PS Applicability of Sequence Stratigraphic Models to Thick Fluvial Successions in Tectonically-Active Basins*

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Abstract

Sequence stratigraphic models for thick fluvial successions continue to evolve to account for controlling factors other than base-level fluctuation. For instance, many models place a sequence boundary at the base of amalgamated channel-belt deposits that cap coarsening-upward accumulations, relating this surface to a drop in base level. However, this surface is often characterized by features more indicative of lateral channel-belt migration under conditions of aggradation. These successions commonly develop significantly inland of likely influence by marine shoreline fluctuations and may not respond to eustatic base-level controls, particularly when factoring lag time for effects to propagate upstream. Additionally, these deposits are typically found in settings of relatively continuous subsidence accompanied by high sedimentation rates, such as foreland basins, in which accommodation is produced proximally to the source, trapping much of the sediment before it reaches a position where it can be impacted by eustatic base-level controls. Deposits that accumulate during early phases of foreland development do not have a connection to the marine realm yet demonstrate similar patterns to those that do. Other models suggest accommodation is produced by tectonically-induced subsidence, with filling in response to either a slowing of space production or to simple progradation, as coarser proximal deposits accumulate over finer distal deposits. Other factors include variability in discharge relative to sediment supply and distributive vs. contributive channel patterns. With each addition comes new terminology that, in the end, still ties successions to "sequence boundaries," which, by definition, are "unconformities and their correlative conformities." Part of the complexity may arise from applying concepts where they do not fit. One model might work for passive margins, another for foreland basins, and another for rift basins, yet there will always be exceptions, even between one foreland basin and another or within the same basin. Sequence stratigraphy is an effective tool for analyzing sedimentary basins, but we might be handicapping ourselves by forcing it into situations for which it was not designed. I propose it would be more effective to refrain from all-encompassing formal labels and return to a simple descriptive terminology, such as "coarsening upward interval" and "gradational contact" to describe and interpret thick fluvial successions.

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APPLICABILITY OF SEQUENCE STRATIGRAPHIC MODELS TO THICK FLUVIAL SUCCESSIONS IN TECTONICALLY-ACTIVE BASINS

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Abstract

Sequence stratigraphic models for thick fluvial successions continue to evolve to account for controlling factors other than base-level fluctuation. For instance, many models place a sequence boundary at the base of amalgamated channel-belt deposits that cap coarsening-upward accumulations, relating this surface to a drop in base level. However, this surface often demonstrates scouring that is no deeper than the thickness of a single channel-fill and may show interbedding between facies above and below, suggesting the surface might, instead, be associated with lateral channel-belt migration. Additionally, these successions commonly develop significantly inland of likely influence by marine shoreline fluctuations and may not respond to eustatic base-level controls, particularly when factoring lag time for effects to propagate upstream. Furthermore, these deposits are typically found in settings of relatively continuous subsidence accompanied by high sedimentation rates, such as foreland basins, in which accommodation is produced proximal to the source, trapping much of the sediment before it reaches a position where it can be impacted by eustatic base-level controls. Deposits that accumulate during early phases of foreland development do not have a connection to the marine realm, yet demonstrate similar patterns to those that do. Other models suggest accommodation is produced by tectonically-induced subsidence, with filling in response to either a slowing of space production or to simple progradation, as coarser proximal deposits accumulate over finer distal deposits. Other factors include variability in discharge relative to sediment supply and distributive vs. contributive channel patterns. With each addition comes new terminology that, in the end, still ties successions to “sequence boundaries,” which, by definition, are “unconformities and their correlative conformities.” Part of the complexity may arise from applying concepts where they don’t fit. One model might work for passive margins, another for foreland basins, and another for rift basins, yet there will always be exceptions, even between one foreland basin and another or within the same basin. Sequence stratigraphy is an effective tool for analyzing sedimentary basins, but we might be handicapping ourselves by forcing it into situations for which it was not designed. It might be more effective to apply simpler, less restrictive terminology to describe and interpret thick fluvial successions.

An Example of Different Sequence Stratigraphic Interpretations for the Same Depositional Succession (Drip Tank Member of the Straight Cliffs Formation, Kaiparowits Plateau, Utah)

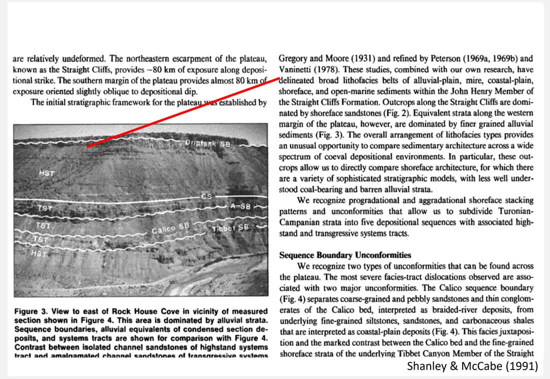
For nearly three decades, sequence stratigraphic terminology has been applied to Upper Cretaceous strata from the Kaiparowits Basin based primarily on changes in alluvial architecture as related to perceived relationships to accommodation production. More recently, controls related to sediment supply and discharge have been considered. Differences in interpretation as to whether the principle driving mechanism is eustasy, tectonics, or sediment supply and discharge have led to “sequence boundaries” being placed both at the top and the bottom of the same stratigraphic unit, with primary focus being on thick amalgamated sheet sandstone deposits, which form either the basal (lowstand) or the capping (highstand) unit of the sequence, depending upon the boundary selection. Here, the Drip Tank Member of the Straight Cliffs Formation is used to illustrate this discrepancy. Similar issues have been tied to the capping sandstone member of the Wahweap Formation, also in the Kaiparowits Basin, and to the Castlegate Sandstone of the Book Cliffs region.

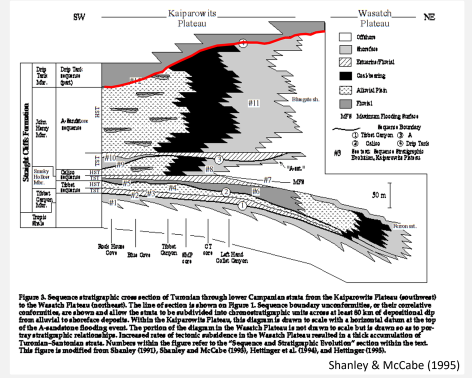
Sequence Boundary = Upper Contact
- Little (1995) – Thrust-induced subsidence
- Christensen & Lawton (2005) – Increased depositional slope
- Lawton & Christensen (2005) – Increased depositional slope
- Jinnah & Roberts (2011) – Eustatic base-level change
- Lawton et al. (2014) – Climate & orogenic relief

Sequence Boundary = Basal Contact
- Shanley & McCabe (1991, 1994, 1995) – Eustatic base-level change
- Lawton et al. (2003) – Eustatic base-level change

Published Figures Placing the Sequence boundary at the Base of the Drip Tank Member

Shanley and McCabe (1995) defined sequence boundaries as ”regional surfaces of erosion that juxtapose amalgamated fluvial deposits over shoreface, alluvial plain, or coal-bearing strata and reflect an abrupt basinward shift in facies tracts.” Lawton et al. followed the reasoning of Shanley and McCabe (1991, 1994, 1995), adding support from petrographic and paleocurrent congruence with underlying (John Henry Member) and overlying (Wahweap Formation) strata.


Shanley & McCabe (1991)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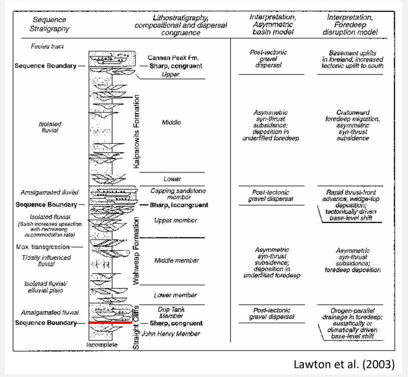
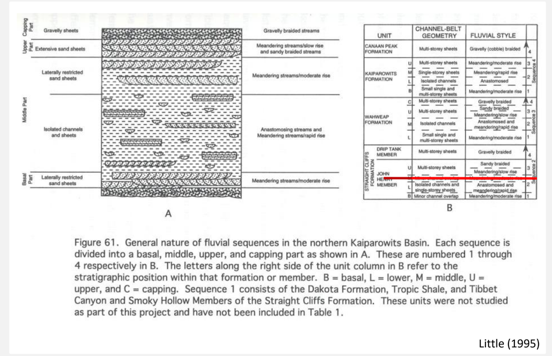
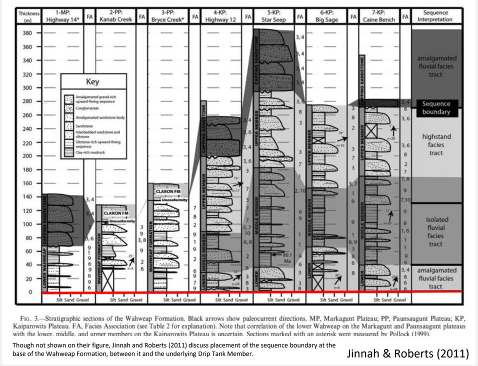
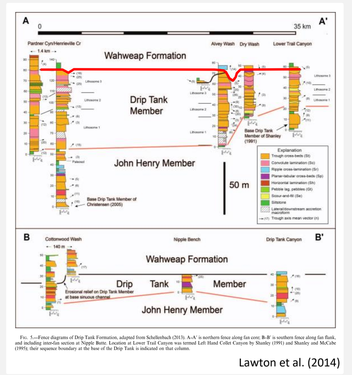

Lawton et al. (2003)

Published Figures Placing the Sequence boundary at the Top of the Drip Tank Member

Little (1995) placed sequence boundaries at the tops of course-grained amalgamated fluvial deposits because of an abrupt shift above to more mud-rich fluvial systems, followed by a gradual coarsening-upward to the top of the succeeding course amalgamated sheet. Lawton et al. (2014) came to a similar interpretation based on distributive megafan characteristics, such as a gradational lower contact with finer-grained fluvial deposits, an overall coarsening and thinning upward of sandstone beds, a radiating paleocurrent trend, thinning of sandstone beds away from an apex, and a highly weathered and erosional upper contact. Jinnah and Roberts (2011) focused on the overlying Wahweap Formation but expressed agreement with Lawton et al’s assessment of the boundary, which forms the basal contact of the Wahweap Formation.


Little (1995)

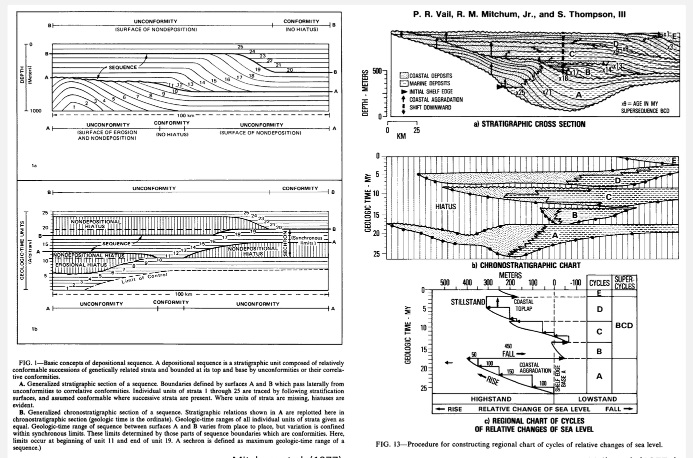

Jinnah & Roberts (2011)


Lawton et al. (2014)

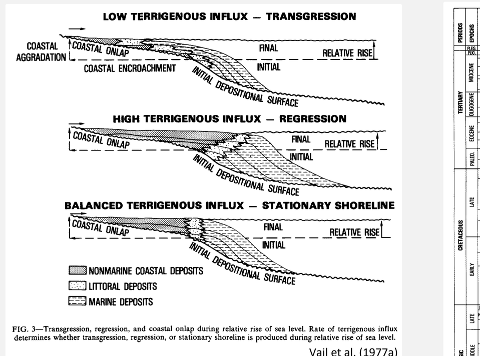
Sequence Stratigraphic Models Were Not Developed for Tectonically-active Basins

Early Model

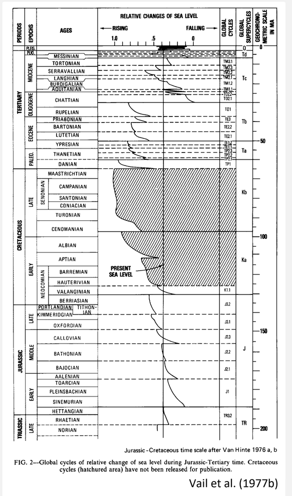
Early sequence stratigraphic models were derived from seismic reflector patterns and terminations for application to coastal/deep marine settings in which space increases basinward from a landward hinge placed within the coastal plain, explicitly in response to eustatic sea-level fluctuation. Thick fluvial successions are not present in these models due to lack of space for their formation and low preservation potential upon drops in base level. Seismic reflectors are considered to have chronostratigraphic significance.


Mitchum et al. (1977) Vail et al. (1977a)

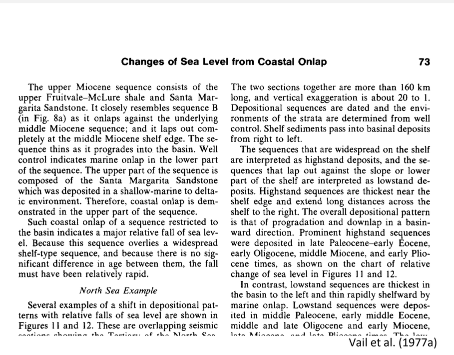
By definition, a sequence is bound in proximal areas by erosional unconformities associated with fluvial incision or subaerial exposure. Because streams cannot cut significantly below base level, they give way basinward to “correlative conformities.” *As the model is based on a passive-margin setting, it does not address fluvial successions that thicken landward, such as those deposited within a foreland basin.*


Vail et al. (1977a)

The term “sequence” is derived from a predictable succession (sequence) of progradational events (parasequences) associated with a balance between rates at which space is produced (accommodation) and subsequently filled (sediment supply). *Early models show minimal accommodation in proximal regions with a steady increase basinward. Additionally, the proximal space actually experiences a reduction during base-level falls, resulting in poor preservation potential for fluvial successions.*


Vail et al. (1977b)

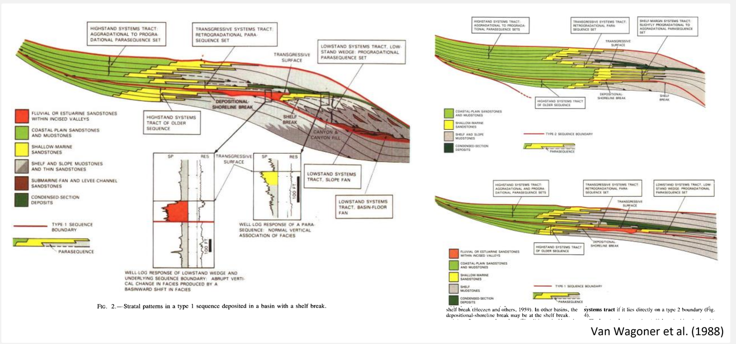
Early sequence stratigraphic models were correlated closely to, and used to refine global sea-level cycles. *Such cycles can be difficult to identify in fluvial deposits of basins in which rates and magnitudes of subsidence might be greater and at significantly different time scales than those associated with base level fluctuations.*

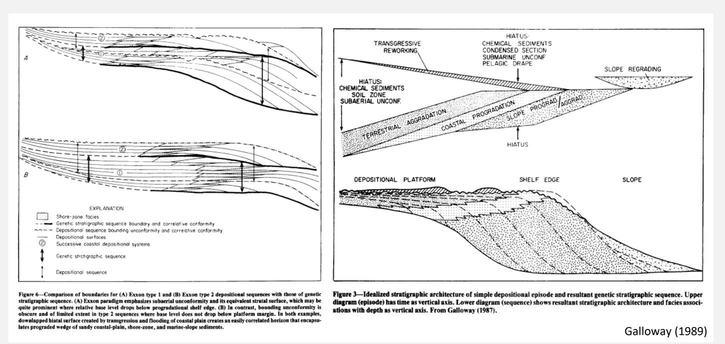

Vail et al. (1977a)

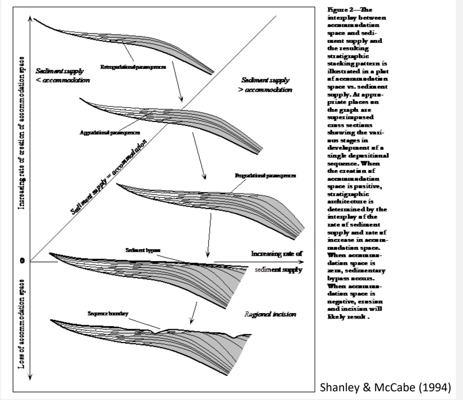
To emphasize association with sea-level cycles, sequence components were named to correspond to different parts of a hypothetical sea-level curve. *In more recent models, great effort has been applied to extend this terminology into thick fluvial successions.*

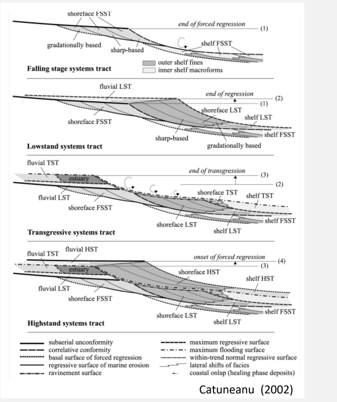
Detailed Revised Models Add a Depositional Ramp Margin but Still Exclude Landward Accommodation Increase

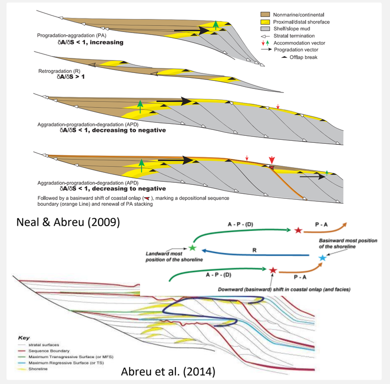
Modifications were made to early models in order to formalize terminology, distinguish between basins with and without a shelf margin break, draw attention to the relative roles of accommodation production and filling, and allow for regional/local impacts on base level. Terminology of most continue to emphasize the role of base-level fluctuation on sequence development. *These models persist in showing a thickening basinward and to exclude significant fluvial deposits landward of the coastal plain.*

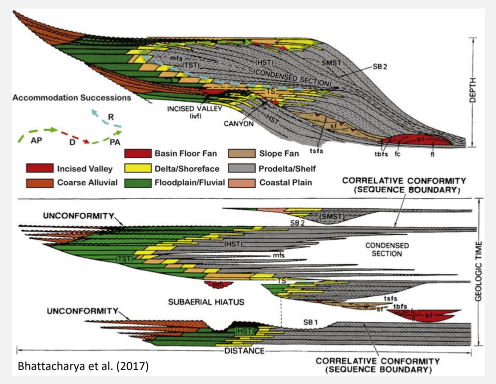

Van Wagoner et al. (1988)


Galloway (1989)


Shanley & McCabe (1994)

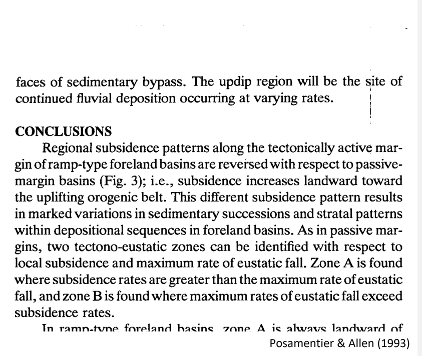

Catuneanu (2002)

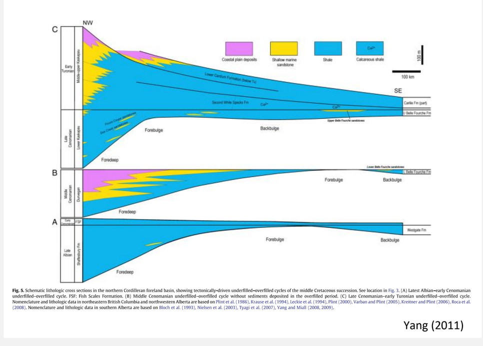

Abreu et al. (2014)

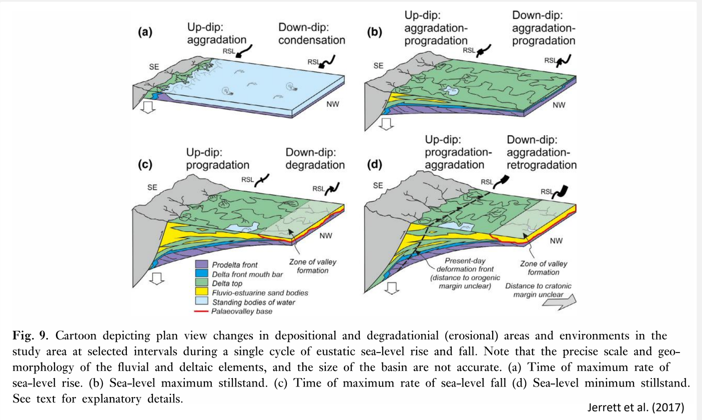

Bhattacharya et al. (2017)

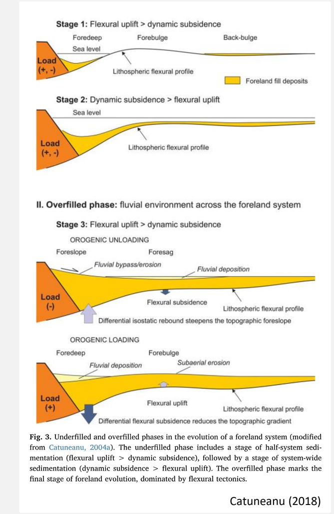
Attempts to Extend Concepts into Thick Foreland Basin Fluvial Sections Lack Detailed Correlations with Coastal Deposits

Many foreland basin studies acknowledge the complications associated with a coeval landward increase in accommodation and in sediment supply but struggle in cross section to show specifically how these deposits correlate to those in coastal regions, leading to highly generalized schemes that lack the detail of traditional sequence stratigraphic models.


Posamentier & Allen (1993)

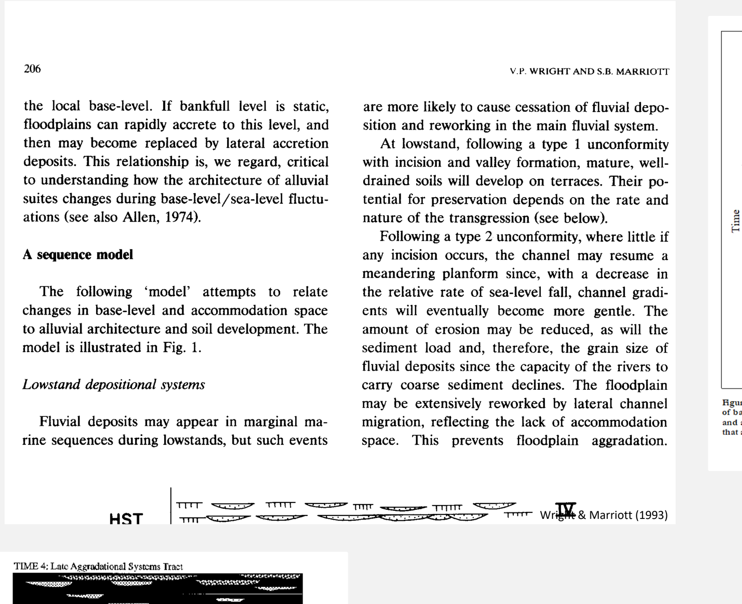

Yang (2011)

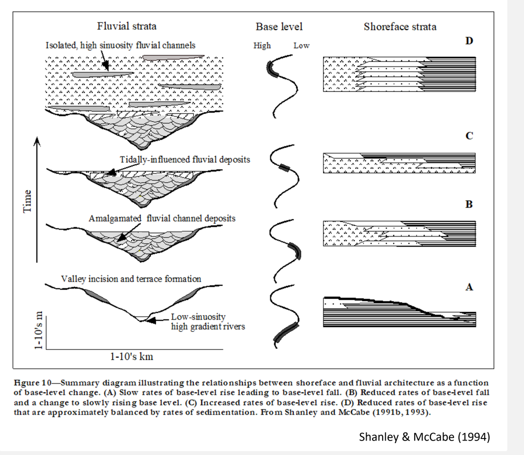

Jerrett et al. (2017)

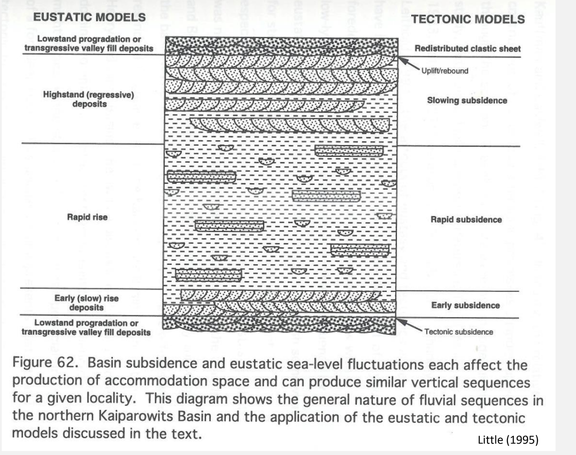

Catuneanu (2018)

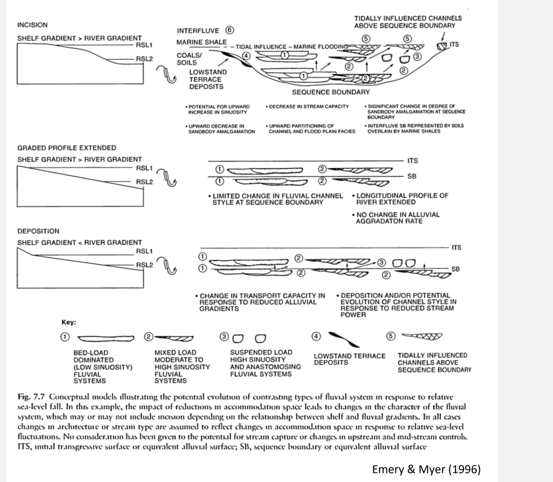
Inclusion of Thick Fluvial Successions into Traditional Sequence Stratigraphic Models

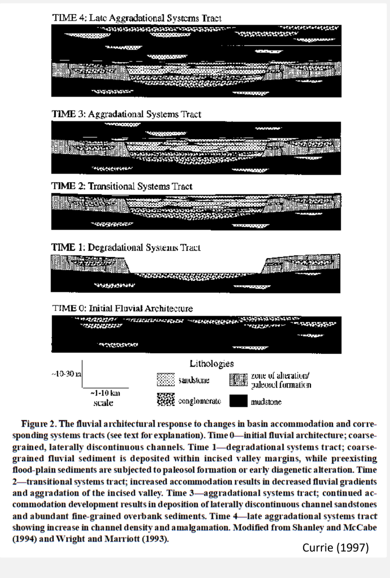
In that coastal sediment is primarily derived from rivers that act as conduits from a source region to a basin, it is logical that changes in base level would affect the fluvial equilibrium profile, leading to episodes dominated by vertical accretion when the rate of accommodation production is high and to lateral migration when low. Once a new profile is established, sediment bypasses the fluvial realm and is transported toward the basin to feed coastal systems. Models relating alluvial architecture to accommodation production attempt correlation between fluvial and coastal successions of foreland basins and, thereby, relate them to standard sequence stratigraphic models. Each assumes a constant sediment supply and shows a common theme, amalgamated sandstone sheets created by braided to meandering rivers during periods of slow accommodation production (lowstand and late highstand) and discontinuous sheets or lenses of sandstone encased in mudstone deposited by high-aggradation meandering to anastomosed rivers during intervals of moderate to rapid accommodation production (transgression), respectively. Terminology varies between models, as some have attempted to maintain traditional vocabulary (e.g. lowstand, transgressive, and highstand systems tracts); whereas, others have employed new terminology to reflect the fluvial setting (e.g. amalgamated fluvial facies vs. isolated fluvial facies tracts of Shanley (1991) or aggradational vs. degradational systems tracts of Currie (1997)). *The principle disagreement between these models pertains as to whether the coarsest sandstone belongs at the base of a cycle as a lowstand/early transgressive deposit or at the top, demonstrating slowing of base-level rise during the later highstand. This has serious implications as to distinguishing between tectonic and eustatic driving mechanisms and timing for regional correlations.*

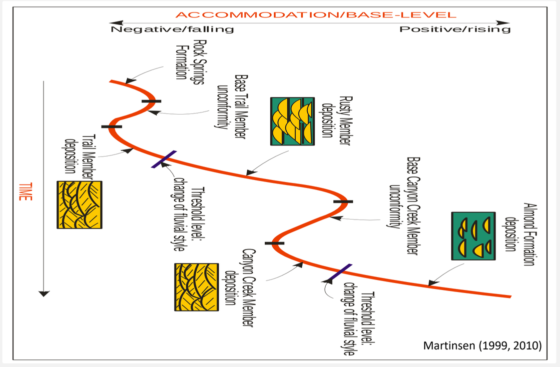

Wright & Marriott (1993)

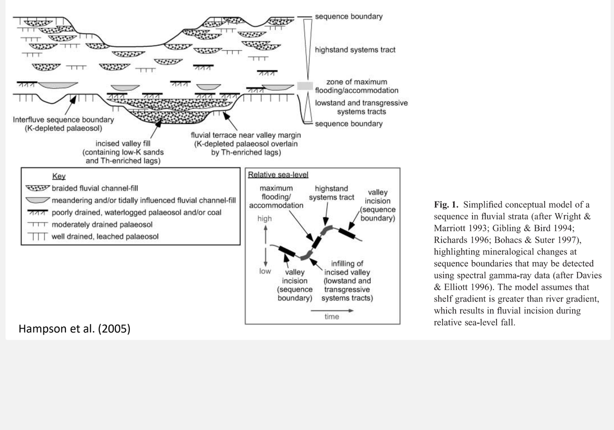

Shanley & McCabe (1994)

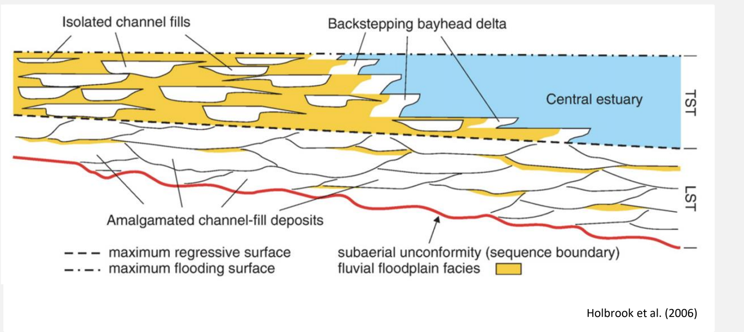

Little (1995)


Emery & Myer (1996)


Currie (1997)

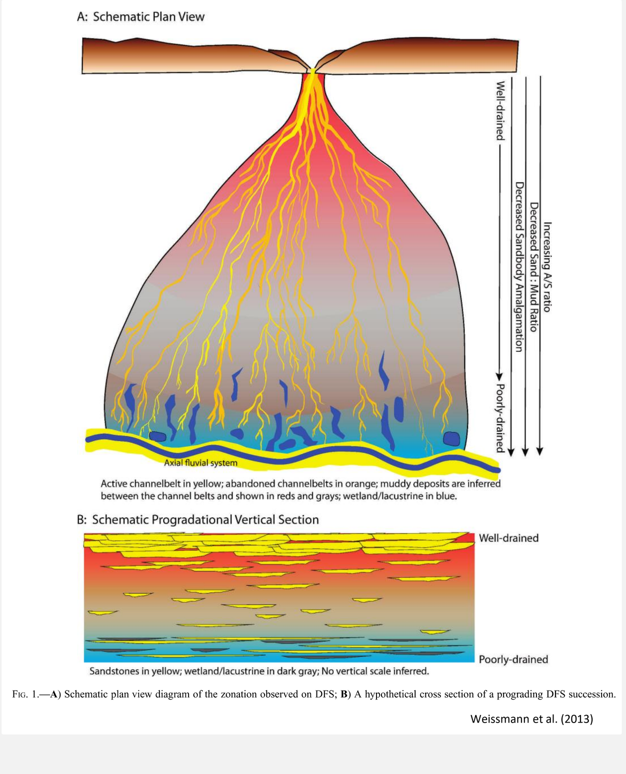

Martinsen (1999, 2010)

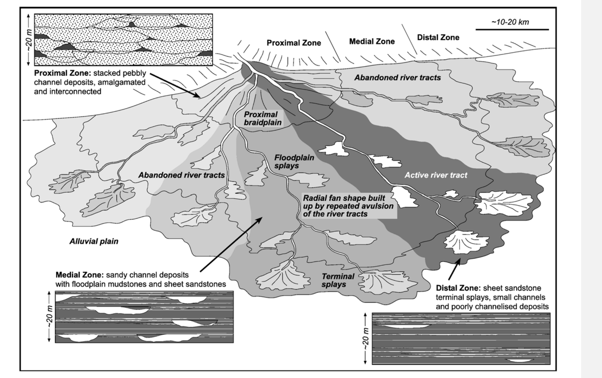

Hampson et al. (2005)

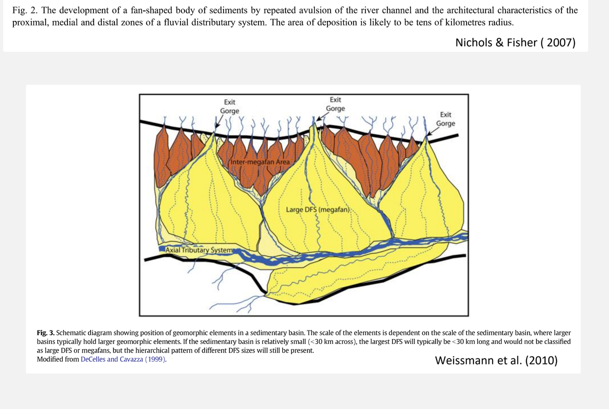

Holbrook et al. (2006)

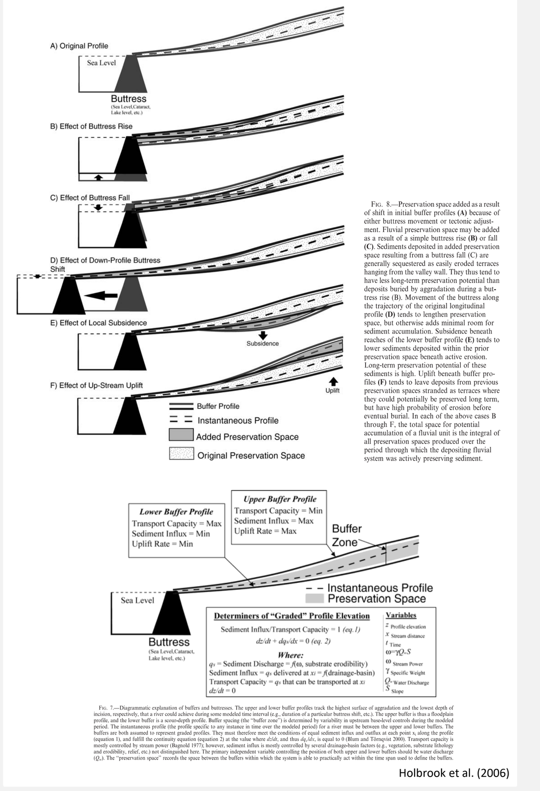
Focus on Non-base-level Controlled (Distributive) Fluvial Systems Demonstrating Similar Depositional Patterns to Base-level Controlled Successions

The primary characteristic of thick foreland basin fluvial successions used to tie them to base-level control is a two-fold lithologic subdivision. One interval is dominated by muddier deposits that become progressively more sand prone toward the top, as sandstone beds become coarser, more amalgamated, and thinner. The other interval forms a thick, sharp-based, multi-story, amalgamated sheet of sandstone. This same subdivision is present in thick fluvial successions that drain into continental interiors and, therefore, are not subject to the same accommodation controls as those connected directly to a standing body of water. In these systems, the course, amalgamated sandstone sheet forms the top of the succession and coarsening upward is attributed to progradation of steep-gradient, high-energy fluvial deposits over more distal, flatter-gradient, low-energy fluvial deposits. This down depositional dip decrease in gradient has a similar effect as decreasing the rate of accommodation production, as the muddier distal deposits accumulate mostly by vertical aggradation with high preservation potential and more sandy proximal sediments exhibit a greater degree of lateral migration and reworking of previous accumulations. These systems demonstrate paleocurrent orientations that radiate from a point source, with deposits fining away from that source. They have been termed distributive fluvial systems and incorporate all the various types of terrestrial fans. Controlling factors are considered to be dominantly changes in discharge, sediment supply, and depositional gradient. *The significant factor here is that patterns similar to those often ascribed to accommodation cycles can be produced in settings in which base-level plays little or no role, though local, temporary influence might be exhibited by a buttress that limits the downstream elevation to which sediment can accumulate.*

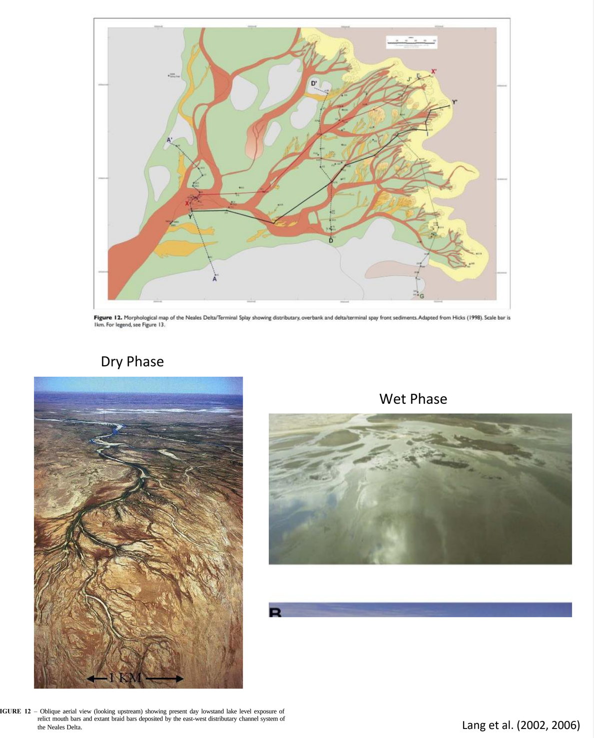

Weissmann et al. (2013)


Nichols & Fisher (2007)


Weissmann et al. (2010)


Holbrook et al. (2006)

Modern Example from the Neales terminal fan/delta, Australia



Lang et al. (2002, 2006)

Discussion and Conclusions

Sequence stratigraphy is an immensely useful tool for interpreting the depositional history of and for making regional correlations in coastal and near coastal settings, particularly along the edges of passive margin basins; however, when applied to settings for which it was not designed, its usefulness is much less, and it may actually lead to interpretations that are incorrect. Attempts have been made since at least as early as the 1990s to apply sequence stratigraphic concepts and terminology to thick fluvial successions of active foreland basins. The primary motive being the remarkable success of sequence stratigraphy in deciphering coastal systems and the fact that fluvial systems are physically connected to the coast. It is, therefore, logical to assume each would be influenced by the same base-level controls. This has led to development of schemes and terminology intended to show a relationship between coastal sequences and thick fluvial successions in terms of response to changes in rates and directions of accommodation production. However, these correlations have proven to be difficult and, in some cases to not be valid for several reasons:

1) Sequence stratigraphic models were developed for passive margin basins, in which space is generated progressively basinward of the shoreline. In these models, the fluvial section is thin, restricted mostly to the coastal plain, accumulates primarily during transgressive events, and is subject to removal during a base-level fall. Conversely, foreland basins experience accommodation production increasingly landward of the shoreline. As such, the fluvial section is likely to be thick, to extend from the coastal plain to the thrust belt, to accumulate during all phases of a eustatic cycle, with much, if not all, being preserved during a base-level fall.

2) A sequence boundary is defined as an unconformity and its correlative conformity. In a passive margin setting, the unconformity exists everywhere landward of the shoreline and the correlative conformity extends basinward from the shoreline due to continuous deposition below base level. In the case of a foreland basin, a second correlative conformity would pass landward into the fluvial succession due to higher sedimentation rates in that region. Even in passive margin settings, which are the most likely to show a simple relationship between base level and adjustments to stream gradient, there are questions as to the upstream extent to which a base-level shift can be expressed by the fluvial equilibrium profile. This is further complicated in foreland basins by a high sedimentation rate that likely keeps proximal portions of the basin overfilled, potentially eliminating any base-level impact in this region. Additionally, there is a lag time for effects of base-level change to propagate up the profile; for instance, as base level begins to rise, it is likely that the sequence boundary continues to incise up gradient, while transgressive deposits simultaneously accumulate within the distal portions of previously incised valleys. Fluvial sequence stratigraphic models place a transgressive surface at the base of highly aggradational stream deposits; therefore, if driven by eustasy in which space creation migrates in a landward direction, it is possible such aggradational rates might not develop prior beginning of the subsequent base-level fall.

3) Because of uncertainty related to the issues above, disagreement exists as to where to place the sequence boundary. Many prefer the base of thick, amalgamated sandstone bodies because of an erosive base, assigning them to the lowstand systems tract. Others choose the top of these sand bodies, citing the gradual coarsening-upward of underlying fluvial deposits, the claim that basal erosion seems to be shallow, and that coarsening upward appears to continue within the amalgamated sheets. A third group places the boundary within these sand bodies, indicating that would be the base level turn-around point, with the lower portions having formed during lowstand/early transgression and the upper during subsequent highstand.

4) Recent studies have begun to move away from solely accommodation-driven models and to focus more on the roles of discharge, sedimentations rates, and changes in gradient due to tectonic processes within the thrust belt. Some models suggest tectonism leads to rapid subsidence with development of mud-dominated axial trunk systems, transporting sediment long distances parallel to the thrust belt, in part a resurrection of a much older idea. These are subsequently overwhelmed as the space is filled by transverse distributive fluvial deposits flowing away from the thrust belt, in which a coarsening-upward profile is developed as more distal, lower-gradient mud-dominated deposits are covered by prograding, more proximal, sand-dominated systems. If these models are correct, then base-level-controlled accommodation plays little, if any, role in development of the succession, yet these models continue to assign a "sequence boundary," despite no obvious correlation to a base-level fall.

5) In essence, in the forced application of sequence stratigraphic principles to these deposits, we may have practiced model-, rather than data-driven science, delaying incorporation of of other important factors, such as climate and sediment supply. Though nearly always mentioned, these other factors have typically been held constant, assuming subordination to accommodation controls. With many current studies focused on documenting changes in provenance and paleocurrent directions, along with recognition of similar fluvial cycles in non base-level controlled modern rivers, we are making substantial changes to model interpretations, but we still seem reluctant to give up the now ingrained terminology.

6) In a setting in which the multiple-working hypothesis approach clearly applies, it is critical to separate data from interpretation. If for no other reason than associated terminology (e.g. lowstand, transgressive, and highstand systems tracts), the sequence stratigraphic approach is inherently interpretive. It may be beneficial to return to the already formalized, data driven approach of allostratigraphy laid out in both the North American stratigraphic code and the international stratigraphic guide. Define units on the basis of bounding unconformities (alloformations, allogroups, etc.) without preconceived interpretations as to driving mechanisms, then interpret what's between the unconformities according to data, rather than trying to force an all-encompassing model, whether that be sequence stratigraphy, the distributive fluvial system, a hybrid of the two, or other.

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