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Modern chronostratigraphic data demonstrate that currently popular sequence models for fluvial systems don't work

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Summary

Currently popular fluvial sequence models models (Wright and Marriott, 1993; Shanley and McCabe, 1994) are based on concepts of fluvial architecture derived from modern floodplains, and contain the assumption that rates of channel migration and avulsion are on time scales that are of the same order of magnitude as geological rates. However, studies of modern rivers and the simulation studies on which the sequence models are based assume rates of processes and accommodation rates that we now know are up to three orders of magnitude more rapid than is typically represented in the preserved ancient record. This assertion is based on a new synthesis of subsidence and sedimentation rates across the full spectrum of time ranges, from the modern record to deep geological time, and is illustrated in this paper by reference to the Castlegate Sandstone (Upper Cretaceous, Book Cliffs, Utah) and other ancient fluvial units. The take-away from this study is the need for caution in using quantitative data from the Recent and post-glacial record as a basis for interpreting the ancient record.

Introduction

A synthesis of modern data concerning rates of accommodation generation and sediment accumulation throws light on many issues of sequence generation and preservation (Miall, 2014a,b). This paper focuses on the strong disconnect that this synthesis reveals between the rates of geological processes that form the basis for currently popular fluvial sequence models (Wright and Marriott, 1993; Shanley and McCabe, 1994), and the rates that can now be reconstructed for the ancient examples in the rock record where these models have been applied. The implication is that the accommodation-based models for fluvial systems that are being used to interpret such parameters as channel density, spacing and connectedness need to be re-evaluated.

The quantitative basis for modern fluvial sequence models

The evolution of sequence models for fluvial systems is documented in detail by Miall (2014b, Chap. 6). Briefly, modern concepts derive originally from a thought-experiment by J. R. L. Allen (1974), who constructed a range of imaginary scenarios speculating about the response of fluvial systems to various combinations of allogenic forcing. This, and subsequent work by Allen, was used by Bridge and Leeder (1979) as the basis for a numerical simulation of the evolution of an alluvial channel belt, in which the main variables of interest were subsidence rate and the rate of channel switching within the alluvial plain (avulsion). The quantitative basis for the simulation model consisted of the limited information available at that time concerning modern alluvial subsidence and avulsion rates. Shanley and McCabe (1994, p. 557) stated that "Our Quaternary models may be superb analogs for the Carboniferous, … thought to be a period of widespread glaciation, but how appropriate are they for the middle Cretaceous, a period of limited glaciation? Application of Quaternary models should be done with at least a modicum of restraint." However, this caution has not been followed. According to Heller and Paola (1996, p. 297) "The link between sedimentation rate and channel stacking architecture in the [Bridge and Leeder] model was a major conceptual breakthrough." It has become a common assumption that changes in accommodation rate are critical in the control of alluvial architecture. For example, Wright and Marriott

(1993, p. 206) stated of the transgressive systems tract (TST): "During the early stages of the TST the rate of accommodation space creation will be low, producing multistorey sand-bodies," and later in the transgressive phase "Increased accommodation rates favour high levels of storage of floodplain sediments resulting in isolated channels." Other workers, noting the inappropriateness of using terms for nonmarine systems that refer to sea-level changes, suggested terminology for systems tracts such as "high accommodation" and "low accommodation" (Olsen et al., 1995) and "aggradational" and "degradational" (Currie, 1997).

According to the prevailing models, channel-stacking patterns are the basis for the differentiation between high- and low-accommodation systems tracts. During high accommodation, the argument is that channel bodies become buried before the active channel returns to erode or re-occupy the channel site on the alluvial plain. During low accommodation, channels comb through their own deposits and are more likely to develop amalgamated, laterally offset, sand bodies. Channel return depends on the pattern of avulsion.

The condition of high accommodation may be defined as a time during which, in some locations, floodplain sedimentation proceeds through at least several channel cycles without evidence of a channel return. The presence of a paleosoil of any level of maturity indicates low accommodation, whereas levees, crevasse plays or pond deposits all indicate normal floodplain accumulation. The distinction between high and low accommodation is therefore a question of the balance between the rate of subsidence/sedimentation and the rate of avulsion. High accommodation may be defined as occurring when channels become completely buried before a channel or meander belt returns to the same location. This will occur whenever ($a * r * R_s$) > h, where a = avulsion frequency, r = the number of avulsion events which occur before the channel/meander belt returns to the same location on the floodplain, R_s = sedimentation rate in m/yr, and h = channel depth. The Bridge and Leeder models use 1000 yrs as a typical avulsion frequency, whereas Stouthamer and Berendsen (2007) demonstrate that in the Rhine-Meuse system the frequency is about 500 yrs. If we set h = 5 m, a = 1000, and r = 5, for continuous floodplain sedimentation to occur (the condition for high-accommodation), R_s must be >0.001 m/yr (1 m/ka = 10^0 m/ka). An extreme case may be imagined, where it takes 10 avulsion events (10,000 years) for a channel return to occur, in which case the sedimentation rate must be > 0.5 m/ka (10^{-1} m/ka). These rates are consistent with modern data from actual Recent and post-glacial alluvial systems (Miall, 2014a,b).

In brief, the Bridge and Leeder model is based on measurements of processes in modern and post-glacial river systems, including channel aggradation and avulsion, and the development and switching of channel belts, at a time scale of 10^3-10^4 years, and sedimentation rates of 10^0-10^{-1} m/ka. These are rates and time scales characteristic of long-term geomorphic processes, encapsulated by Miall (2014a) as Sedimentation Rate Scale (*SRS*) *7* to *8*. As discussed in the next section, these rates are typically at least an order of magnitude more rapid than the rates that may be deduced from modern chronostratigraphic studies of the ancient record.

Castlegate Sandstone (Upper Cretaceous, Book Cliffs, Utah)

The Campanian portion of the Sevier clastic wedge, in the classic area of the Book Cliffs (Utah-Colorado) has long been interpreted as the product of repeated thrust loading along the Sevier fold-thrust belt. Aschoff and Steel (2011) calculated rates of coastal progradation and rates of sediment accumulation. The central portion of the section, which they term Wedge B, and which includes most of the Castlegate Sandstone, yields an accumulation rate 47 m/my (= 0.047 m/ka) over 1.92 my.

Robinson and Slingerland (1998, Fig. 3) defined the stratigraphy slightly differently. Their Castlegate sequence, comprising 200 m of section at the type section (Price Canyon) was deposited in 4 my, yielding an accumulation rate of 0.05 m/ka. These rates are at order of magnitude 10^{-2} m/ka, and correspond to SRS 9 or 11 of Miall (2014a), up to two orders of magnitude slower than the rates on which current sequence models are based.

Olsen et al. (1995) subdivided the Campanian to Paleocene strata of the Book Cliffs into five sequences, of which the Castlegate Sandstone comprises one. They defined and subdivided the sequences based on a contrast between sandstone-dominated successions at the top and base of the sequences (low accommodation sections), and shale-rich middle portions (the "high-accommodation" Upper Castlegate unit), in which some evidence of tidal influence is present, in the form of tidal bedding and *Skolithos* traces. The gradation between these contrasting facies assemblages was attributed to increasing and decreasing rates of base-level rise (Olsen et al., 1995, Fig. 10). Their model is illustrated here in Fig. 1.

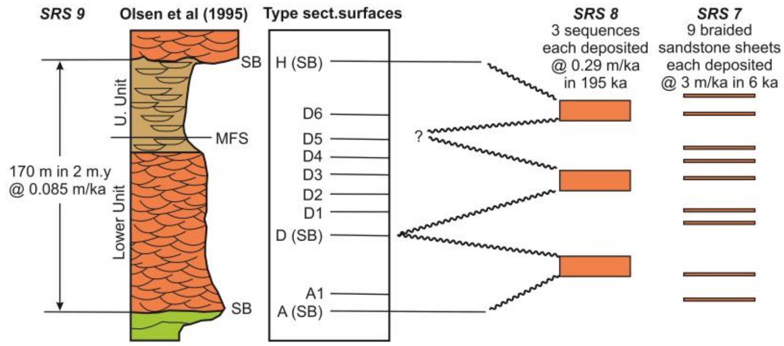

Fig. 1. Different interpretations of the Castlegate Sandstone at the type section. See text for explanation (from Miall, 2014c).

Olsen et al. (1995, p. 276) state that "A similar model with a similar structure and dominance of the transgressive aspects, with more weight to the positions and maturity of soils within a fluvial sequence, has been developed by Wright and Marriott (1993)." However, the sedimentation rates calculated above cannot be reconciled with this type of changing accommodation model. Avulsion periodicity (channel return rate) in modern systems is around 10^4 years and does not vary by orders of magnitude from this range in natural systems. Therefore, at sedimentation rates corresponding to *SRS 9* and *11*, channels will always return to a former position before the earlier deposit is buried, and therefore amalgamated architectures are always to be expected.

The sedimentological observations of Olsen et al. (1995, Fig. 10) and Yoshida (2000) require a different interpretation. Whereas a model based on changing rates of accommodation will not work, one base on shifting facies belts does. Sea-level change or tectonic adjustments to accommodation may cause influx and retreat of marine influence. Intraplate stress changes can generate accommodation at 0.01 to 0.1 m/ka at time scales of 10^6 yrs., which is within the range of *SRS 9-11*. Episodic thrust loading within a foreland-basin setting may generate regional basement adjustments at a higher rate. This would be consistent with the regional model of Aschoff and Steel (2011).

I have not been able to replicate the two-part subdivision of the Castlegate Sandstone proposed by Olsen et al. (1995), at least, not at the type section. The bounding surfaces there are repeated in Fig. 1 (the lettering is shown for convenience, using the original labels A, D and H from Miall and Arush, 2001a). The type section consists of a succession of braided sandstone sheets bounded by surfaces of at least 5th-order rank, in the terminology of Miall (1996). At least one of these, surface D of Miall and Arush (2001a), is interpreted as a sequence boundary (a 6th order surface) but we have no evidence about the greater or lesser significance of the other surfaces in this outcrop. More than one could be "cryptic" sequence boundaries, in the terminology of Miall and Arush (2001b).

At the right hand side of Fig. 1, two other scenarios for the Castlegate Sandstone are shown. One shows a version of Bhattacharya's (2011) speculation about three Castlegate sequences. The sequence boundary between the two lower sequences is correlated to surface D at the type section. The upper sequence boundary cannot be located in the type section. None of the surfaces between D and H exhibit any features, such as cut-and-fill relief, extensive lag deposits, or evidence of early cementation that would indicate their significance. This could be a characteristic of a "cryptic" sequence boundary, of the type suggested by Miall and Arush (2001b). The three sequences are envisaged as sequences formed at *SRS 8* rates, deposited at average sedimentation rates of 0.29 m/ka and each representing 195 ka of elapsed time. As seen in Fig. 1, this leaves a substantial amount of "Castlegate" time unrepresented, with only 29% of the 2 m.y. of time allotted to this formation represented by sediments, at the *SRS 8* time scale. The sequences would likely represent a response to allogenic forcing, such as flexural loading and/or changes in intraplate stress.

Another interpretation of the Castlegate Sandstone is that it consists simply of a set of unrelated braided sandstone sheets, some formed successively over a limited time range, some separated by longer intervals such as the unconformity represented by surface D. These would represent long-term geomorphic processes, and should be evaluated at *SRS 7*. This is how they are presented at the right side of Fig. 1. Nine braided sandstone sheets, averaging 19 m thick (bounded by the ten surfaces A to H at the type section), accumulating at an average *SRS 7* rate of 3 m/ka would require in total only 57 ka to accumulate, which is less than 3% of the 2 m.y. age range of the Castlegate Sandstone. Each sheet would represent an average of about 6 ka. How to account for the remaining elapsed time? Intervals of non-deposition/erosion between each sheet would average 216 ka. The sandstone sheets are probably accidental remnants of long-lived braid-plain deposits across which temporary sediment storage and remobilization were the norm, with preservation only taking place because of abandonment following avulsion events. The lengthy intervals between each sheet have not left any identifiable signature, such as mature paleosoils, or evidence or early cementation (except for surface D) or of deep erosion.

Discussion

Several other examples of ancient fluvial sequences interpreted using the standard sequence models of Wright and Marriott (1994) and Shanley and McCabe (1994) are discussed in Miall (2014b, Chap. 6). In each, there is an orders-of-magnitude difference in sedimentation rates between those measured from modern sediments and the post-glacial record, and those recorded from the ancient geological record. The high-frequency processes that form the basis for the Bridge and Leeder models, based in turn on the post-glacial record, are not preserved from the more remote geological past. High accumulation rates occur regionally in only a very few geological settings, such as in the source-proximal corners of some convergent-margin basins, and it requires special circumstances for the shorter-term high frequency processes that constitute *SRS 1* to *7* to achieve long-term preservation. Therefore, **in a significant way the present is not the key to the past.**

Gibling (2006, p. 761) made a related point. Focusing on the many controls on alluvial architecture, including discharge, sediment supply, bank materials, and so on, he warned that: “The recent tendency in sequence stratigraphy to relate channel-body form to accommodation (e.g., Shanley and McCabe 1994) is thus subject to many caveats.” There is not necessarily a simple relationship between forcing processes and a stratigraphic result. Gibling et al. (2011, p. 439-441) offered similar comments, suggesting that the alluvial stacking pattern on which accommodation models have been based may in fact be controlled by climate change or changes in fluvial paleogeography unrelated to subsidence rates. They suggested that the Quaternary record, characterized by an icehouse climate, with high-magnitude and high-frequency environmental change, is not necessarily a good model for interpreting the ancient record. Valleys formed by glacial sea-level cycles during the Neogene are likely to be a more prominent part of the coastal sedimentary record than during the Mesozoic, for example, when it assumed that glacioeustasy was of minor importance to non-existent.

It is argued here that systematic stratigraphic changes in alluvial architecture in the ancient rock record are not the product of changing avulsion rates and changes in fluvial style under the influence of variable rates of accommodation, but reflect regional shifts in facies belts, that themselves are a response to tectonism and to changes in accommodation and other variables (climate, discharge, sediment supply, etc.) at much slower rates, by one to several orders of magnitude, than those assumed for the simulation models. Interpretations of channel density, spacing, stacking and interconnectedness need to be re-thought on this basis.

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