Reading Sandstones

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In recent years, major research trends in several areas, including sequence (and seismic) stratigraphy, sedimentology, geochronology and tectonic basin analysis have come together to provide detailed and sophisticated analyses of the stratigraphic record, thus providing powerful tools for extracting basin-scale to global interpretations from the geological record ("**reading the sandstones**!"). These improved methods, where aided by detailed drill and core records and/or high resolution seismic data may substantially improve the geological services that the profession may be able to offer to the resource industries (Miall, 2022).

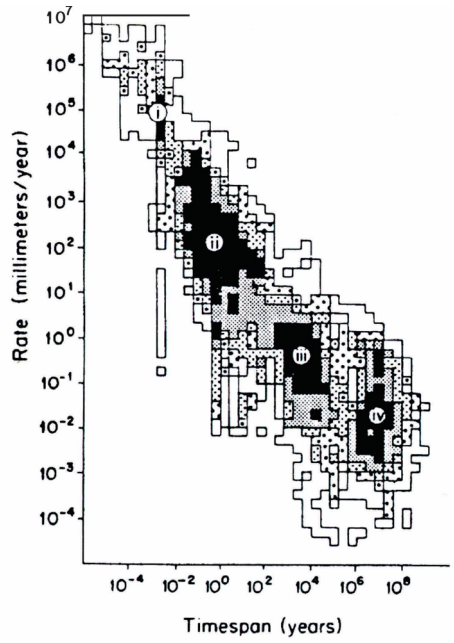


Fig. 1. Sedimentation rate is inversely proportional to elapsed time (Sadler, 1981)

The application of modern geochronological methods to the stratigraphic record has demonstrated that it comprises fragmentary sedimentary accumulations ("frozen accidents") that can be interpreted in terms of largely familiar depositional environments and processes based on uniformitarian principles. Sadler (1981) compiled data showing that sedimentation rate is inversely proportional to the elapsed time represented by the sampled section (Fig. 1). This has been called the "**Sadler Effect**." It indicates that sedimentary breaks of increasing duration are incorporated into longer sections. Frozen accidents and intervening breaks can tell us a lot.

Attempts to explain this fragmentary nature of the record quantitatively (stratigraphic completeness), starting with Tipper (1983), consist largely of stochastic models based on the idea of a "random walk" of sedimentary increments and hiatal intervals (Fig. 2). Time increments (a,b,c,d) and thickness increments (lithosomes A,B,C,D) are shown with random lengths and are summed along a "line of accumulation."

However, stratigraphic accumulation is not random, for at least three reasons (Fig. 3): 1) on the bed scale, vertical successions typically develop as autogenic facies cycles; 2) on a larger scale, sediment supply and accommodation changes are the predominant processes, and follow the precepts of sequence stratigraphy. 3) commonly lateral accretion or progradation is quantitatively more significant than vertical aggradation, as on meander bends, deltas and clinoforms.

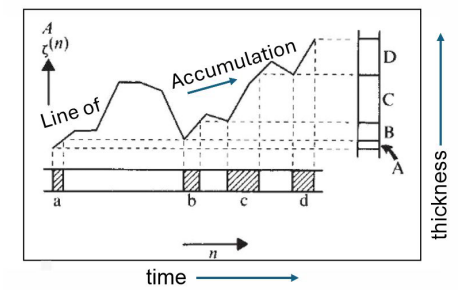


Fig. 2. The "random walk" model of sediment accumulation (Tipper, 1983)

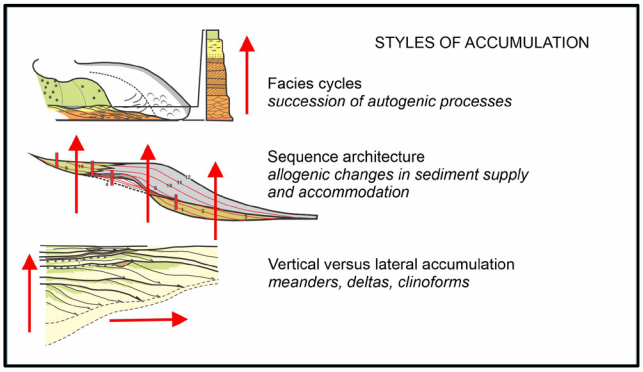


Fig. 3. Styles of non-random accumulation

These issues are best dealt with within a hierarchical framework of depositional units from the bed scale to the basin fill (Fig. 4). Sedimentary processes and sedimentation rates can be characterized for each level within this hierarchy. When tracing the stratigraphic record at the surface, or in the subsurface, the predictable vertical and lateral architectures of each level of the scale of deposits (such as stratigraphic architectural units, systems tracts and sequence boundaries) can serve as essential guides to the mapping of the basin architecture.

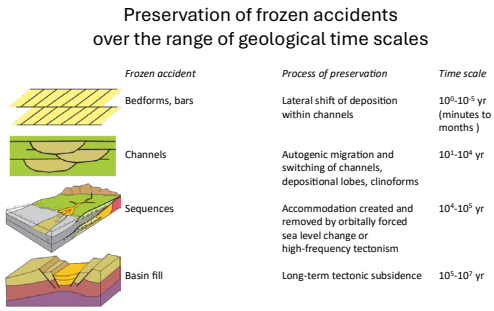


Fig. 4. Specific geological processes operate over specific rates and time scales.

We can now see that "frozen accidents" (to use the useful term proposed by Bailey and Smith, 2010) at all scales are developed simultaneously over their respective times scales, and their accumulation and amalgamation over time is what constitutes the stratigraphic record. So, reading from Figure 4 from bottom to top, a basin fill is developed over geologically significant periods of millions of years, typically by the accumulation of successive stratigraphic sequences, as sediment supply and accommodation change systematically in response to allogenic forcing. Each systems tract is composed of large and small architectural elements, the larger consisting of alluvial belts, deltas, coastal complexes, submarine fans (and carbonate equivalents); the smaller elements comprise various bedforms and bars, and related deposits representing equivalent physical size and time scales.

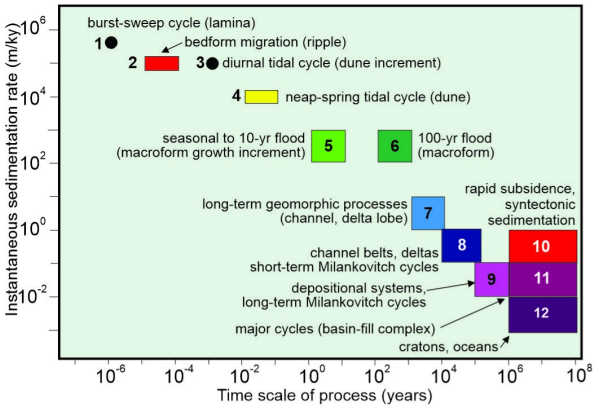


Fig. 5. The hierarchy of architectural units representing sedimentology's "frozen accidents", diagrammed to represent an interpreted version of Sadler's famous plot (Miall, 2015). The numerals in boldface represent the Sedimentation Rates Scale (SRS)

Modern work on **sedimentation rates**, aided by new methods of geochronology and sequence stratigraphy, and using sedimentological analysis to determine the dominant processes acting at a given time scale, have provided a wholly new approach to the subject of sedimentary accumulation. Miall (2015, p. 14) demonstrated that "*The record shows that when measurements of sedimentation rate are calculated at the appropriate [time] scale, they are internally consistent and can be related to natural processes occurring within that time scale*." This idea is illustrated in an annotated or interpreted version of Sadler's diagram (Fig. 5). Recent work applying these concepts includes Bhattacharya et al. (2019), Holbrook and Miall (2020) and Miall et al. (2021)

Given the presence of an active sedimentary basin, the most important processes affecting long-term geological accumulation (time scales ranging from 10^4 to 10^8 years) are created by:

- Sea-floor spreading kinematics (changing in-plane stress vectors, affecting coastal topography and sediment dispersal patterns);
- High-frequency orogenic tectonism (changes in relative sea level, changes in sediment flux, rapid changes in accommodation, shifting in continental dispersal systems);

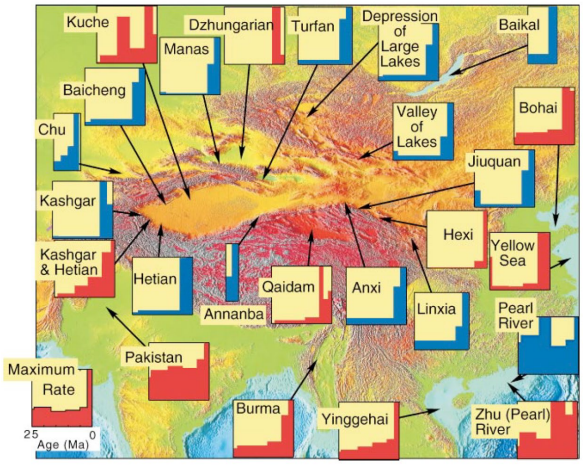


Fig. 6. Sediment volumes in 10^{18} kg per 5-my time increments (Molnar, 2004).

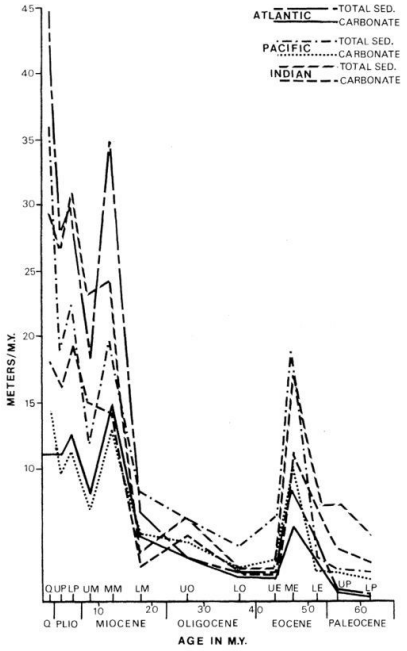


Fig. 7. Mass/age distribution of ocean floor sediments, based on DSDP data. From Hay et al. (1988, Fig. 1).

- Sea-level change (orbital forcing, including glacioeustasy, on a 10^4-10^5-year time scale, affecting accommodation and sediment supply);
- Autogenic shifting of sediment dispersal systems (meanders, deltas and marine clinoforms; lateral accretion is important)
- Long-term environmental change (eolian supersurfaces, hardgrounds, drowning unconformities, stasis surfaces)

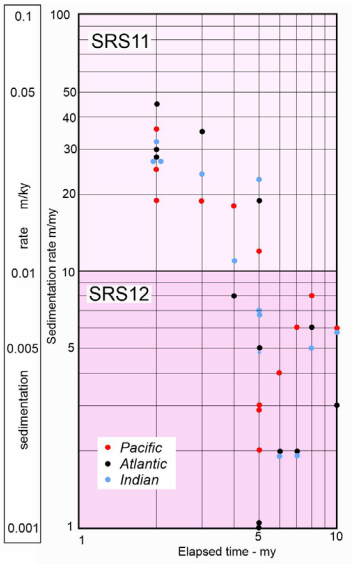


Fig. 8. Replotting of Davies et al. (1977) data to show DSDP sedimentation rate against elapsed time span (c.f. Sadler, 1981).

The pattern of accumulation, including the frequency and duration of sedimentary breaks (unconformities: Miall, 2016) and the rates of sedimentation (Miall, in revision) are a direct response to these processes, and the signatures they create in the rock record are important clues to regional geological processes. The need for petroleum exploration and development programs to be based on an accurate reconstruction of basin stratigraphy, means that explorationists and development geologists and engineers must be able to explore and resolve these many controlling factors.

Understanding stratigraphy

Did sedimentation speed up in the late Cenozoic?

Molnar (2004) argued that global sedimentation rates have exhibited a dramatic increase during the last few million years. He cited the work of many earlier workers, notably Davies et al. (1977), Hay et al (1988), and Métivier et al. (1999). His compilation shows that, indeed, in most of his examples, data for the last 5 million years shows a marked increase in sediment volumes (Fig. 6). However, this conclusion fails to acknowledge one of the most important corollaries of the Sader Effect: If

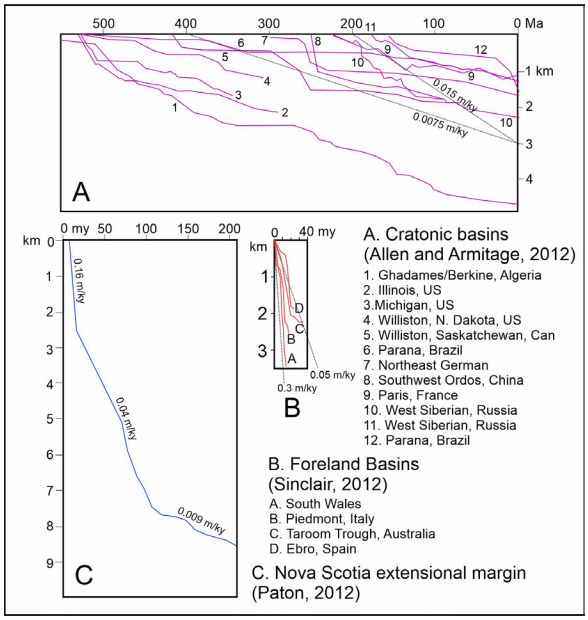


Fig. 9. Typical time-depth subsidence plots for three major classes of sedimentary basin, drawn at the same scale. Adapted from chapters in the book “Tectonics of sedimentary basins” (Busby and Azor, 2012).

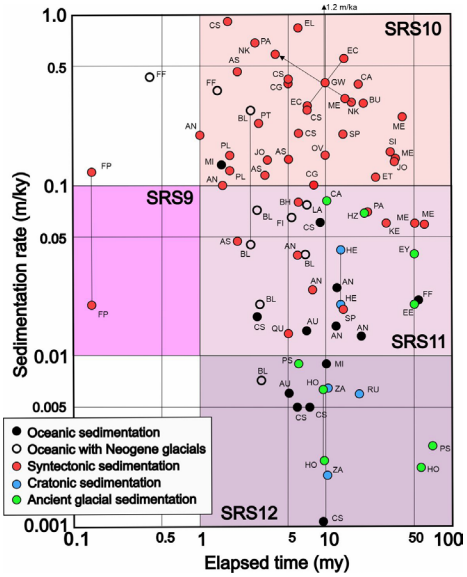


Fig. 10. The relationship between sedimentation rate and elapsed time for various classes of stratigraphic data. The time-rate bounds for the Sedimentation Rate Scale (SRS), are as shown in Fig. 5. The two-letter acronyms for each data point are used to identify the sources of the data listed in a Table in Miall (in revision) and can be provided on request. Data points AN are from Anell et al. (2011) and are discussed in the text.

sedimentation rates are inversely proportional to the elapsed time represented by the measured section, then sections that are short in time span, particularly those representing the last few million years, are likely to show more rapid accumulation rates, for that reason alone. Sections that end at the present day will always show rates increasing towards the top because the later section increments have not been fully processed by longer-term geological processes.

This can be demonstrated using a data set cited by Molnar (2004). Fig. 7 reproduces a key diagram from Hay et al. (1977). It appears to show high accumulation rates in the Miocene to Recent and the Eocene, and low rates during the Oligocene and the Paleocene. Molnar (2004, p. 78) suggested that the Hay et al. “compilation shows that the accumulation in the past 5 million years exceeds that in any other 5-million-year bin by more than two times.” However, this is an artefact of the time spans used to construct the diagram. The authors were trying to relate sedimentation rate to changes through the Cenozoic, but they used section age increments of variable duration that ranged from 2 to 10 million years. When the same data are re-plotted using the elapsed time represented by each data point, instead of its age range, the late-Cenozoic increase disappears, and the data then follow the Sadler rule (Fig. 8).

How does stratigraphic architecture reflect basin setting?

Fig. 9 provides a series of typical time-depth plots illustrating the subsidence rates of three major classes of basin, cratonic basins, foreland basins, and continental-margin extensional basins. Note the high rates and relatively short durations of foreland basins. With these curves

and indicated rates in the background, we can now look at some examples in more detail.

The importance of tectonism

The relationship between elapsed time and sedimentation rate for selected basin-fill sections is shown in Fig. 10. Within the range of time scales and sedimentation rates illustrated in Fig. 10, the Sadler Effect is not discernible, except possibly for those data points identified as glacigenic in origin (see Miall, in revision for a discussion of this point). Most basins characterized by tectonically enhanced sedimentation rates fall within SRS 10, that is, sedimentation rates are greater than 0.1 m/ka. Most Neogene glacigenic deposits exhibit sedimentation rates within the SRS11 envelope.

The North Sea Basin, a "failed rift" basin, offers an instructive argument regarding the influence of tectonism and sediment supply (Anell et al., 2011). Paleocene sedimentation in the northern and western parts of the basin was triggered by a major episode of mantle underplating beneath the British Isles, centered on the Irish Sea region, which caused uplift and exhumation of the northern and western parts of the islands by as much as 2-3 km. This triggered a major erosional episode, with much of the resulting detritus ending up in the North Sea (Fig. 11), where it was deposited as giant submarine fans up to 700 m thick and extending over a total area of 60,000 km^2 (White and Lovell, 1997). These fans now constitute some of the most important natural gas reservoirs in Britain. The sedimentation rate for the 6-my Paleocene unit in the North

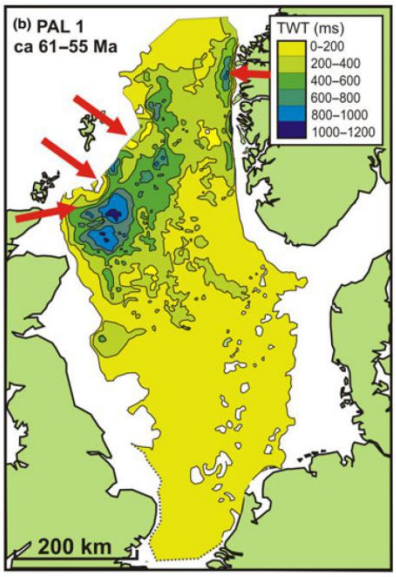


Fig. 11. TWT isopachs for the Paleocene-early Eocene fill of the North Sea (Anell et al.,

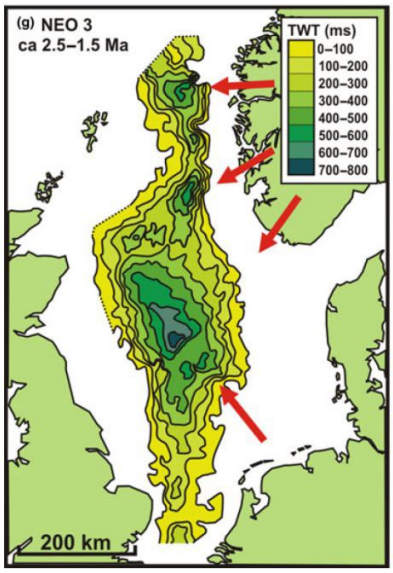


Fig. 12. TWT isopachs for the early Pleistocene seismic unit in the North Sea (Anell et al., 2011)

Sea has been measured at 0.039 m/ka (Anell et al., 2011).

From the late Miocene to the mid-Pliocene, the eastern North Sea basin was dominated by an extensive fluvial system that drained the Fennoscandian and Baltic shields directly, and also through a broad valley corresponding to the present Baltic Sea. The dimensions of the drainage area and the thickness of the fluvio-deltaic deposits in the present North Sea, termed the Eridanos Delta, are comparable to those of the present Orinoco delta system. Overeem et al. (2001) and Anell et al. (2011) calculated different accumulation rates for the delta, based on different data sets, with the highest value reaching 0.196 m/ka for the 1-my duration of the Early to Middle Pleistocene NEO3 seismic unit (Fig. 12). This significant sediment input was triggered by Late Cenozoic uplift and by the commencement of the Neogene ice age, with a large ice cap

developing over the Scandinavian continent. Seismic data reveal a complex pattern of prograding and offlapping clinoforms gradually building the delta westward across the North Sea basin. (Anell et al., 2011).

Visualizing a stratigraphic interpretation

Hassan et al. (2018, Fig. 16) adopted Tipper's (1983) sediment accumulation diagram as an aid in understanding the regional transition from the fluvial Kayenta Formation to the eolian Navajo Formation near Kanab in southern Utah. This diagram is reproduced here, with slight modifications, as Fig. 13. The transition consists of a series of three cycles totaling 200 m in thickness through which fluvial deposits are replaced upward by eolian sediments three times, with the latter becoming more dominant through time. Hassan et al. (2018) pointed to comparisons with other fluvial-eolian transitions recorded in the rock record, and suggested tentatively that the primary driving mechanism was orbitally-forced climate cyclicity on a 405,000-year periodicity, pacing a gradual increase on overall aridity in the sedimentary basin. Two and one half such cycles are represented by the section.

Although no useful age dates for this succession are available, the relative timing of the succession of sedimentological events can be reconstructed given the framework of orbital forcing, and the interpreted process of accumulation is indicated by the sloping green "accumulation line". This process includes surfaces of stasis, indicated by the blue arrows, and periods of eolian deflation, indicated by the downward slope of the accumulation line. The presence of two eolian super-surfaces (Kocurek, 1988) is suggested. The overall sedimentation rate (200 m of sediment in 1.01 my, based on the interpreted cyclicity) is 0.19 m/ka, which is above the bounds for SRS 9 — the approximate limit for long-term Milankovitch cycles, as shown in Fig. 2. Based on the interpreted slope of the accumulation line, 66% of the elapsed time represented by the 200 m of sediments is interpreted to represent periods of stasis or erosion. The sedimentation rate calculated for the 34% of the elapsed time represented by deposits (the summed width of the green bars) is 0.58 m/ka, which corresponds to SRS 8, the rate typified by major architectural elements in siliciclastic systems, such as channel belts, delta lobes, etc.

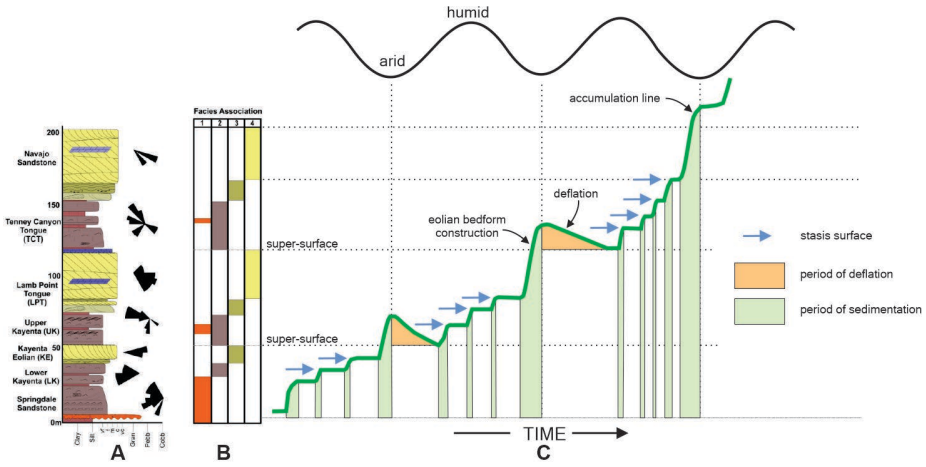


Fig. 13. Visualizing sediment accumulation: the Kayenta–Navajo transition near Kanab, Utah. A) Generalized vertical section through the transition, with representative paleoflow rose diagram for each unit. B) Facies associations: 1: braided river deposits; 2: Sheet flood deposits; 3: erg-margin fluvial-eolian deposits; 4: eolian erg deposits. C) Stratigraphic thickness accumulation versus time, showing the interpreted relationship to an arid–humid climate cycle (modified slightly from Hassan et al., 2018).

Conclusions

Geologists have long been troubled by the partial nature of stratigraphic preservation, and have sought quantitative means to document and understand it, through such concepts as "stratigraphic completeness." While such approaches have provided useful general models, Sadler's (1981) compilation being particularly valuable, a focus on geologic setting and geologic processes over the full range of space and time scales offers the most productive approach to understanding the stratigraphic record on the local and regional scale. Stratigraphic completeness may then be understood as a composite value, comprising nested sedimentary units formed at time scales ranging over fourteen orders of magnitude, separated by breaks representing a similar wide range of time scales. A focus on the integrated time-hierarchy of processes, from the turbulence of bedload transport to the progress of thermal subsidence in a sedimentary basin, strengthens the interpretation of the preserved product, from the cross-bed set to the basin fill. These concepts have real value in the work of reconstructing subsurface stratigraphies for the purpose of resource extraction.

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