

# **The Emptiness of the Stratigraphic Record: A Preliminary Evaluation of Missing Time in the Mesaverde Group, Book Cliffs, Utah\***

**Andrew D. Miall<sup>1</sup>**

Search and Discovery Article #51081 (2015)

Posted March 30, 2015

\*Adapted from extended abstract prepared in conjunction with an oral presentation given at the 2014 GeoConvention, Calgary, Alberta, Canada, May 12-16, 2014, GeoConvention/Datapages © 2015

<sup>1</sup>Department of Earth Sciences, University of Toronto, Toronto, Ontario M5S 3B1 ([miall@es.utoronto.ca](mailto:miall@es.utoronto.ca))

## **Summary**

Observations of modern sedimentation rates in nonmarine and shallow-marine clastic environments indicate that deposits formed in comparable settings in the ancient record could accumulate in a fraction of the time that would appear to be available according to conventional chronostratigraphic dating methods. Typically as little as 10% of elapsed time is represented by sediment, the remainder by breaks in sedimentation, many of which are inconspicuous. In the Book Cliffs of eastern Utah, ravinement surfaces may each account for up to 105-years of missing time. Coastal deltaic and nonmarine successions are considered to be particularly fragmentary. In the sedimentary record of shallow-marine and nonmarine deposits stratigraphic continuity is not to be expected, and calculation of time-related issues, such as mass-balance transport rates and the trajectories of shoreline transgression and regression, must take this into account.

## **Introduction**

In several influential books, Ager (1973, 1993) argued that “the sedimentary record is more gap than record.” He noted that many sedimentary units are deposited over very short periods of time and that the record is replete with gaps, the significance of which commonly goes unrecognized. Such gaps may, in total, represent more elapsed time than that of the preserved sediment. Observations of modern sedimentation rates in nonmarine and shallow-marine clastic environments indicate that deposits formed in comparable settings in the ancient record could accumulate in a fraction of the time that would appear to be available according to conventional chronostratigraphic dating methods.

Miall (1991, 2013a), building on Sadler (1981, 1999) argued that there is a natural hierarchy of process and preservation based on the natural time scales of sedimentary processes, and in the latter paper proposed the erection of a formal set of *Sedimentation Rate Scales (SRS)* as a basis for analysis at the appropriate time scale ([Figure 1](#)). Stratigraphic and sedimentologic studies ranging from the micro-scale to the regional, and based on time scales ranging from the short-term (e.g., studies of processes in laboratory models or modern settings) to the long-term (e.g., the evolution of major sedimentary basins), are best carried out and understood geologically at the appropriate *SRS*.

## The Mesaverde Group

The Mesaverde Group is well-exposed in the Book Cliffs of east-central Utah and western Colorado. It constitutes a classic foreland basin clastic wedge, which developed in response to uplift and erosion along the Sevier Orogen during the Late Cretaceous. A resistant, nonmarine sandstone, the Castlegate Sandstone, constitutes a prominent cliff-forming unit that caps the cliffs over a distance of about 200 km ([Figures 2 and 3](#)).

The Mesaverde Group encompasses two formations, the Blackhawk and the Castlegate. The Blackhawk Formation consists of undifferentiated fluvial and deltaic deposits in the western Book Cliffs (Hampson et al., 2013), and passes eastward into a series of shoreface to shallow-marine tongues that were assigned to six members by the early stratigraphic workers ([Figure 3](#)). Van Wagoner et al. (1990) established the six members of the Blackhawk Formation as sequences, at a time when most sequences were interpreted as the product of eustatic sea-level change. But these units have subsequently been much discussed as examples of a type of high-frequency sequence stratigraphy that may have had a different origin, with regional tectonism and its effect on accommodation being the most favoured alternative (e.g., Krystinik and DeJarnett, 1995; Aschoff and Steel, 2011).

The Castlegate Sandstone, named after the Castle Gate, a prominent landmark in the canyon north of Price, was interpreted as a third-order sequence by Olsen et al. (1995), but comprises two sequences, according to Miall and Arush (2001a), although, as suggested by Bhattacharya (2011), and as discussed later, other interpretations must be considered.

The age range of the Mesaverde Group and its constituent units has been interpreted primarily from the ammonite fauna contained in the marine portions of the Blackhawk and in the Mancos Shale, with which it is interbedded to the east. Hampson (2010), Aschoff and Steel (2011) and Seymour and Fielding (2013) provided overviews of the biostratigraphic and other work that have been carried out on these rocks since mapping began in the 1920s. Three of the ammonite zones can be correlated to the global time scale, providing numerical-age tie points. The following data are taken from Aschoff and Steel (2011).

The base of the Blackhawk Formation is early Campanian in age and is dated at 81.86 Ma. The top is placed at 79 Ma, and the top of the Castlegate is middle Campanian, at 77 Ma. The time span of the Mesaverde Group is therefore 4.86 my. Near Price the section is up to 700 m thick, which indicates an average sedimentation rate of 0.14 m/ka. This rate ( $10^{-1}$  m/ka) is at the upper end (more rapid) of rates characteristic of long-term geological subsidence measured over periods of  $10^5$ - $10^7$  yr, including thermal subsidence and flexural loading of the crust (*SRS 10-11*), and is comparable to rates associated with low-frequency orbital cycles (*SRS 9*) (Miall, 2013a). If all six members of the Blackhawk plus the two constituent sequences of the Castlegate Formation are assumed to represent equal time spans (for which there is no evidence), this equates to an average duration of 607 ka per unit, a value that corresponds to no known geological frequency, such as that of orbital cycles. Furthermore, each of the members has now been subdivided into submembers, totalling 23 for the Blackhawk Formation (the individual shoreface tongues in [Figure 3](#)), averaging 125 ka in duration. This is close to the time range of low-frequency orbital cycles (the so-called 4th-order cycles), although there is nothing about the thickness or arrangement of the submembers to suggest the regularity that is normally associated with orbital cyclicity. At this time there is no method by which the ages and time spans of the constituent units of the Mesaverde Group may be individually dated with greater precision.

A speculative chronostratigraphic chart for the Mesaverde Group that includes the suggestion of significant gaps at the sequence boundaries is presented here as [Figure 4](#). This follows the approximate timing of the sequence boundaries shown by Hampson (2010, Figure 7), but otherwise differs substantially from that chart in the following principal ways:

(1) In the updip coastal-plain region represented by the Blackhawk Formation, most of the elapsed time is completely unrepresented. Some of this unit consists of fluvial deposits formed above marine base level (Hampson et al., 2013) and here, accommodation may be explained by the buffer concept of Holbrook et al. (2006). These deposits are shown schematically in [Figure 4](#).

(2) The arrangement of sequence boundaries in Hampson's (2010, Figure 7) suggests that the completeness of the Blackhawk and the contemporary shallow-marine record (that of the Blackhawk members) decreases basinward, whereas the opposite is more likely to be the case. Sedimentation of the Mancos Shale towards the basin centre is likely to be much more continuous and therefore more complete at the  $10^4$ - $10^6$  time scale than the proximal sediments of the coastal region, but may contain substantial unconformities, as shown in [Figure 4](#). The pattern shown here is more like that developed by Krystinik and DeJarnett (1995, Figure 3), in which it was suggested that the proximal region to the west of the basin was a region of uplift and erosion. Units of condensed (slow) sedimentation may be expected to develop offshore at times of regional transgression, and there is also evidence that sediment-gravity flows occurred on distal clinoform slopes during the falling stage of some of the sequence cycles (shown by Hampson (2010, Figure 7), but not included in [Figure 4](#)).

(3) Following from the previous point, the time span represented by the member (sequence) boundaries increases landward, and the undifferentiated proximal, deltaic Blackhawk formation represents, in total, much less than one half of the available elapsed time, with substantial erosional breaks embedded in this coastal succession.

### **Chronostratigraphy of the Spring Canyon and Aberdeen Members**

The next step in this analysis is to examine sedimentation rates and preservation at shorter time scales. *SRS 7* is the time scale for long-term geomorphic processes, those occurring over time periods of  $10^3$ - $10^4$  years. Such processes include the development of major delta lobes and alluvial channel belts, regressive shoreface complexes, major coal seams, etc.

Sedimentation rates that have been calculated for such deposits include the following examples of post-glacial successions (details in Miall, 2013a): Fluvial channel aggradation in coastal-plain rivers in Texas, up to 1.7 m/ka; modern floodplain rates compiled by Bridge and Leeder (1979) as the basis for their simulation experiments, 0.35-2 m/ka; the Holocene Mississippi Delta, 6-12 m/ka; Rhone delta, 6.1 m/ka; Rhine-Meuse system, 1.5 m/ka; Galveston barrier island, 3.4 m/ka; Sapelo Island tidal inlet, 4.5 m/ka. The rate of post-glacial sea-level change is comparable, at 1-18 m/ka. All of these rates are in the range of  $10^0$ - $10^1$  m/ka, which is up to an order of magnitude greater than the *SRS 8* range that applies to high-frequency orbital cycles, and up to two orders of magnitude greater than long-term geological rates (*SRS 11*).

To study sedimentation at this scale, a detailed examination is presented here of the Spring Canyon Member at the Spring Canyon section, located west of Helper ([Figure 5](#); location shown in [Figure 2](#)). The section is shown in the traditional form, as a continuous succession of facies units, just as it appears in actuality in the field. However, as first pointed out by Barrell (1917), this form of plot obscures the numerous cryptic hiatuses that permeate all stratigraphic sections.

In [Figure 5](#) units 1-15 are plotted against an *SRS 8* time scale. At an *SRS 8* sedimentation rate of 0.29 m/ka, the 79.2 m of section shown in this figure would represent 273 ka of elapsed time. The same fifteen units are shown at the right re-plotted using *SRS 7* rates. At an *SRS 7* sedimentation rate range of 1.5-6 m/ka, this 79.2 m of section would accumulate over a time span of between 52.8 ka and 13.2 ka. A mid-range of 27 ka used here (arbitrarily) as an average for illustration, is one tenth the time assumed for the sequences timed at the longer-term *SRS 8* rate in the previous section (and comparable to the 7% of elapsed time represented by sediment that was calculated by de Natris (2012)). How is preservation and non-preservation distributed through the estimated 273 ka represented by the section?

As suggested in [Figure 5](#), and following all previous interpretations, the section may be interpreted in terms of four progradational successions. Using the same lithofacies unit numbers as in the original section, these are displayed at the right in this figure. Three regressive shoreface successions, the last capped by a coal swamp, were followed by a progradational delta.

At the *SRS 7* scale, the most significant time-related events represented in the Spring Canyon outcrops are the ravinement surfaces that cap the shoreface successions and include the surfaces that cap each of the Blackhawk constituent members. Ravinement occurs during a rise in relative sea-level. Nummedal and Swift (1987) described various examples of ravinement developed during post-glacial sea-level rise, a process that during the Holocene continued for thousands of years. We cannot know the duration of this process during the Cretaceous, but we may speculate. The driving process for episodicity in stratigraphic accommodation seems likely to include flexural subsidence and changes in intraplate stress (Aschoff and Steel, 2011). These are processes that operate over rates and time scales in the *SRS 8-9* range, that is, time periods of  $10^4$ - $10^6$  years. It is conceivable, therefore, that the ravinement and flooding process that preceded each of the progradational shoreface successions could have taken many tens of thousands of years, a significant proportion of the time available for each of these cycles.

### **Chronostratigraphy of the Nonmarine Facies of the Blackhawk Formation and Castlegate Sandstone**

The first sequence-stratigraphic analysis of the Castlegate Sandstone was carried out by Olsen et al. (1995). They divided the formation near the type section (Castle Gate, at the mouth of the Price River Canyon, north of Helper; location shown in [Figure 2](#)) into a lower, sandstone-dominated member, deposited in a braided-stream environment, following the fluvial architectural analyses of Miall (1993, 1994), and an upper member containing a significant proportion of interbedded mudstones, units of inclined heterolithic strata (terminology of Thomas et al., 1987), and evidence of marine, tidal influence in the form of flaser bedding and *Skolithos* burrows. They interpreted the formation thus subdivided as a “third-order” sequence. To explain the subdivision into the two members Olsen et al. (1995) turned to the fluvial models of Wright and Marriot (1993) and Shanley and McCabe (1994). The sandstone-rich lower member and the more heterogeneous upper member were interpreted, respectively, as low- and high-accommodation systems tracts. Miall (2013b) has argued that such interpretations are untenable, given the issue of dramatically different sedimentation rates for the models and for the Castlegate Sandstone.

In a further analysis McLaurin and Steel (2000) subdivided the upper member into five higher order (fourth order) sequences and mapped a transition within these sequences between the fluvial deposits in the west into barrier, deltaic, and estuarine deposits near Green River, and ultimately into the offshore mudstones of the Buck Tongue. However, Willis (2000), who recognized a high-frequency sequence stratigraphy in the Sego Sandstone east of Green River, was unable to trace these sequences westward into the predominantly fluvial upper Castlegate Sandstone.

In an alternative analysis based on detailed mapping north of Green River, Yoshida et al. (1996), Willis (2000) and Yoshida (2000) argued that the Buck Tongue is truncated by the upper member of the Castlegate, at an angular unconformity that cuts gradually down section along the Book Cliffs to the northwest. According to this interpretation (shown in [Figure 6](#)) the beds overlying the unconformity above the Buck Tongue in the east (Sego Sandstone) are stratigraphically equivalent to the upper part of the lower Castlegate Sandstone at the type section. As noted by Miall and Arush (2001a), based on this interpretation, the truncation of the Buck Tongue implies that updip from the pinch-out of this unit, approximately 1 m.y. of section are missing in proximal parts of the Book Cliffs, including at the type section of the Castlegate Sandstone.

The evidence to enable a choice to be made for any of these interpretations depends on the ability to trace (“walk out”) key surfaces between sections. Even in the case of the Book Cliffs, where exposure is much better than average, it is not possible reliably to trace key surfaces based on facies and outcrop characteristics for long distances within what is a very heterogeneous succession. Accordingly, Miall and Arush (2001a) sought to develop other means to analyse the stratigraphy and determined, on the basis of petrographic evidence, that the best evidence for missing time at the type section consists of changes in detrital composition and evidence for early cementation at surface “D” in the type section ([Figure 7](#)). According to this interpretation, the lower Castlegate at this location comprises parts of two sequences (sequences 1 and 2 in [Figure 6](#)), and the upper part of this unit at the type section passes laterally (downdip) through a facies transition into the more heterogeneous beds of the upper Castlegate and the Sego Sandstone to the east and southeast (Willis, 2000).

Yet another interpretation of Castlegate sequence stratigraphy was offered by Bhattacharya (2011, Figure 7), in which he speculated about the relationship between the lower Castlegate Sandstone and the underlying Desert Member in the area east of Green River. The original interpretation of Van Wagoner et al. (1990) and Van Wagoner and Bertram (1995) was that the Desert member is entirely older than the Castlegate. However, Bhattacharya (2011), referring to a discussion by Van Wagoner and Bertram (1995) about the whereabouts of the coastal marine equivalents of the Castlegate fluvial sandstones (i.e., where are the mouths of the Castlegate rivers?), suggested that the Castlegate may in fact comprise a suite of high-frequency sequences, each with its own attached “Desert” shoreface (Bhattacharya, 2011, Figure 8). Again, this is a debate that could only be answered by detailed local correlations for which the evidence is not available, and a definitive answer is beyond the scope of this article to provide. However, we may speculate. It is entirely possible that the Castlegate Sandstone consists of a set of sequence fragments, number unknown.

[Figure 8](#) represents a speculative attempt to account for the distribution of elapsed time between preserved deposits and bounding surfaces in the Castlegate Sandstone at the type section. On the left of it is the sequence model of Olsen et al. (1995). The interpretation of the two-part succession in terms of low- and high-accommodation depositional environments is not consistent with the data now available on the relationship between channel migration and avulsion rates and rates of accommodation (Miall, 2013b, Section 6.2). Fluvial sequence models, such as those of Wright and Marriott (1993) and Shanley and McCabe (1994) are based on observations at *SRS-7* rates, that is, a time scale of  $10^3$ - $10^4$  years, and sedimentation rates of  $10^0$ - $10^1$  m/ka. They used modern studies and simulations that assume an accommodation rate up to three orders of magnitude more rapid than is typically represented in the preserved ancient record.

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 Figure 8 (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 (Miall, 1993), 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 (2001a,b).

At the right hand side of [Figure 8](#), 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 [Figure 8](#), 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 Figure 8. 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 of early cementation (except for surface D) or of deep erosion. As Willis (2000, Figure 7) demonstrated, paleocurrent patterns shifted significantly during deposition of the Castlegate Sandstone, from southeasterly during the deposition of sequence 1 (sequence definitions as in [Figure 6](#)), to S to SSE in sequence 2, to E to NE in sequence 3. Such shifts presumably reflect subtle tectonic tilts in regional paleoslope, and could have facilitated switches in local flow directions, particularly where aggradation of a channel belt created slope advantages for alternative flow directions, the same type of process that leads to the fan shape of alluvial fans and the distributary pattern of deltas. Some of the younger sheets contain evidence of tidal influence, indicating a slow but steady rise of sea level during the deposition of this formation.

It is possible that both the *SRS 8* and *SRS 7* scenarios of [Figure 8](#) are correct, with the latter nested within the former. In other words, the Castlegate Sandstone consists of sequences that are themselves composed of unrelated braided sandstone sheets.



## **Conclusions**

When sedimentation rates for modern equivalents of the nonmarine to shallow-marine environments in which the Mesaverde Group was deposited are applied to the preserved facies successions that comprise this group, less than 10% of the 4.86 m.y. elapsed time represented by the group can be accounted for. The remainder is “missing” at bedding planes and other bounding surfaces of all types, a pattern predicted by Sadler (1999). In the shallow-marine environment, widespread non-deposition or erosion is thought to have preceded ravinement and the development of flooding surfaces from which shoaling-upward successions (parasequences) then prograded. In the Mesaverde Group there are 23 such major surfaces that define the boundaries of the six members and submembers. Each of these could account for a time span of up to ~100,000 years. The major sequence boundary at the base of the Castlegate Sandstone, which can be traced for more than 150 km eastward into Colorado, could represent as much as 1 m.y., and the surface that truncates the Buck Tongue could also represent a comparable interval of missing time. Many other bounding surfaces simply represent long-term sediment bypass, with no net accumulation. The Castlegate Sandstone may consist of a set of unrelated fragments of braided sandstone sheets separated by significant erosional or non-depositional breaks.

Analyses of long-term processes, including mass-balance transport models, and interpretations of shoreline trajectories through time, need to take into account the fact that far more time is missing than is represented. Continuity is the exception in nonmarine and shallow-marine stratigraphy. Bounding surfaces are the “dark matter” of sedimentology. We know they are there, but means are not yet available for a complete analysis of their range of characteristics and time significance.

## **Acknowledgements**

Thanks are due to Ian Young and Cenovus and to Ron Boyd and ConocoPhillips for funding that made the project possible. Brian Pratt read an early draft of the paper and made many useful suggestions.

## **References Cited**

Ager, D.V., 1973, *The Nature of the Stratigraphical Record*: John Wiley, New York, 114 p.

Ager, D.V., 1993, *The New Catastrophism*: Cambridge University Press, 231 p.

Aschoff, J.L., and R.J. Steel, 2011, Anomalous clastic wedge development during the Sevier-Laramide transition, North American Cordilleran foreland basin, USA: *Geological Society of America Bulletin*, v. 123, p. 1822-1835.

Barrell, J., 1917, Rhythms and the measurement of geologic time: *Geological Society of America Bulletin*, v. 28, p. 745-904.

Bhattacharya, J.P., 2011, Practical problems in the application of the sequence stratigraphic method and key surfaces: Integrating observations from ancient fluvial-deltaic wedges with Quaternary and modeling studies: *Sedimentology*, v. 58, p. 120-169.

Bridge, J.S. and M.R. Leeder, 1979, A simulation model of alluvial stratigraphy: *Sedimentology*, v. 26, p. 617-644.

Cole, R.D., and J.F. Friberg, 1989, Stratigraphy and sedimentation of the Book Cliffs, Utah, *in* D. Nummedal and R. Wright, R., editors, Cretaceous shelf sandstone and shelf depositional sequences, Western Interior Basin, Utah, Colorado, and New Mexico: Field Trip Guidebook T119, 28th International Geological Congress.

de Natris, M.F., 2012, Facies- and time-analysis of the upper part of the Brent Group (mid-Upper Jurassic) in the Greater Oseberg area, northern North Sea: M.Sc., thesis, University of Bergen, 90 p.

Hampson, G.J., 2010, Sediment dispersal and quantitative stratigraphic architecture across an ancient shelf: *Sedimentology*, v. 57, p. 96-141.

Hampson, G.J., T.O. Jewell, N. Irfan, M.R. Gani, and B. Bracken, 2013, Modest changes in fluvial style with varying accommodation in regressive alluvial-to-coastal-plain wedge: Upper Cretaceous Blackhawk Formation, Wasatch Plateau, central Utah, U.S.A.: *Journal of Sedimentary Research*, v. 83, p. 145-169.

Holbrook, J., R.W. Scott, and F.E. Oboh-Ikuenobe, 2006, Base-level buffers and buttresses: a model for upstream versus downstream control on fluvial geometry and architecture within sequences: *Journal of Sedimentary Research*, v. 76, p. 162-174.

Krystinik, L.F., and B.B. DeJarnett, 1995, Lateral variability of sequence stratigraphic framework in the Campanian and lower Maastrichtian of the Western Interior Seaway, *in* J.C. Van Wagoner and G.T. Bertram, editors, *Sequence Stratigraphy of Foreland Basins: AAPG Memoir 64*, p. 11-25.

McLaurin, B.T., and R.J. Steel, 2000, Fourth-order nonmarine to marine sequences, middle Castlegate Formation, Book Cliffs, Utah: *Geology*, v. 28, p. 359-362.

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

Miall, A.D., 1993, The architecture of fluvial-deltaic sequences in the Upper Mesaverde Group (Upper Cretaceous), Book Cliffs, Utah, *in* J.L. Best and C.S. Bristow, editors, *Braided Rivers: Geological Society, London, Special Publication 75*, p. 305-332.

Miall, A.D., 1994, Reconstructing fluvial macroform architecture from two-dimensional outcrops: Examples from the Castlegate Sandstone, Book Cliffs, Utah: *Journal of Sedimentary Research*, v. B64, p. 146-158.

Miall, A.D., 1996, *The Geology of Fluvial Deposits: Sedimentary Facies, Basin Analysis and Petroleum Geology*: Springer-Verlag Inc., Heidelberg, 582 p.



Miall, A.D., 2013a, Updating uniformitarianism: stratigraphy as just a set of “frozen accidents,” *in* D.G. Smith, R.J. Bailey, P. Burgess, and A. Fraser, editors, *Strata and Time: Geological Society, London Special Publication*.

Miall, A.D., 2013b, *Fluvial Depositional Systems: Springer-Verlag, Berlin, 316 p.*

Miall, A.D., and M. Arush, 2001a, The Castlegate Sandstone of the Book Cliffs, Utah: Sequence stratigraphy, paleogeography, and tectonic controls: *Journal of Sedimentary Research*, v. 71, p. 536-547.

Miall, A.D., and M. Arush, 2001b, Cryptic sequence boundaries in braided fluvial successions: *Sedimentology*, v. 48/5, p. 971-985.

Nummedal, D., and D.J.P. Swift, 1987, Transgressive stratigraphy at sequence-bounding unconformities: Some principles derived from Holocene and Cretaceous examples, *in* D. Nummedal, O.H. Pilkey, and J.D. Howard, editors, *Sea-level Fluctuation and Coastal Evolution; SEPM Special Publication 41*, p. 241-260.

Olsen, T., R.J. Steel, K. Høgseth, T. Skar, S.-L. Røe, 1995, Sequential architecture in a fluvial succession: sequence stratigraphy in the Upper Cretaceous Mesaverde Group, Price Canyon, Utah: *Journal of Sedimentary Research*, v. B65, p. 265-280.

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

Sadler, P.M., 1999, The influence of hiatuses on sediment accumulation rates: *GeoResearch Forum*, v. 5, p. 15-40.

Seymour, D.L., and C.R. Fielding, 2013, high resolution correlation of the Upper Cretaceous stratigraphy between the Book Cliffs and the western Henry Mountains Syncline, Utah, U.S.A.: *Journal of Sedimentary Research*, v. 83, p. 475-494.

Shanley, K.W., and P.J. McCabe, 1994, Perspectives on the sequence stratigraphy of continental strata: *AAPG Bulletin*, v. 78, p. 544-568.

Thomas, R.G., D.G. Smith, J.M. Wood, J. Visser, E.A. Calverley-Range, and E.H. Koster, 1987, Inclined heterolithic stratification - terminology, description, interpretation and significance: *Sedimentary Geology*, v. 53, p. 123-179.

Van Wagoner, J.C., and G.T. Bertram, editors, 1995, *Sequence Stratigraphy of Foreland Basin Deposits - Outcrop and Subsurface Examples from the Cretaceous of North America: AAPG Memoir 64, 489 p.*

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

Willis, A.J., 2000, Tectonic control of nested sequence architecture in the Sejo Sandstone, Neslen Formation, and Upper Castlegate Sandstone (Upper Cretaceous), Sevier Foreland Basin, Utah, USA: *Sedimentary Geology*, v. 136, p. 277-317.

Wright, V. P., and S.B. Marriott, 1993, The sequence stratigraphy of fluvial depositional systems: The role of floodplain sediment storage: *Sedimentary Geology*, v. 86, p. 203-210.

Yoshida, S., 2000, Sequence stratigraphy and facies architecture of the upper Blackhawk Formation and the Lower Castlegate Sandstone (Upper Cretaceous), Book Cliffs, Utah, USA: *Sedimentary Geology*, v. 136, p. 239-276.

Yoshida, S., A. Willis, and A.D. Miall, 1996, Tectonic control of nested sequence architecture in the Castlegate Sandstone (Upper Cretaceous), Book Cliffs, Utah: *Journal of Sedimentary Research*, v. 66, p. 737-748.

Young, R. G., 1955, Sedimentary facies and intertonguing in the Upper Cretaceous of the Book Cliffs, Utah-Colorado: *Geological Society of America Bulletin*, v. 66, p. 177-202.

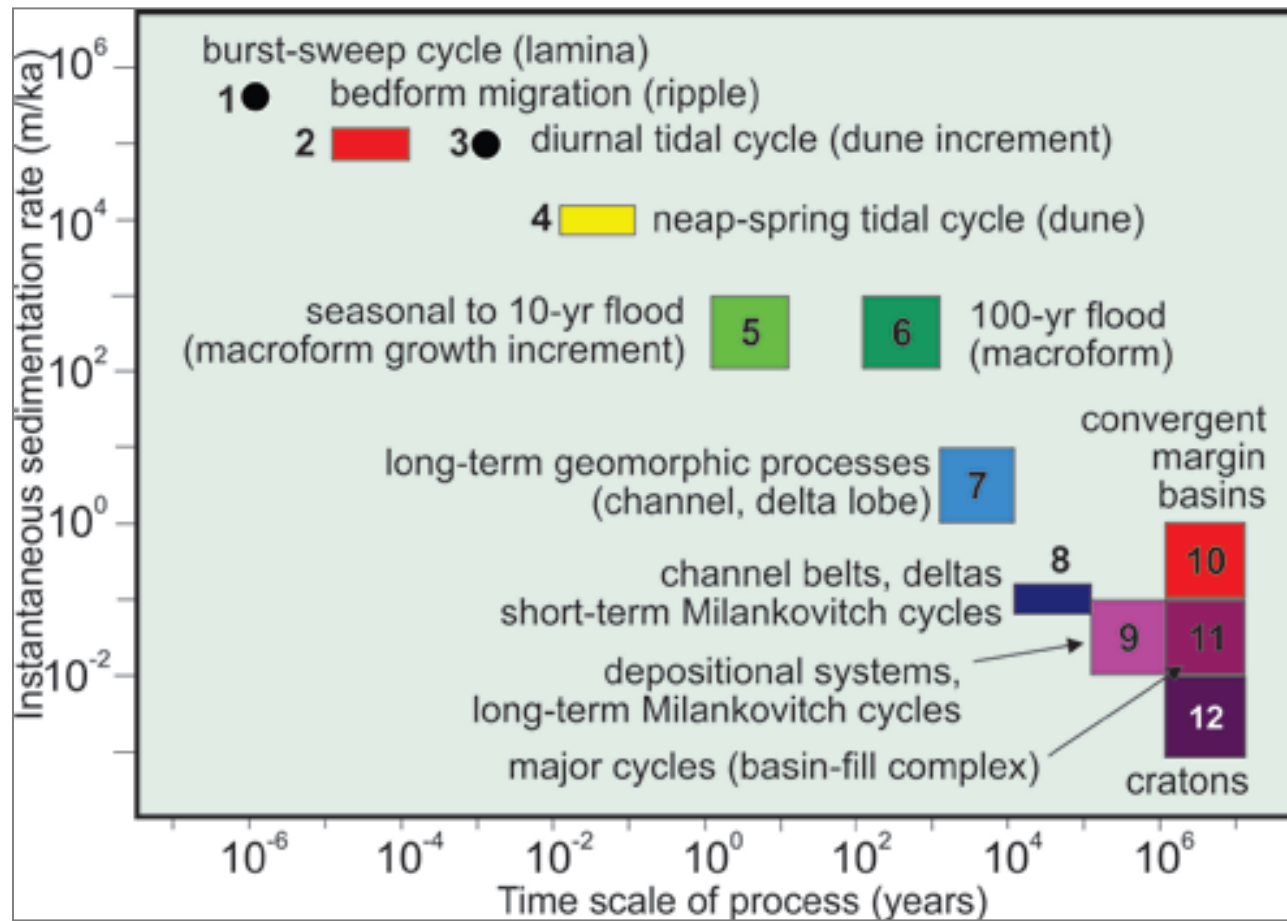


Figure 1. Rates and durations of sedimentary processes. Numerals refer to the Sedimentation Rate Scale of Miall (2013a).

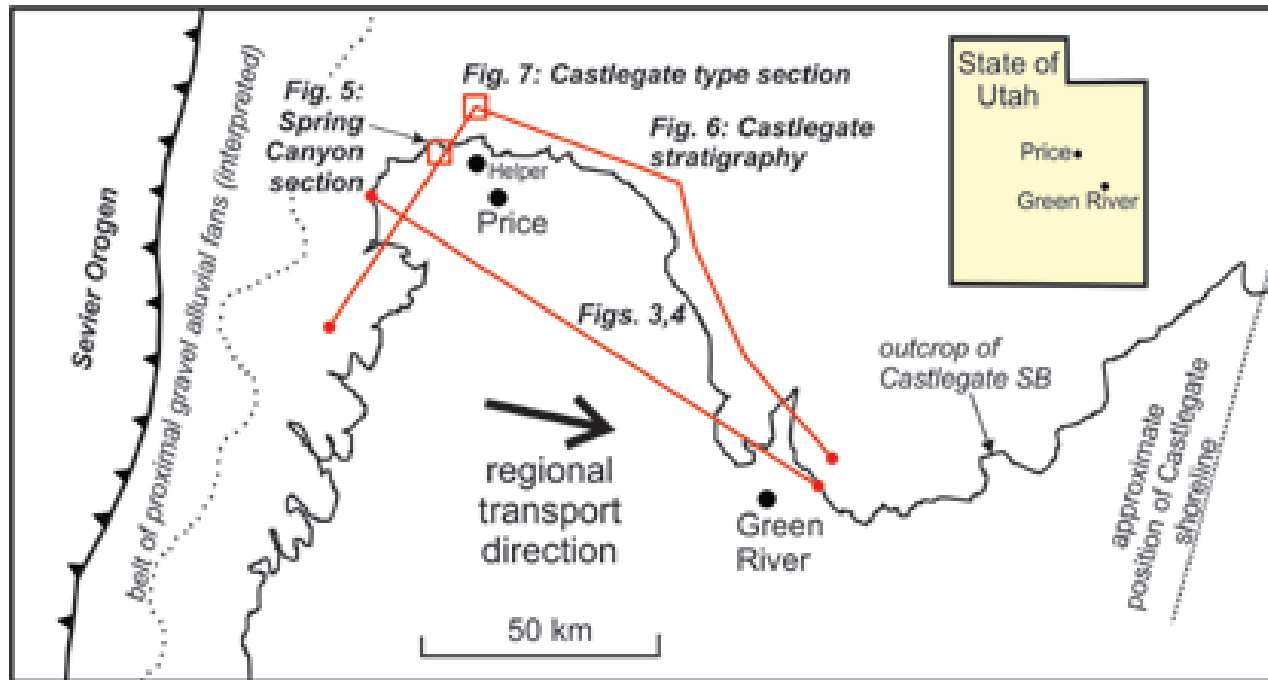


Figure 2. Location of study area, showing the locations of detailed sections and other illustrations.

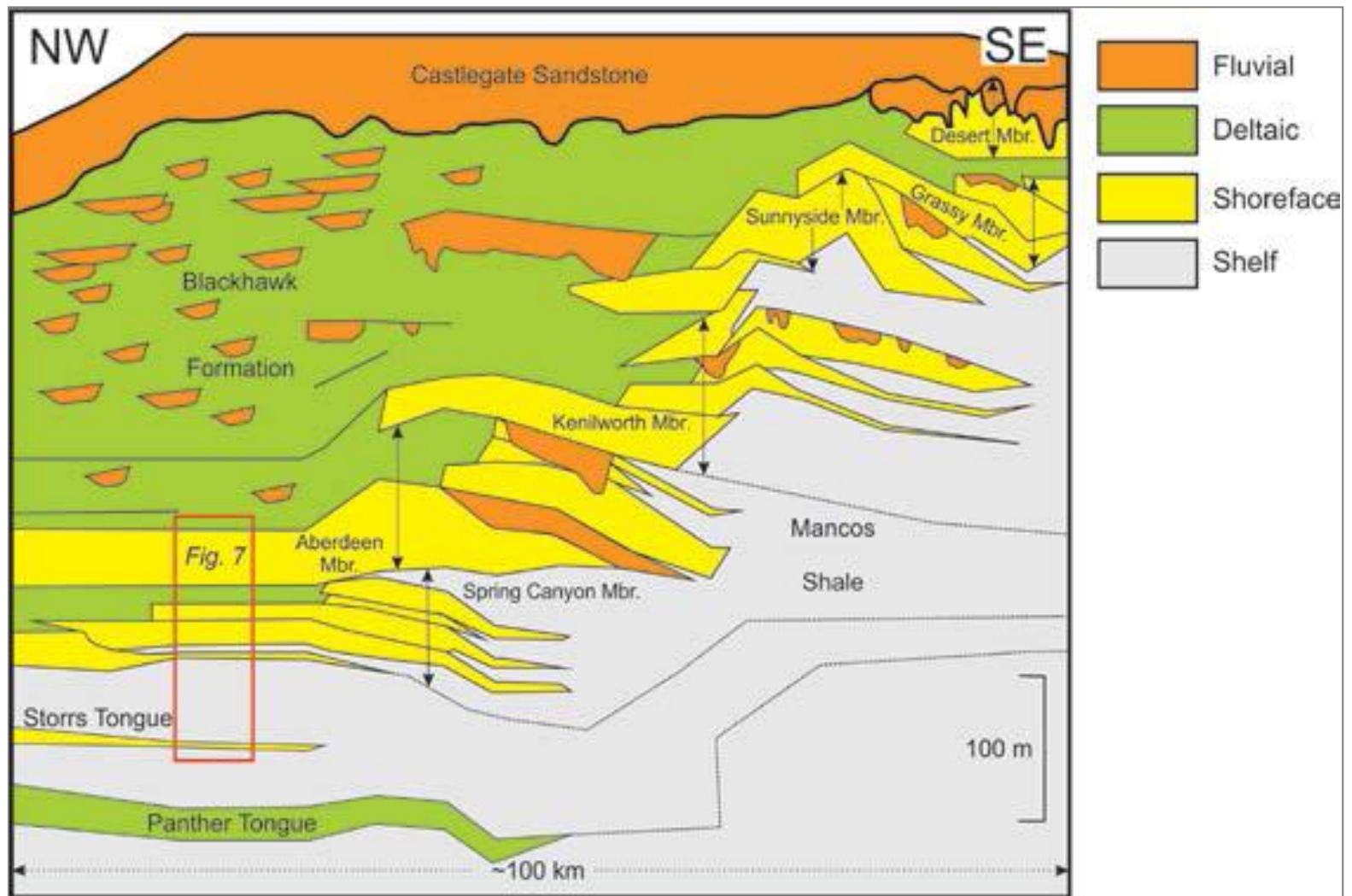


Figure 3. Regional cross-section of the Mesaverde Group; adapted from Seymour and Fielding (2013), after the detailed mapping of Young (1955).

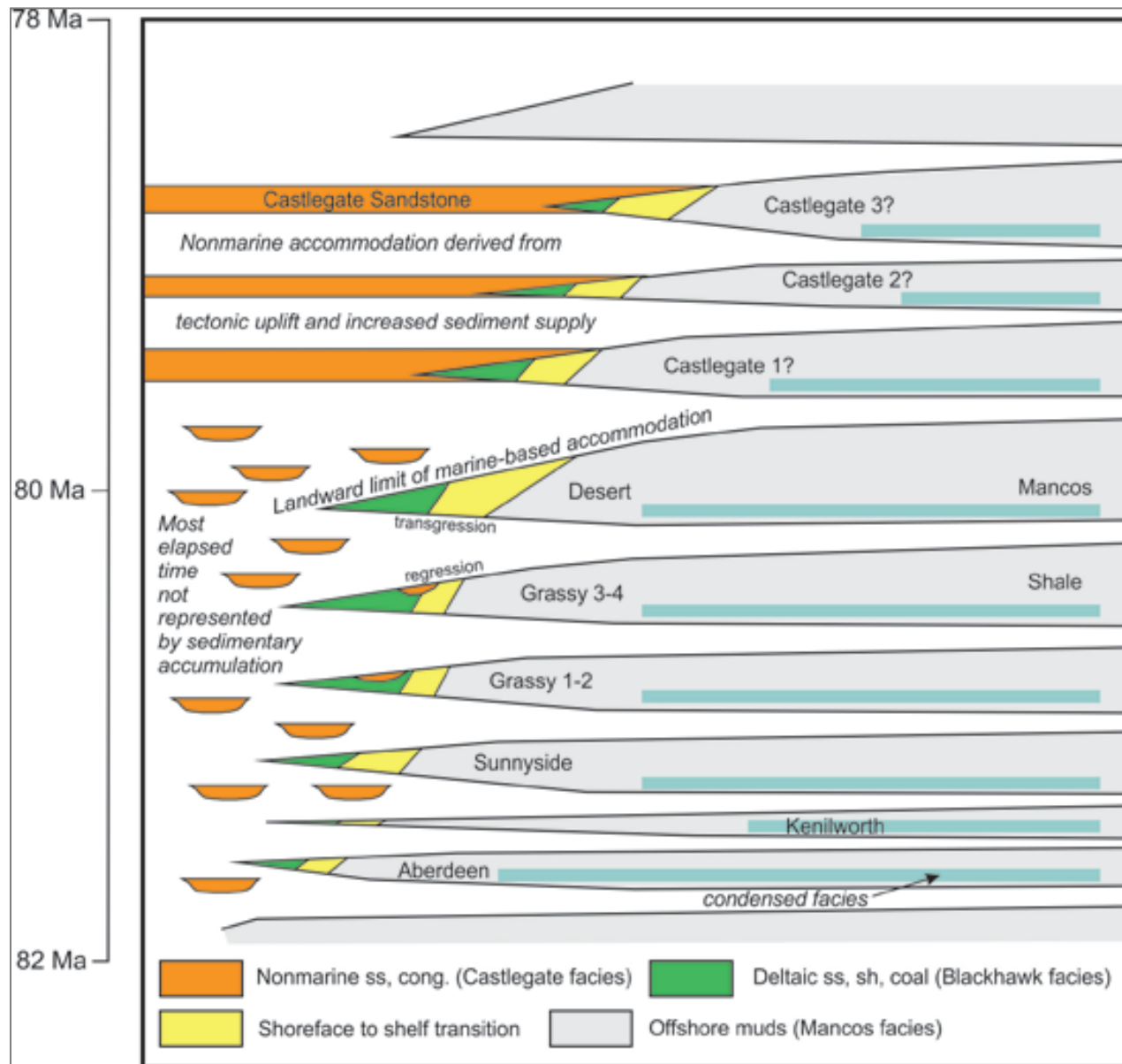


Figure 4. An interpretation of the chronostratigraphy of the Mesaverde Group. Age information is from Hampson (2010) and Seymour and Fielding (2013).

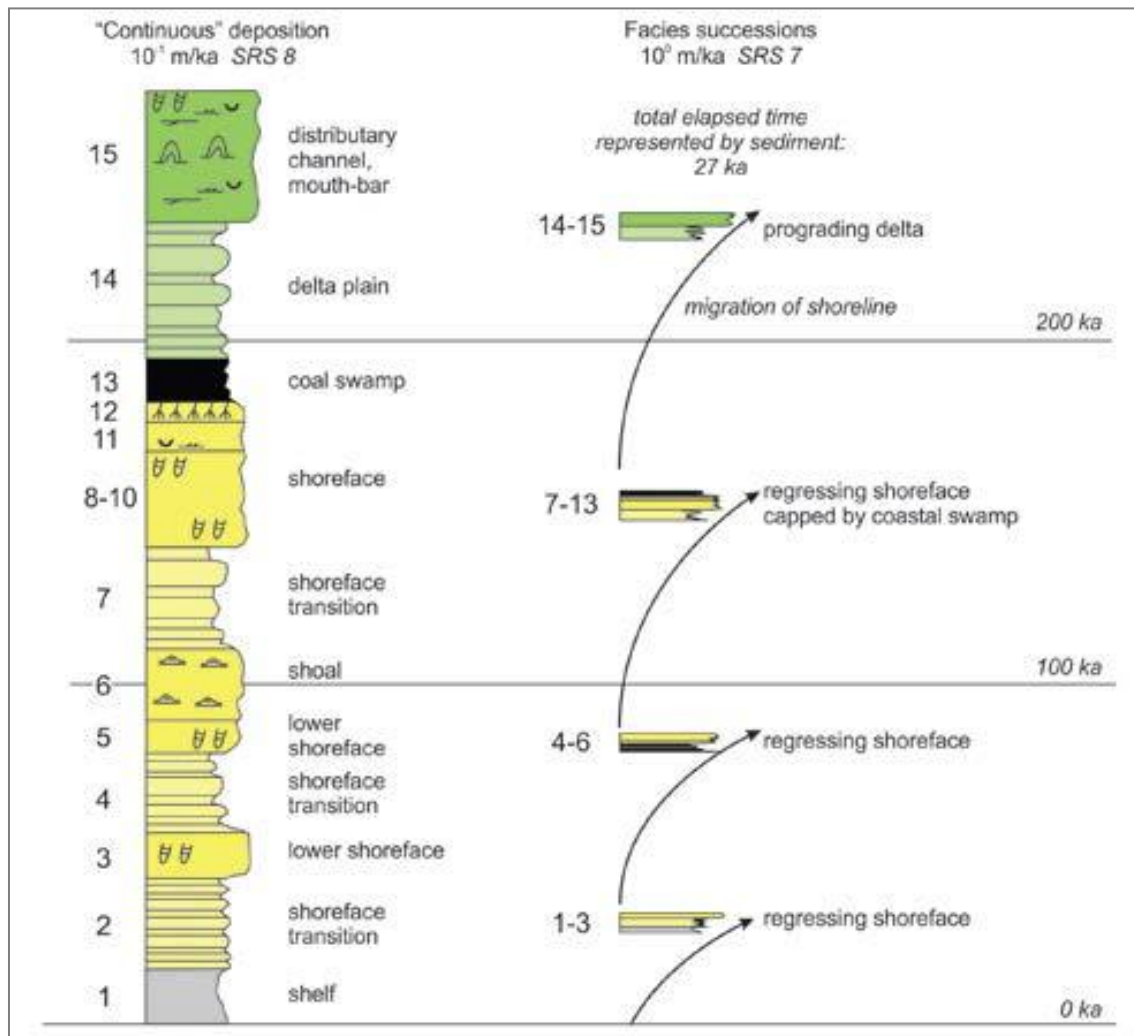


Figure 5. The Spring Canyon Member dismembered. Fifteen numbered lithofacies units are present. At left, the section is plotted to correspond to a *SRS 8* time scale, suggesting an approximate 273 ka timespan for the accumulation of the succession. At right, the same section is evaluated in terms of an *SRS 7* time scale, for which sedimentation rates are an order of magnitude more rapid. The section is subdivided into a set of progradational coastal plain and shoreface successions (original section from Cole and Friberg, 1989).



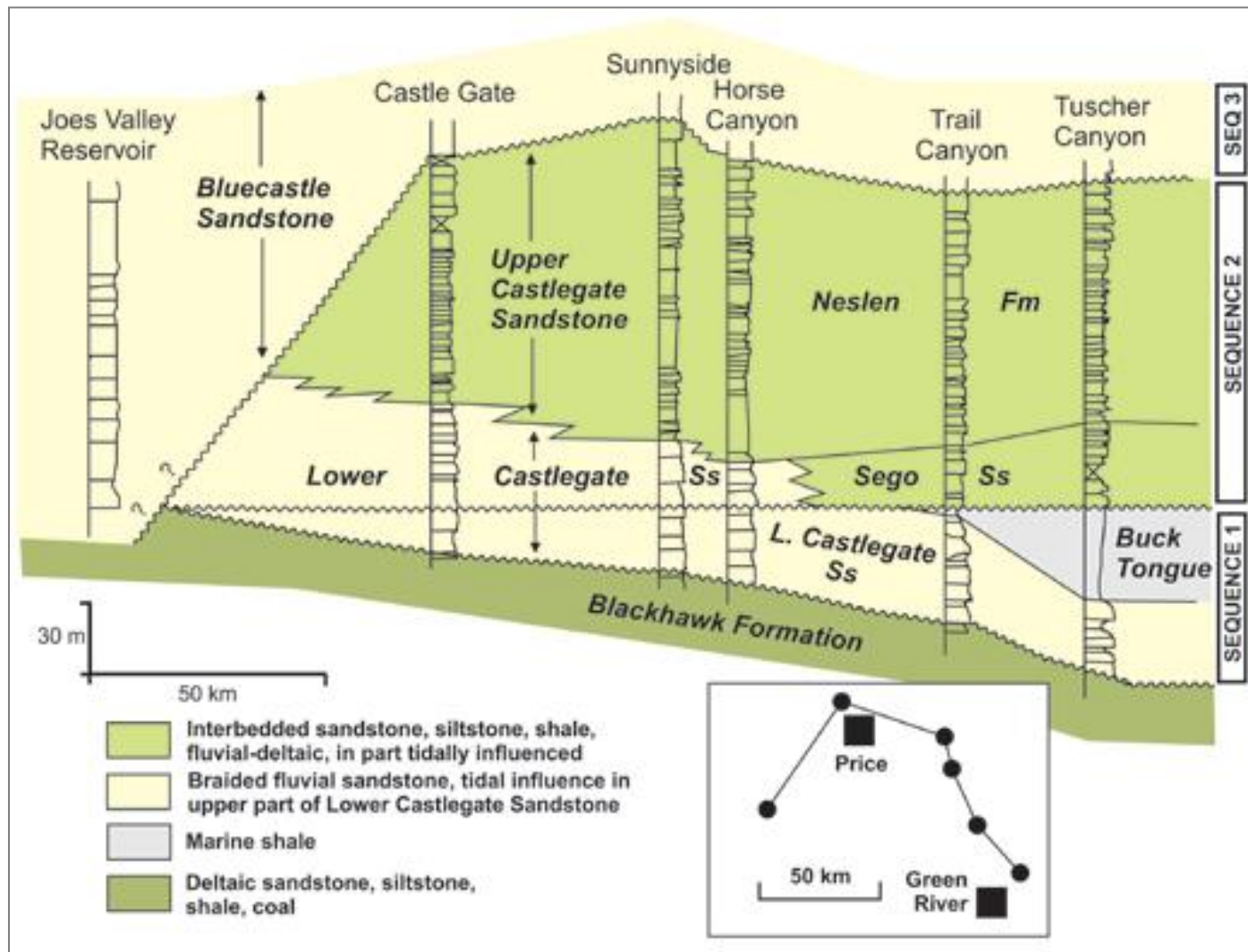


Figure 6. Stratigraphy of the Castlegate Sandstone (from Miall and Arush, 2001a; based on Willis, 2000 and Yoshida, 2000).

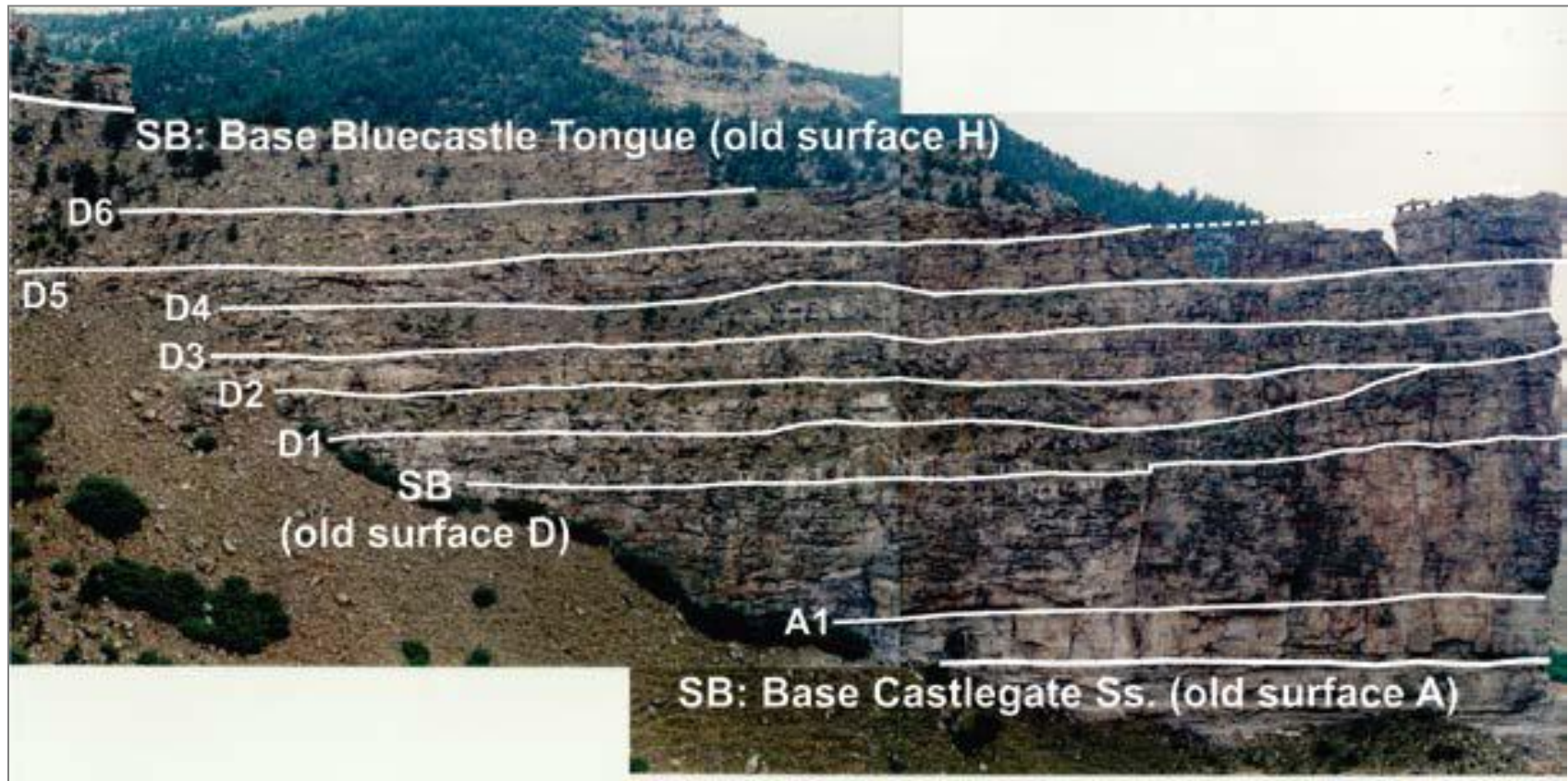


Figure 7. The type section of the Castlegate Sandstone, with key bounding surfaces. Surface D of Miall and Arush (2001a). is tentatively identified as a major intraformational unconformity and sequence boundary. Width of field of view about 250 m.

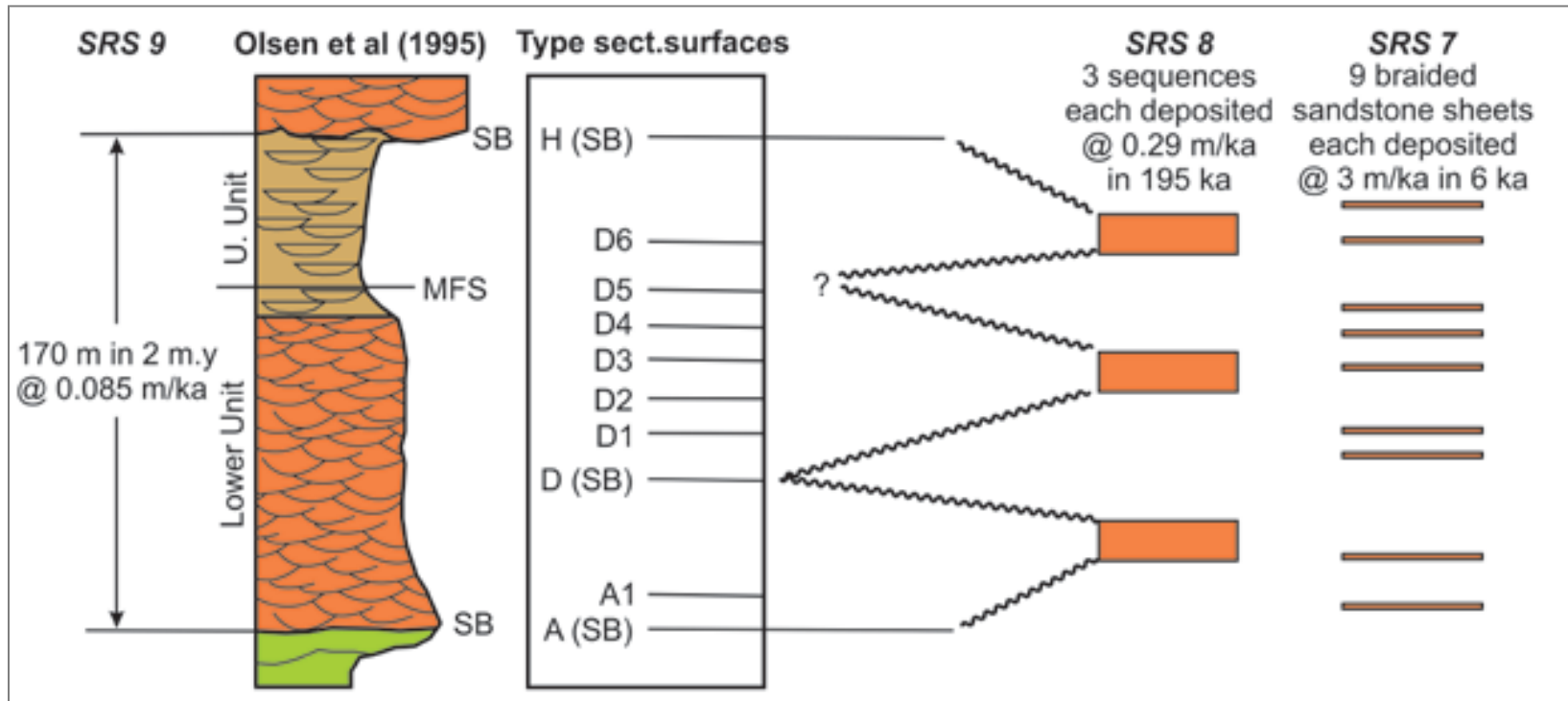


Figure 8. Different interpretations of the Castlegate Sandstone at the type section. See text for explanation.