Sedimentary process**	**Preservational accident**	**True cyclicity**
1	10^{-6}	10^{6}	Burst-sweep cycle	Small-scale autogenic shifts in distribution of grain carpet due to aggradation, turbulent bursts	None
2	10^{-5}-10^{-4}	10^{5}	Ripple migration	Small-scale autogenic shifts	Repetition by climbing
3	10^{-3}	10^{5}	Dune migration, foreset bundles	Small-scale autogenic shifts	Repetition by climbing
4	10^{-2}-10^{-1}	10^{4}	Diurnal variability to normal meteorological floods (dynamic events)	1) Accommodation represents lateral space on bars. Preservation by abandonment by meander cutoff or minor shift in channel during high-discharge event 2) Crevasse splays abandoned by autogenic shifting	Bar accretion
5	10^{0}-10^{1}	10^{2-3}	Seasonal to 10-yr flood: macroform growth increment	A for SRS 4, above	Bar accretion
6	10^{2}-10^{3}	10^{2-3}	Long-term (100-yr) flood: macroform, point bar, splay	As for SRS 4, above	Bar accretion
7	10^{3}-10^{4}	10^{0}-10^{1}	Long-term geomorphic process: channel, delta lobe, coal seam	Avulsion, delta-lobe switching, valley fill	Channel aggradation
8	10^{4}-10^{5}	10^{-1}	Channel belt; orbital cycle, delta	1) Channel-belt avulsion, 2) Valley fill 3) Intraplate stress changes adjusting paleoslope	Channel aggradation; orbital forcing
9	10^{5}-10^{6}	10^{-2}-10^{-1}	Depositional system, alluvial fan, major delta complex, orbital cycle	As for SRS 8, above	Orbital forcing
10	10^{6}-10^{7}	10^{-2}-10^{-1}	Basin-fill complex, tectonic cyclothem (e.g., "clastic wedge")	Tectonic changes in location and rate of accommodation	Crude cyclicity related to tectonic episodicity
11	10^{6}	10^{-1}-10^{0}	Rapid subsidence of foreland basins accompanied by syntectonic clastic progradation	Accommodation generation at geologically rapid rates	Crude cyclicity related to tectonic episodicity

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Table 2. Stratigraphic cycles and their causes (from Miall, 1995)

Sequence type	Duration (m.y.)	Other terminology
A. Global supercontinent cycle	200-400	First-order cycle (Vail et al., 1977)
B. Cycles generated by continental-scale mantle thermal processes (dynamic topography), and by plate kinematics, including: 1. Eustatic cycles induced by volume changes in global mid-oceanic spreading centres 2. Regional cycles of basement movement induced by extensional downwarp and crustal loading.	10-100	Second-order cycle (Vail et al., 1977), supercycle (Vail et al., 1977), sequence (Sloss, 1963)
C. Regional to local cycles of basement movement caused by regional plate kinematics, including changes in intraplate-stress regime	0.01-10	3rd- to 5th order cycles (Vail et al., 1977). 3rd-order cycles also termed megacyclothem (Heckel, 1986), or mesothem (Ramsbottom, 1979)
D. Global cycles generated by orbital forcing, including glacioeustasy, productivity cycles, etc.	0.01-2	4th- and 5th-order cycles (Vail et al.,1977), Milankovitch cycles, cyclothem (Wanless and Weller, 1932), major and minor cycles (Heckel, 1986),