No evidence for sea level fall in the Cretaceous strata of the Book Cliffs of Eastern Utah

John A Howell[1], Christian H. Eide[2], and Adrian J. Hartley[1]

[1]Department of Geology and Petroleum Geology, University of Aberdeen, Kings College, Aberdeen, UK.

[2]Deptartment of Earth Sciences, University of Bergen, Allegaten 41, Bergen, Norway

Corresponding author John.howell@abdn.ac.uk

This is a ***preprint*** for a manuscript, uploaded to EarthArXiv.

Abstract

A core component of the sequence stratigraphic model is the implicit assumption of a semi-sinusoidal relative sea-level curve, and the occurrence of "sequence boundaries" formed during intervals of sea-level fall, recognized primarily by the presence of incised valleys. Late Cretaceous paralic deposits in the Book Cliffs, Utah, have been one of the main testing and teaching grounds for high-resolution sequence stratigraphy. The commonly accepted sequence stratigraphic model for the Santonian-Campanian section recognises up to ten sequence boundaries. Analysis of each proposed sequence boundary indicates no conclusive stratigraphic evidence for any relative sea-level falls during this period of deposition in the Book Cliffs area. These observations indicate that a key aspect of the sequence stratigraphic model is not applicable in outcrops which are widely considered to be one of the type areas for sequence stratigraphic teaching and research. This has important implications for sequence stratigraphic applications during greenhouse times.

Introduction

Late Cretaceous strata that crop out in the Book Cliffs, Eastern Utah have long been used as one of the main teaching and research areas for high resolution sequence stratigraphy (e.g. Van Wagoner et al 1990, Howell & Flint 2004, Catuneanu 2006). An inherent part of the sequence stratigraphic paradigm is the occurrence of incised valleys cut by fluvial systems during periods of relative sea-level fall. These incised valleys and the sea-level falls which are believed to have caused them, are taken as important bounding elements in the stratigraphic framework, and to be of great use in correlation and facies prediction (Posamentier and Vail 1988; Van Wagoner 1990). In the Cretaceous of the Book Cliffs area, ten distinct intervals have previously been identified as containing sequence boundaries overlain by lowstand and transgressive valley fill successions (e.g. Hampson et al., 2001, Hampson & Howell 2005). In a recent paper Pattison (2018) has questioned the validity of interpreting the base of the Castlegate Sandstone as a regional unconformity (sequence boundary). In this paper we review the evidence for each of the sequence boundaries in the Book Cliffs succession and consider alternative explanations for the surfaces that have previously been mapped as sequence boundaries and review the evidence for sea-level fall. We also discuss the implications of our findings for studies in the Book Cliffs and for sequence stratigraphy in general.

Lithostratigraphy and setting

The Late Santonian and Early Campanian strata of the Book Cliffs of eastern Utah (Fig 1) largely comprise the Blackhawk Formation, together with the underlying Star Point Formation and the overlying Castlegate Sandstone of the Price River Formation (Young, 1995). These paralic to fluvial successions interfinger with the offshore deposits of the Mancos Shale Formation (Fig 1b).

The Blackhawk Formation comprises 6 lithostratigraphic members composed predominantly of wave dominated shoreface successions (Young, 1955) and undifferentiated non-marine coastal plain deposits (Fig 1b). These members and their constituent shoreface parasequences, prograded from the Sevier orogen in the west into the epeiric seaway that occupied the western US during the Middle to Late Cretaceous (Horton et al., 2004). The underlying Star Point Formation includes two members, the Storrs and Panther Tongue. The Storrs is comprised of shoreface deposits, similar to those of the Blackhawk Formation. The river-dominated mouth bar deposits of the Panther Tongue are significantly different from any of the other marine deposits in the Book Cliffs. The lower Castlegate Sandstone overlies the Blackhawk Formation and is composed of a wedge of predominantly braided fluvial deposits which thins from 160 m near Helper (Miall, 1994), passing eastwards into meandering fluvial deposits and pinching out east of Green River (Fig 1b).

Current sequence stratigraphic interpretation

Since the initial work of Van Wagoner et al. (1990) the Book Cliffs has been the focus of numerous sequence stratigraphic studies and a broad consensus on the sequence stratigraphic framework has been established and is summarised in Fig 1 and Table 1 (refs there-in). In these models, a major Type 1 sequence boundary (sensu Posamentier and Vail 1998) occurs at the base of the Panther Tongue with associated transgressive deposits in the Storrs Member. The Blackhawk Formation is comprised of 8, high-frequency sequences arranged in a highstand sequence set, capped by a major sequence boundary at the base of the Castlegate Sandstone. Sequence boundaries are typically defined by channelized erosion surfaces overlain by tidal-estuarine successions interpreted as incised valleys. Other commonly cited evidence for sea-level fall includes forced regressive shorelines such as in the upper Aberdeen and Kenilworth members, changes in parasequence stacking (e.g. in the Kenilworth Member) and an overall upward increase in "sequence boundary" frequency, and fluvial channel stacking patterns in the non-marine part of the Blackhawk Formation. In the following section we review this evidence.Reviewing the evidence

A number of aspects are commonly cited as providing evidence for sea-level fall. These include: (1) incision of valleys into older shoreface and shelf strata which are filled during subsequent transgression (incised valleys); (2) valley fills that are commonly tidal in an otherwise wave dominated settings; (3) valleys that are significantly wider and deeper than "typical" distributary channels in a given setting; (4) valleys that have multi-storey fills, providing evidence for a number of discrete base-levels during transgression; (5) sharp based shoreface deposits in which upper or lower shorface deposits lie directly on offshore shelf deposits, without offshore transition zone deposits typically associated with normal progradation (forced regressions); (6) paleosols upon offshore deposits (interfluve sequence boundaries); and (7) lowstand deposits, which may be lowstand shorelines or basin floor fans. Virtually all of these criteria have been cited as evidence for sea-level fall within the strata of the Book Cliffs (Table 1)

"Incised Valley Fills"

The most commonly cited evidenced for sea-level fall in the Book Cliffs is the occurrence of tidally influenced estuarine successions interpreted as incised valley fills. These occur in the Desert, Grassy, Sunnyside, Kenilworth and Aberdeen members (Fig. 1, Table 1). These "valley fills" are typically 10 to 30 m deep and include strata with a high degree of tidal influence, including large scale inclined hetrolithic strata, sub-tidal bars, tidal flat heteroliths, shell beds and coals (Fig 2). They are interpreted to represent the transgressive fill of valleys cut by fluvial incision during sea-level fall, then widened and filled by tidal processes during sea-level rise. The switch from wave dominated shoreface to tidal estuarine deposition is cited as key evidence for the sequence boundary.

In all cases except for the upper Sunnyside Sequence boundary in Woodside Canyon (Fig 1, Table 1, Fig 3), the tidal bedforms include large scale inclined heterolthic strata that are no larger than the containing channel body. A good example of this is the well visited Desert "incised valley fill" in Tuscher, Thompson and Blaze Canyons (Van Wagoner 1995; Fig 1, Fig 2). While the depth of incision associated with the valley may reach up to 20 m, because the associated bedforms are of a comparable size, this suggests that while tidal influence may be greater than previously suggested, there is no evidence for a base-level that is lower than the top of the incised channel (Fig 2).

The upper Sunnyside Sequence boundary (Fig 3) cuts into the top of the uppermost Sunnyside parasequence (SPS3) and is associated with a 28 m deep, multi-story, tidal package interpreted as an incised valley (Howell and Flint 2004; Sømme et al., 2008). The surface is also associated with a major change in coal facies within the Sunnyside Coal adjacent to the valley which was interpreted as an interfluve sequence boundary by (Davies et al., 2006). The “valley” contains 4 stacked tidal point bars, minor shell banks, coals and some paleosols.

We consider this succession to be the most difficult to explain without invoking sea-level fall. The key to an alternative explanation is the presence of the Sunnyside Coal which, at up to 5m, is the thickest of all of the Book Cliffs coal successions. The Sunnyside coal represents a major raised mire (Davies et al., 2006) which significantly modified the regional paleogeography. Outcrop evidence illustrates that the coal lies within the channelized sandbody and therefore is concurrent with it. Given that the two metres of coal adjacent to the “valley” would have represented 15 to 20 m of peat and an aggrading topography of at least 10 m (Esterle & Ferm 1994) then it is possible to explain the multi-storey nature of the “valley fill” succession through accumulation within the growing mire topography which then differentially compacted leaving the geometries observed today. This mechanism may also apply to other multi-storey “valley-fills” associated with coal mires in the Book Cliffs.

Overall 90% of the tidal-estuarine packages that cut through the shorefaces of the Book Cliffs are single storey in nature (Fig 4). These are contemporaneous with the shoreface deposits and do not represent a drop in base level. They do however suggest that the Blackhawk Formation in the Book Cliffs is more tidally influenced than previously described with large 20m deep tidal incisions. In the classification of Ainsworth et al. (2011) the succession would be described as Wt rather than W with an upward increase in the occurrence of tidally influenced strata. This trend continues into the overlying Sago SST (van Cappelle et al. 2016) which is Tw. The rare exceptions which show multi-storey stacking, such as the Upper Sunnyside example are associated with aggradation of the coastal plain due to raised coal mires (Fig 4).

“Forced Regressions”

There are three intervals that are typically associated with forced regressive shorefaces within the Book Cliffs: The Panther Tongue, the lower Aberdeen sequence boundary and the Kenilworth sequence boundary.

It is easy to see why the Panther Tongue (Fig 5) is interpreted as a forced regression, not only does it represent a major change in depositional style it also lacks associated coastal plain which suggests a falling shoreline trajectory (*sensu* Helland-Hansen & Martinsen 1996). The sandstone body also extends a significant distance basinward. However, when the succession in the Wasatch Plateau west of the Book Cliffs, is considered (Hampson et al 2012), the Panther Tongue is not associated with any significant change in shoreline stacking patterns and is simply an anomalous, short lived progradational event. An alternative to the forced regressive model is that the Panther Tongue records a sudden influx of sediment, possibly associated with movement in hinterland thrusts and drainage basin reorganisation. An interpretation supported by provenance data (Fig 5), which shows a much greater proportion of chert fragments in the Panther Tongue compared to any of the other units in the Book Cliffs. This likely caused very rapid progradation similar to that seen in the modern Wax Lake Delta (Wellner et al. 2005) which has prograded to a scale comparable to the Panther Tongue delta in less than 40 years through controlled avulsion of approximately 30% of the Atchafalaya River in Louisiana by the Army Corp of Engineers.

The lower Aberdeen sequence boundary described by Kamola and Huntoon (1995) as a “stranded lowstand parasequence” or forced regression has been studied recently by Chavin et al (2010) who interpreted it to represent an along-strike change in shoreline style to a fluvial dominated delta.

The Kenilworth sequence boundary has attracted significant attention (Tayor and Lovell 1995, Pattison 1995, Ainsworth & Pattison 1994). The deposits have been variably interpreted as late highstand, falling stage, and attached lowstands. Evidence cited to support sea-level fall is primarily the sharp based nature of the upper parasequence on Battleship Butte and also the existence of a series of large channels along strike in areas such as Woodside and Whitmore canyons (Fig 6).

Eide et al (2014) reported evidence for an ascending shoreline trajectory in the parasequence at Battleship Butte including the presence of a 6 m thick coastal plain succession above the shoreface on top of Battleship Butte. This suggests a climbing shoreline trajectory and therefore normal rather than forced regression (Fig 6). Further evidence for this can be observed in the form of clinoform surfaces on Battleship Butte which pass through the shoreface sandstone body into the underlying shales, effectively crossing the apparent sharp based surface (Sech et al., 2009).

“Changes in fluvial stacking patterns” – The Castlegate Sequence Boundary

The uppermost sequence boundary in the Book Cliffs is the surface at the base of the Castlegate Sandstone. The Castlegate is a sandstone dominated (>85%) succession composed of braided fluvial deposits. The unit thins basinward over a 150 km long profile from c. 160 m thick in the area around the town of Helper in the west of the Book Cliffs to less than 10 m thick around Thompson Canyon in the east. The sequence boundary is typically defined at the transition from heterolithic coastal plain deposits with a moderate to high proportion of overbank mudstones, coals and fine sandstones to the sand-dominated braided fluvial deposits.

In most sections the "Base Castlegate Sequence Boundary" is apparently easy to define. However regional studies, including heli-lidar and fieldwork suggest that it is not a single surface across a wider area (Fig 7). Hajek and Heller (2011) reported no change in bedform style or scale across the boundary and heli-lidar studies- suggest a gradual rather than sharp transition (Fig 8; Rittersbacher et al 2014). We propose, in accord with Pattison (2018), that the upward transition to the Castlegate is the expression of a lateral facies change with the sand-dominated, braided fluvial deposits representing the proximal part of a large mega-fan or DFS (distributive fluvial system sensu Weissman et al., 2010). The fluvial channels in the upper part of the non-marine Blackhawk formation represent the braided to meandering, medial part of the same fan and the tidally influenced, fluvial channels in the lower part of the non-marine Blackhawk represent its distal portion (Fig 8). The modern data Mitchell DFS in the Gulf of Carpentaria is considered to be a useful, similar scaled analogue (Fig 8).

In addition, Horton et al. (2004) demonstrated that progradation of the Castlegate was likely forced by up-dip changes in sediment supply, associated with tectonics in the hinterland developing time-equivalent angular unconformities in the west, indicating that there is no evidence that the base of the unit in the Book Cliffs was the product of a fall in sea-level.

Other Evidence for base-level fall in the Book Cliffs

Other aspects of the sequence stratigraphic model commonly described and cited from the Book Cliffs as evidence for sea-level fall include the existence of lowstand shoreline and/or turbidites; interfluve surfaces and changes in parasequence stacking patterns.

Work by Pattison et al (2007) and Hampson (2010) suggests that the various shelf sandbodies that lie below and east of the Book Cliffs (Prairie Canyon Mb or Mancos B) do not correlate directly to any of the inferred sequence boundaries described above (Fig 9). These stratigraphic relationships have been explained by the proximity to fluvial input points along a shoreline dominated by basinal (wave and tide) processes (Eide et al 2015) and occasional structural creation of ponded accommodation on the shelf (Pattison et al., 2007; Hampson 2010;). No clear evidence for interfluves or paleosols within the Mancos Shale has ever been documented in the area.

The c. 30 parasequences in the Book Cliffs (Fig. 1) record an overall progradational stacking pattern punctuated by 6 major marine flooding surfaces that equate to the original lithostratigraphic member boundaries of Young (1955). The classic sequence model predicts a progradational highstand succession overlain by a sequence boundary, which in turn is overlain by a transgressive systems tract with retrogradational parasequence stacking. Of the 30 parasequences in the entire Book Cliffs succession, only one backstepping parasequence occurs (KPS5 at the top of the

Kenilworth Member). We propose that KPS 5 can be explained by autocyclic switching along the coastline or by changes in thrust driven subsidence. Significantly, no other transgressive systems tract deposits have been recorded.

Discussion and Conclusions

For the last 25 years, the well exposed successions of the Book Cliffs have been cited as the "text-book example" for many of the features described in the basic sequence model. They have been the site of countless fieldtrips, close to a hundred publications in scientific journals and several textbooks. We suggest that that evidence for one part of this model, the sea-level fall component, is scant to non-existent in this area. This has important implications, not only for our understanding of the Book Cliffs region but also for our understanding of sequence stratigraphy as a whole, especially during greenhouse times

Firstly, the shorelines of the Book Cliffs are traditionally considered to be wave dominated shorefaces with minor fluvial influence at widely spaced input points. Ericksen and Slingerland (1990) predicted that the Western interior basin was entirely micro-tidal. If however the tidal intervals, especially in the upper members do not represent incised valleys, then it follows that the shorelines actually exhibit a stronger tidal component than previously described. Howell and Flint (2004) suggested that the thickness of the foreshore facies could be used as a proxy for the tidal range, which for most the members of the Blackhawk would imply an average tidal range of 3 m (meso-tidal). The thickness increases through the succession from 2m in the Spring Canyon to 3-4 m in the Sunnyside and Grassy members suggesting an upward increase in tidal range. The overlying Desert Member is dominated by tidal channel deposits which in many places eroded foreshore deposits, suggesting an even greater, tidal range. There is an overall upward trend from wave dominated to tidally influenced shorefaces within the Blackhawk Formation, extending upward into the tidal shorefaces of the overlying Sego Fm. This trend may relate to the long term progradation and associated changes in basin morphology or to long term changes in the tidal regime within the basin. Secondly, the interpretation of the tidal packages as an integral part of the shoreline, rather than a discrete stratigraphically controlled entity suggests significantly more variety along the coastline than inferred from previous models. All existing paleogeographic reconstructions show the shorelines as simple, straight N-S to NE-SW trending bodies (Fig 1). Observations of large tidal embayments, such as those in the Sunnyside, potentially associated with large, thick coal mires, suggest much greater along strike variability (Fig 3).

Our studies indicate that there is no evidence for sequence boundaries associated with sea-level fall. However, up to 30 very well defined parasequences and 8 parasequence sets bounded by flooding surfaces that can be traced for 10s and in some cases 100s of kilometres. This suggests that at least in part, the sequence model is applicable but also suggests that the driving mechanism is intra-basinal rather than eustatic, most probably related to pulsed tectonic subsidence driven by thrust sheet loading as proposed by Kamola and Huntoon (1995).

Perhaps more interesting than the observation that there is no evidence for sea-level fall, is the question, why is there no evidence for sea-level falls in such a well exposed succession? The succession represents c.4.5 Myr, from the base of the Panther Tongue to maximum regression of the Lower Castlegate Sandstone (Fig 10) Krystinik & DeJarnett, 1995). Given that the interval is c. 500 m thick we can assume an average subsidence rate of 0.1m/ky. Relative sea-level fall requires either tectonic uplift or eustatic sea-level fall (Catunean, 2006). The lack of evidence for sequence boundaries would suggest that there was no uplift within the basin. The most recent eustatic sea-level curves (Miller et al., 2005, Kominez et al. 2008) show a generally stable eustatic sea-level (Fig 10) during most of the Lower-Middle Campanian with only minor sea-level falls which occur at a rate (0.05m/kyr) which is not fast enough to outpace that subsidence and produce sub-aerial exposure (0.1m/kyr).

In addition to questioning the validity of the Book Cliffs as a sequence stratigraphic training ground, the results of this reappraisal also has implications for sequence stratigraphic models in general. Glacio-eustatic sea level falls have occurred throughout Earth history and have a major impact on sedimentary architectures during icehouse times such as the Plio-Pleistocene, where they control stratal stacking patterns in many of the World's passive margins (Miller et al., 2005). However, the recognition that eustatic sea-level fall does not outpace relatively slow subsidence rates in a foreland basin has important implications for predicting the distribution of lowstand systems during greenhouse times. It also suggests that the deep water component of the Late Cretaceous deep water margins will be less sand prone than their Neogene counterparts especially in areas with wide shelves and moderate to low rates of sediment supply.

Our studies suggest that the Late Cretaceous deposits of the Book Cliffs lack conclusive evidence for sea-level fall and that all the surfaces previously interpreted as "sequence boundaries" have an alternative and simpler interpretation. We also suggest that there is a stronger tidal component in the Book Cliffs strata than previously reported, especially in the upper parts of the Blackhawk Formation. This also has implications for hydrocarbon exploration in Cretaceous basins and passive margins.

Sequence Boundary	**Key Evidence**	**Main Locations (Fig 1)**	**Main References**
Castlegate	Transition from meandering to braided fluvial deposits	Widespread	Van Wagoner (1995) Others

Desert	Widespread incision with tidal estuarine succession up to 18 m thick	Southern Book Cliffs, Tuscher, Blaze, Thompson C.	Van Wagoner (1995)
Upper Grassy	Widespread incision on top of Grassy Member (into GPS4)	Southern Book Cliffs, Grey, Tuscher, Coal	O'Bryne and Flint (1995)
Lower Grassy	Widespread incision on top of Grassy Member (into GPS2) , channels in offshore deposits	Southern Book Cliffs, Grey Canyon, Tuscher, Coal	O'Bryne and Flint (1995)
Upper Sunnyside	Formation of 28 m deep, 3 km wide, multi-storey, tidal estuarine package	Woodside Canyon	Howell and Flint 2004, Davies et al 2006, Sømme et al 2007
Lower Sunnyside	A major tidal sandstone with the coastal plain	Numerous canyons in northern Book Cliffs. Whitmore Canyon	Howell and Flint 2004
Kenilworth	Tidal valley fills and a major sharp based shoreface in Battleship Butte	Whitmore Canyon, Battleship Butte, Green River embayment	Taylor and Lovell 1995, Pattison 1995
Upper Aberdeen	Large tidal estuarine complex	Coal Creek Canyon	Kamola pers comm
Lower Aberdeen	Forced regressive, river dominated delta on shoreface deposits	Coal Creek Canyon	Kamola pers comm. Charvin et al 2009
Panther Tongue	Major fluvial dominated delta with falling trajectory, no coastal plain, change in dominant paleocurrent direction	Northern Book Cliffs around town of Helper. Northern Wasatch Plateau	Posamentier and Morris 2000

Table 1 Summary of existing sequence stratigraphic interpretation of the Book Cliffs, see Hampson et al 2001, Howell and and Flint, Hampson and Howell 2006 for more detailed descriptions

Figure Captions

Fig 1. Current sequence stratigraphic interpretation of the Book Cliffs. A) Map of outcrop belt showing selected shoreline positions (see B) and the position of tidal estuarine deposits previously interpreted as incised valleys generated by sea-level fall and the position of selected highstand and "forced regressive" shorelines. B) Projected depositional dip section showing the sequence stratigraphic interpretation of the Book Cliffs. PT Panther Tongue; St Storrs Mb; SC 1-4 Spring Canyon Parasequences, A1 - 5 Aberdeen parasequences; K1-5 Kenilworth Parasequences; S1-3 Sunnyside Parasequences; G1-4 Grassy Parasequences; D1-9 Desert Parasequences.

Fig 2. Detail of the Desert succession in Thompson Canyon previously interpreted as an incised valley by Van Wagoner (1995). Upper section is taken from a virtual outcrop (built from UAV acquired photographs using SfM) and illustrates that the heterolithic tidal macro-forms scale to the channel. Lower view shows the "classic" Thompson outcrop which also shows tidal heterolithic strata, capped by a thin coal which also scale to the size of the channel, illustrating that the interval is a single-storey complex.

Fig 3. Multi-storey tidal estuarine succession in the Sunnyside Member in Woodside Canyon. A) A series of logged sections showing detail of the complex. B) A photograph of the section in log 3. Note the thick coal in Log 1.

Fig 4. Model to illustrate the multi-storey vs single-storey channel stacking. In A. a multi-storey channel body is formed because base-level is rsing within a valley previously cut by base-level fall. This is a true incised valley. B. A single-storey channel where the tidal macro-forms scale to the channel. This shows no evidence for base-level fall despite the depth of incision. C. Shows a multi-storey body which is formed due to aggradation of the coastal plain, in this case caused by growth of a raised peat-mire. This is the suggested model for the Sunnyside outcrops in Woodside Canyon.

Fig 5. The Panther Tongue near Helper. A. Outcrop photo and sedimentary log showing the seaward dipping clinoforms (towards the south, RHS of image) which suggest a fluvial dominated delta. The photo and log show that there is no sharp base and also the unit has a sharp top with no associated coastal plain deposits. B. QFR plot of the Blackhawk and Starpoint formations showing a distinct petrographic composition in the Panther Tongue (from Mette Lundberg unpublished data) sandstones. C. The modern Wax Lake Delta, an analogue for the Panther Tongue which has similar scale and deposits and was laid down in 40 years following rapid avulsion (from Wellner et al 2006).

Fig 6. The Kenilworth “Forced Regression” at Battleship Butte. A. Log through the succession, note the presence of 6 m of coastal plain strata on top of the shoreface, illustrating that the unit had a climbing rather than falling trajectory. B. Dip-parallel section derived from heli-lidar data showing the coastal plain (green) and the clinoforms that interfinger with the underlying marine shales (see Eide et al. 2016 for more detail). C. Schematic to show the difference between a normal regression (climbing trajectory) and forced regression (falling trajectory). Note the lack of coastal plain in the lower section.

Fig 7. Base Castlegate surface. A. View of Castlegate/Blackhawk contact from the Beckwith Plateau near the I70-US 191 junction, taken from helicopter. B. Detail of the basal surface in A, note that the two units interfinger. C. View in outcrop of the interfingering of the top formations.

Fig 8. Fluvial stacking patterns. A. Upward increase in average sandbody size, showing a gradual upward increase and no sharp boundary at the transition to the Castlegate. This data is derived from heli-lidar data in the Wasatch Plateau and is described in full by Rittersbacher et al 2014. B. GoogleEarth view of the Mitchell Base in the Gulf of Capentaria which is considered analogues to the Blackhawk/Castlegate system. The proximal DFS is represented by stacked braided sandstones similar to the Castlegate SST, the medial is comprised of sheet like, meandering fluvial deposits, similar to the main part of the non-marine Blackhawk. The distal DFS is comprised of isolated channels with a degree of tidal modification, similar to the lower part of the non-marine Blackhawk.

Fig 9. Shelf turbidites in the basin. The Prairie Canyon Mb, seen here at Hatch Mesa, was original interpreted to represent lowstand deposits deposited seaward of the incised valleys in the Book Cliffs. Recent work by Pattison (2007) and Hampson (2010) has revised these correlations and suggested that they are potentially associated with salt movement on the Salt Valley Anticline. Cross section from Hampson (2010).

Fig 10. Stratigraphy of the Book Cliffs succession with most recent eustatic sea-level curve of Kominz et al. (2008). Comparison of the rate of eustatic sea-level change and the rate of subsidence suggests that at no point during the deposition of the succession was there a “relative fall” so no type-1 sequence boundaries should be expected.

References

Ainsworth, R.B., and Pattison S.A.J., 1994, Where have all the lowstands gone? Evidence for attached lowstand systems tracts in the Western Interior of North America: Geology, v. 22, p. 415-418

Catuneanu, O., 2006, Principles of Sequence Stratigraphy: Amsterdam, Elsevier, 375 p.

Charvin, K., Hampson, G.J., Gallagher, K.L., and Labourdette, R., 2010, Intra-parasequence architecture of an interpreted asymmetrical wave-dominated delta: Sedimentology, v. 57 p. 760-785.

Ainsworth, R.B. & Vakarelov, Boyan & Nanson, Rachel, 2011, Dynamic spatial and temporal prediction of changes in depositional processes on clastic shorelines: Toward improved subsurface uncertainty reduction and management. AAPG Bulletin. 95. 267-297.

Davies, R., Howell, J., Boyd, J., Flint, S. S., and Diessel, C., 2006, High resolution sequence stratigraphic correlation between shallow marine and nonmarine strata: Expression of accommodation changes within the Sunnyside Coal Book Cliffs, Eastern Utah, USA: The American Association of Petroleum Geologists Bulletin, v. 90, p. 1121-1140.

Ericksen, M.C., and Slingerland, R., 1990, Numerical simulations of tidal and wind-driven circulation in the Cretaceous Interior Seaway of North America: Geological Society of America Bulletin, v. 102, p. 1499-1516.

Eide, C.H., and Howell J.A., 2014, Distribution of discontinuous mudstone beds within wave-dominated shallow-marine deposits: Star Point and Blackhawk Formations, eastern Utah: The American Association of Petroleum Geologists Bulletin, v. 98, p. 1401–1429.

Eide, C.H., Howell, J.A., and Buckley, S.J., 2015, Sedimentology and reservoir properties of tabular and erosive offshore transition deposits in wave-dominated, shallow-marine strata: Book cliffs, USA: Petroleum Geoscience, v. 21, p. 55-73.

Esterle, J.S., and Ferm, J.C., 1994, Spatial variability in modern tropical peat deposits from Sarawak, Malaysia and Sumatra, Indonesia: analogues for coal: International Journal of Coal Geology, v. 26, p. 1-41.

Hajek, E.A., and Heller, P.L., 2012, Flow-depth scaling in alluvial architecture and nonmarine sequence stratigraphy: example from the Castlegate Sandstone, Central Utah, U.S.A.: Journal of Sedimentary Research, v.82, p. 121-130.

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

Hampson, G.J., Burgess, P.M., and Howell, J.A., 2001, Shoreface tongue geometry constrains history of relative sea-level fall: Examples from Late Cretaceous strata in the Book Cliffs area, Utah: Terra Nova, v. 13, p. 188-196.

Hampson, G.J., and Howell,J.A., 2005, Sedimentological and geomorphic characterization of ancient wave-dominated deltaic shorelines: Late Cretaceous Blackhawk Formation, Book Cliffs Utah, in Giosan, L., and Bhattacharya, J.P., eds. River Deltas – Concepts, Models and Examples: Society of Economic Paleontologists and Mineralogists Special Publication No. 83, p. 133-154

Hampson, G.J., Royhan Gani, M., Sahoo, H., Rittersbacher, A., Irfan, N., Ranson, A., Jewell T.O., Gani, N.D.S., Howell, J.A., Buckley, S.J., and Bracken, B., 2012, Controls on large-scale patterns of fluvial sandbody distribution in alluvial to coastal plain strata: Upper Cretaceous Blackhawk Formation, Wasatch Plateau, Central Utah, USA: Sedimentology, v. 59, p. 2226-2258

Helland-Hansen, W., and Martinsen, O.J. 1996, Shoreline trajectories and sequences: Description of variable depositional-dip scenarios: Journal of Sedimentary Research, v. 66, p. 670-688.

Horton, B.K., Constenius, K.N., and DeCelles, P.G. 2004, Tectonic control on coarse-grained foreland-basin sequences: An example from the Cordilleran foreland basin, Utah: Geology, v. 32, p. 637-640.

Howell, J., and Flint, S., 2004, Sequences and systems tracts in the Book Cliffs, in Coe, A., ed., The Sedimentary Record of Sea-level Change. Cambridge University Press, p. 135-208.

Kamola, D.L., and Huntoon, J.E., 1995, Repetitive stratal patterns in a foreland basin sandstone and their possible tectonic significance: Geology, v. 23, p. 177-180.

Kominz, M. A., Browning J. V., Miller, K. G., Sugarman, P. J., Mizintsevaw S. and Scotese C. R. 2008 Late Cretaceous to Miocene sea-level estimates from the New Jerseyand Delaware coastalplain coreholes: an error analysis. Basin Research 20, 211–226, doi: 10.1111/j.1365-2117.2008.00354.x

Krystinik, L.F., and DeJarnett, B., 1995, Lateral variability of sequence stratigraphic framework in the Campanian and Lower Maastrichtian of the Western Interior Seaway, in in J. C. Van Wagoner, and G. T. Bertram, eds., Sequence Stratigraphy of Foreland Basin Deposits: Outcrop and Subsurface Examples from the Cretaceous of North America: AAPG Memoir 64 pp. 11-25.

Miall, A.D., 1994, Reconstructing fluvial macroform architecture from two-dimensional outcrops: examples from the Castlegate Sandstone, Book Cliffs, Utah: Journal of Sedimentary Research B: Stratigraphy & Global Studies, v. B64, p. 2.

Miller, K.G., Wright, J.D., and Browning, J.V., 2005, Visions of ice sheets in a greenhouse world: Marine Geology, v. 217, p. 215-231.

O'Byrne, C.J., and Flint, S., 1995, Sequence, parasequence, and intraparasequence architecture of the Grassy Member, Blackhawk Formation, Book Cliffs, Utah, USA: in J. C. Van Wagoner, and G. T. Bertram, eds., Sequence Stratigraphy of Foreland Basin Deposits: Outcrop and Subsurface Examples from the Cretaceous of North America: AAPG Memoir 64 pp. 225-255

Pattison, S.A.J., 1995, Sequence stratigraphic significance of sharp-based lowstand shoreface deposits, Kenilworth Member, Book Cliffs, Utah: American Association of Petroleum Geologists Bulletin, v. 79, p. 444-462

Pattison, S.A.J., 2018 Using classic outcrops to revise sequence stratigraphic models: Reevaluating the Campanian Desert Member (Blackhawk Formation) to lower Castlegate Sandstone interval, Book Cliffs, Utah and Colorado, USA. Geology. doi.org/10.1130/G45592.1

Pattison, S.A.J., Ainsworth, B.R., and Hoffman, T.A. 2007, Evidence of across-shelf transport of fine-grained sediments: Turbidite-filled shelf channels in the Campanian Aberdeen Member, Book Cliffs, Utah, USA: Sedimentology, v. 54, p. 1033-1063

Posamentier, H.W., and Vail, P.T., 1988, Eustatic controls on clastic deposition II - Sequence and system tract model, in Wilgus, CK et al., eds., Sea-Level Changes: An integrated approach: Society of Economic Palentologists and Mineralogists Special Publication 42, p. 125-154

Posamentier H.W., Morris W.R. 2000, Aspects of the stratal architecture of forced regressive deposits: Geological Society Special Publication, 172, pp. 19-46.

Rittersbacher, A, Howell, J.A., and Buckley, S.J., 2014, Analysis of fluvial architecture in the Blackhawk Formation, Wasatch Plateau, Utah using large 3D photorealistic models: Journal of Sedimentary Research, v. 84, p. 72–87.

Sech ,R.P., Jackson, M.D., and Hampson, G.J. 2009, Three-dimensional modeling of a shoreface-shelf parasequence reservoir analog: Part 1. surface-based modeling to capture high-resolution fades architecture: The American Association of Petroleum Geologists Bulletin, v. 93, p. 1155-1181.

Sømme, T.O.; Howell, J., and Hampson, G. J. 2008, Architecture and genesis of intra-parasequence discontinuity surfaces in wave-dominated deltaic deposits: Upper Cretaceous Sunnyside Member, Book Cliffs, Utah, U.S.A, in Hampson, G.J., Steel, R.J., Burgess, P.M., and Dalrymple, R.W., eds, Recent Advances in Models of Siliciclastic Shallow-Marine Stratigraphy. Society of Economic Paleontologists and Mineralogists Special Publication No. 90 p 437-456.

Taylor, D.R., and Lovell R.W.W. 1995, High-frequency sequence stratigraphy and paleogeography of the Kenilworth Member, Blackhawk Formation, Book Cliffs, Utah, USA. In J. C. Van Wagoner, and G. T. Bertram, eds., Sequence Stratigraphy of Foreland Basin Deposits: Outcrop and Subsurface Examples from the Cretaceous of North America: AAPG Memoir 64, pp. 257-275.

van Cappelle, M.S., Stephen J., Hampson, G. J. and Johnson, H., 2016, Fluvial to tidal transition in proximal, mixed tide-influenced and wave-influenced deltaic deposits: Cretaceous lower Sego Sandstone, Utah, USA. Sedimentology. 63.

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

Van Wagoner, J.C., 1995, Sequence stratigraphy and marine to nonmarine facies architecture of foreland basin strata, Book Cliffs, Utah, USA, in in J. C. Van Wagoner, and G. T. Bertram, eds., Sequence Stratigraphy of Foreland Basin Deposits: Outcrop and Subsurface Examples from the Cretaceous of North America: AAPG Memoir 64 pp. 137-223.

Weissmann, G.S., Hartley, A.J., Nichols, G.J., Scuderi, L.A., Olson, M., Buehler, H., Banteah, R. 2010, Fluvial form in modern continental sedimentary basins: Distributive fluvial systems: Geology, v. 38, p. 39-42.

Wellner, R; Beaubouef, R., Van Wagoner, J.C., Roberts, H., and Sun, T. 2005, Jet-Plume Depositional Bodies—The Primary Building Blocks of Wax Lake Delta: Gulf Coast Association of Geological Societies Transactions, v. 55, p.867-909

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

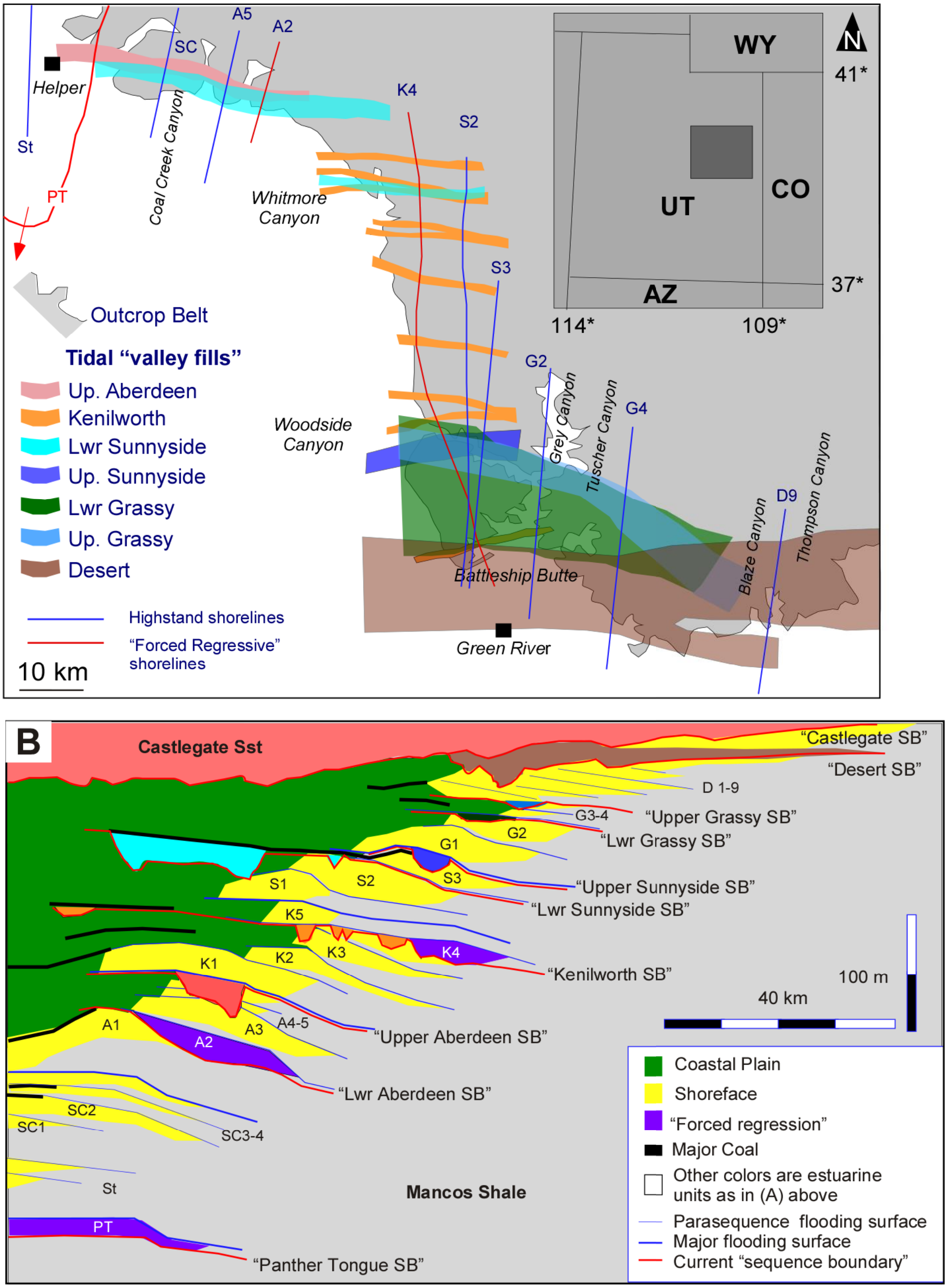


Fig 1. Current sequence stratigraphic interpretation of the Book Cliffs. A) Map of outcrop belt showing selected shoreline positions (see B) and the position of tidal estuarine deposits previously interpreted as incised valleys generated by sea-level fall and the position of selected highstand and "forced regressive" shorelines. B) Projected depositional dip section showing the sequence stratigraphic interpretation of the Book Cliffs. PT Panther Tongue; St Storrs Mb; SC 1-4 Spring Canyon Parasequences, A1 - 5 Aberdeen parasequences; K1-5 Kenilworth Parasequences; S1-3 Sunnyside Parasequences; G1-4 Grassy Parasequences; D1-9 Desert Parasequences.

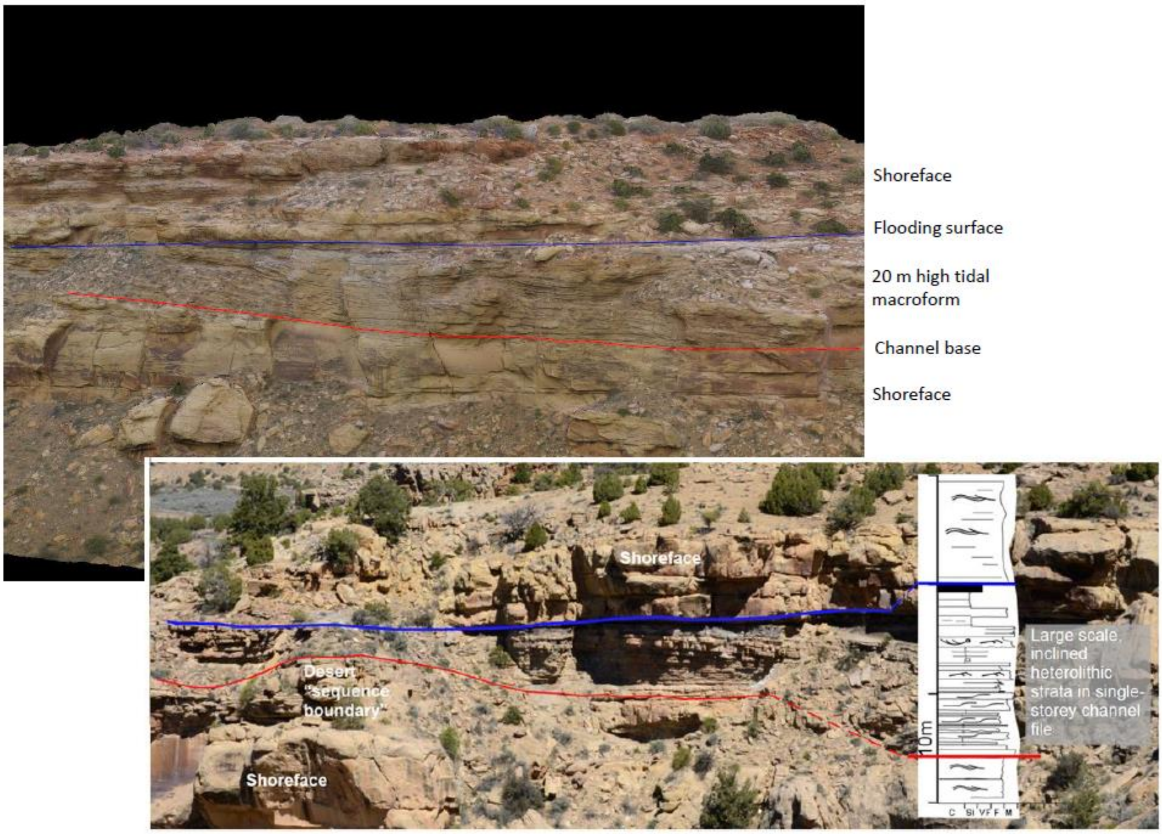


Fig 2. Detail of the Desert succession in Thompson Canyon previously interpreted as an incised valley by Van Wagoner (1995). Upper section is taken from a virtual outcrop (built from UAV acquired photographs using SfM) and illustrates that the heterolithic tidal macro-forms scale to the channel. Lower view shows the "classic" Thompson outcrop which also shows tidal heterolithic strata, capped by a thin coal which also scale to the size of the channel, illustrating that the interval is a single-storey complex.

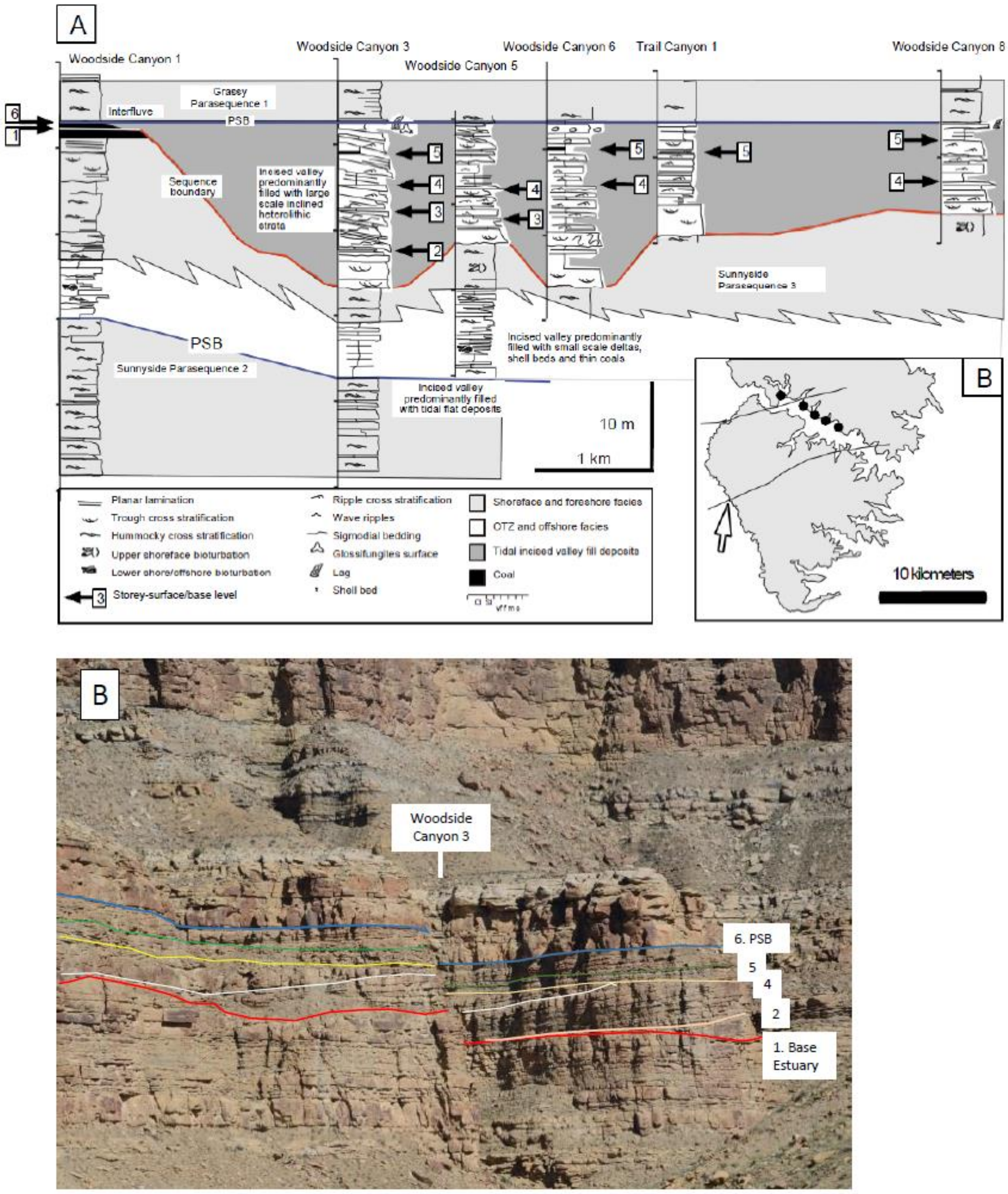


Fig 3. Multi-storey tidal estuarine succession in the Sunnyside Member in Woodside Canyon. A) A series of logged sections showing detail of the complex. B) A photograph of the section in log 3. Note the thick coal in Log 1.

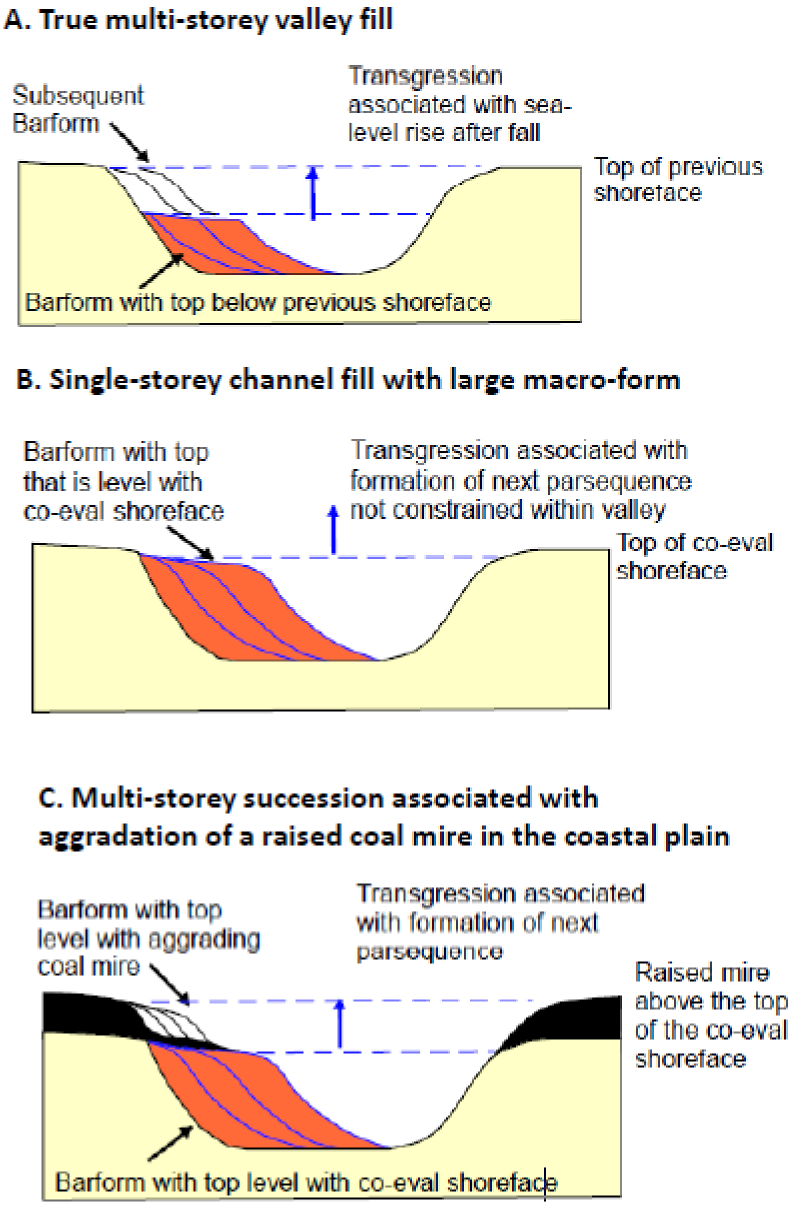


Fig 4. Model to illustrate the multi-storey vs single-storey channel stacking. In A. a multi-storey channel body is formed because base-level is rsing within a valley previously cut by base-level fall. This is a true incised valley. B. A single-storey channel where the tidal macro-forms scale to the channel. This shows no evidence for base-level fall despite the depth of incision. C. Shows a multi-storey body which is formed due to aggradation of the coastal plain, in this case caused by growth of a raised peat-mire. This is the suggested model for the Sunnyside outcrops in Woodside Canyon.

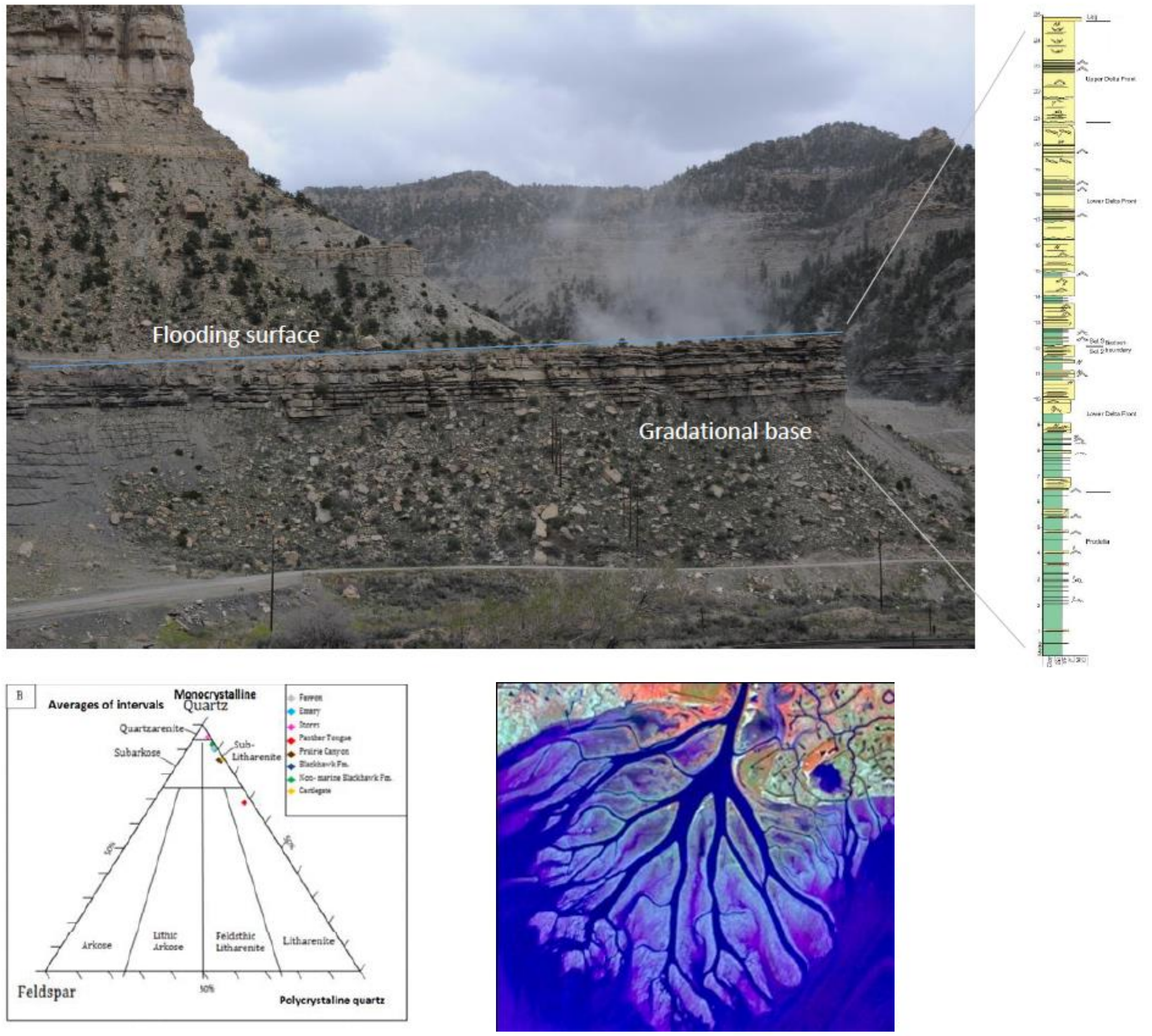
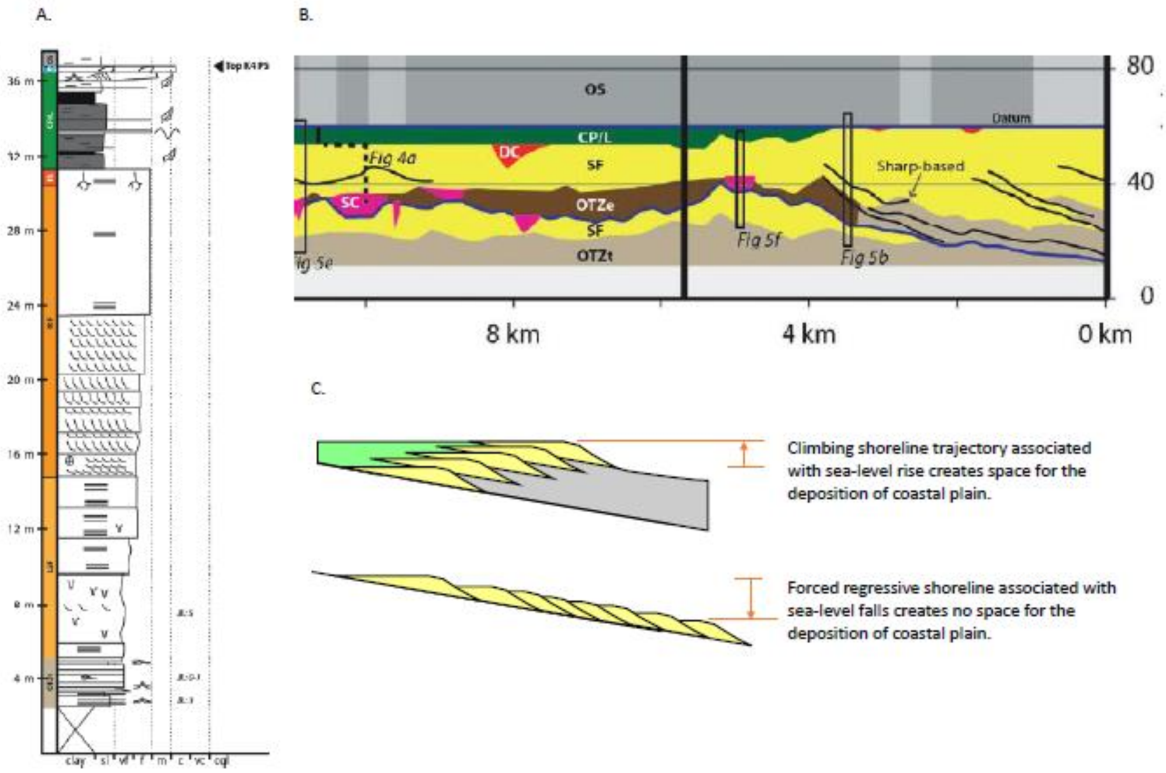


Fig 5. The Panther Tongue near Helper. A. Outcrop photo and sedimentary log showing the seaward dipping clinoforms (towards the south, RHS of image) which suggest a fluvial dominated delta. The photo and log show that there is no sharp base and also the unit has a sharp top with no associated coastal plain deposits. B. QFR plot of the Blackhawk and Starpoint formations showing a distinct petrographic composition in the Panther Tongue (from Mette Lundberg unpublished data) sandstones. C. The modern Wax Lake Delta, an analogue for the Panther Tongue which has similar scale and deposits and was laid down in 40 years following rapid avulsion (from Wikipedia).



Climbing shoreline trajectory associated with sea-level rise creates space for the deposition of coastal plain.

Forced regressive shoreline associated with sea-level falls creates no space for the deposition of coastal plain.

Fig 6. The Kenilworth “Forced Regression” at Battleship Butte. A. Log through the succession, note the presence of 6 m of coastal plain strata on top of the shoreface, illustrating that the unit had a climbing rather than falling trajectory. B. Dip-parallel section derived from heli-lidar data showing the coastal plain (green) and the clinoforms that interfinger with the underlying marine shales (see Eide et al. 2016 for more detail). C. Schematic to show the difference between a normal regression (climbing trajectory) and forced regression (falling trajectory). Note the lack of coastal plain in the lower section.

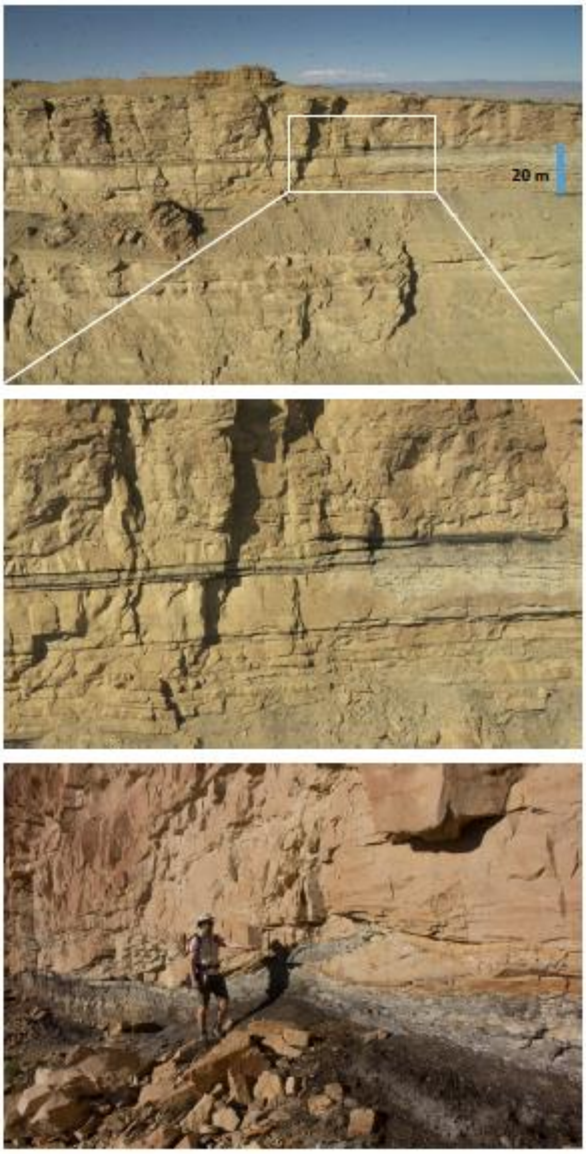


Fig 7. Base Castlegate surface. A. View of Castlegate/Blackhawk contact from the Beckwith Plateau near the I70-US 191 junction, taken from helicopter. B. Detail of the basal surface in A, note that the two units interfinger. C. View in outcrop of the interfingering of the top formations.

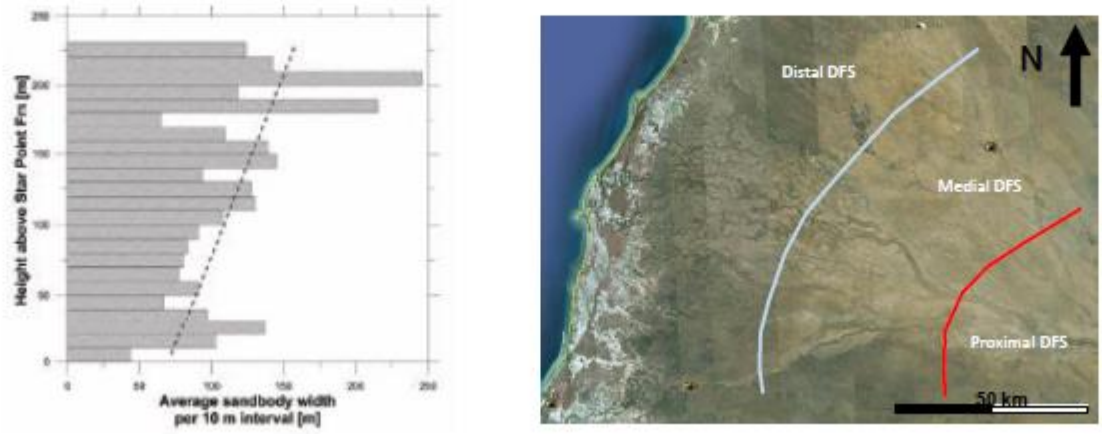


Fig 8. Fluvial stacking patterns. A. Upward increase in average sandbody size, showing a gradual upward increase and no sharp boundary at the transition to the Castlegate. This data is derived from heli-lidar data in the Wasatch Plateau and is described in full by Rittersbacher et al 2014. B. GoogleEarth view of the Mitchell Base in the Gulf of Capentaria which is considered analogues to the Blackhawk/Castlegate system. The proximal DFS is represented by stacked braided sandstones similar to the Castlegate SST, the medial is comprised of sheet like, meandering fluvial deposits, similar to the main part of the non-marine Blackhawk. The distal DFS is comprised of isolated channels with a degree of tidal modification, similar to the lower part of the non-marine Blackhawk.

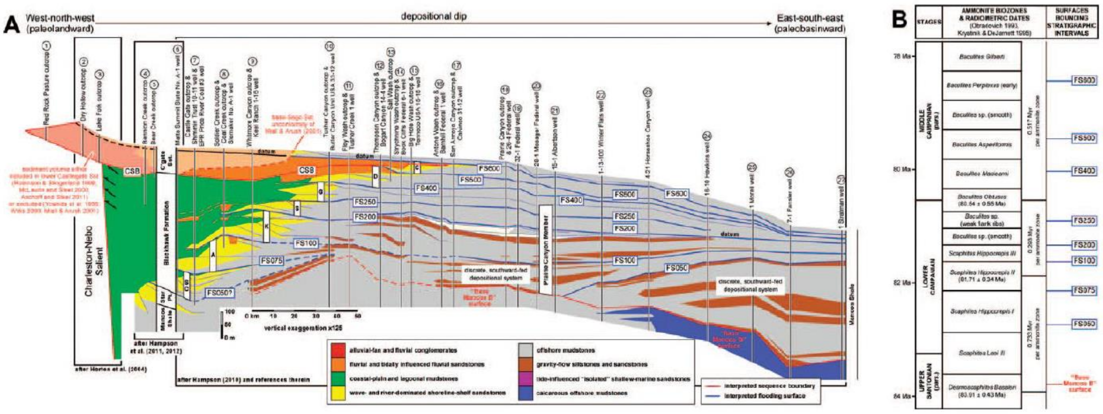


Fig 9. Shelf turbidites in the basin. The Prairie Canyon Mb, seen here at Hatch Mesa, was original interpreted to represent lowstand deposits deposited seaward of the incised valleys in the Book Cliffs. Recent work by Pattison (2007) and Hampson (2010) has revised these correlations and suggested that they are potentially associated with salt movement on the Salt Valley Anticline. Cross section from Hampson (2010).

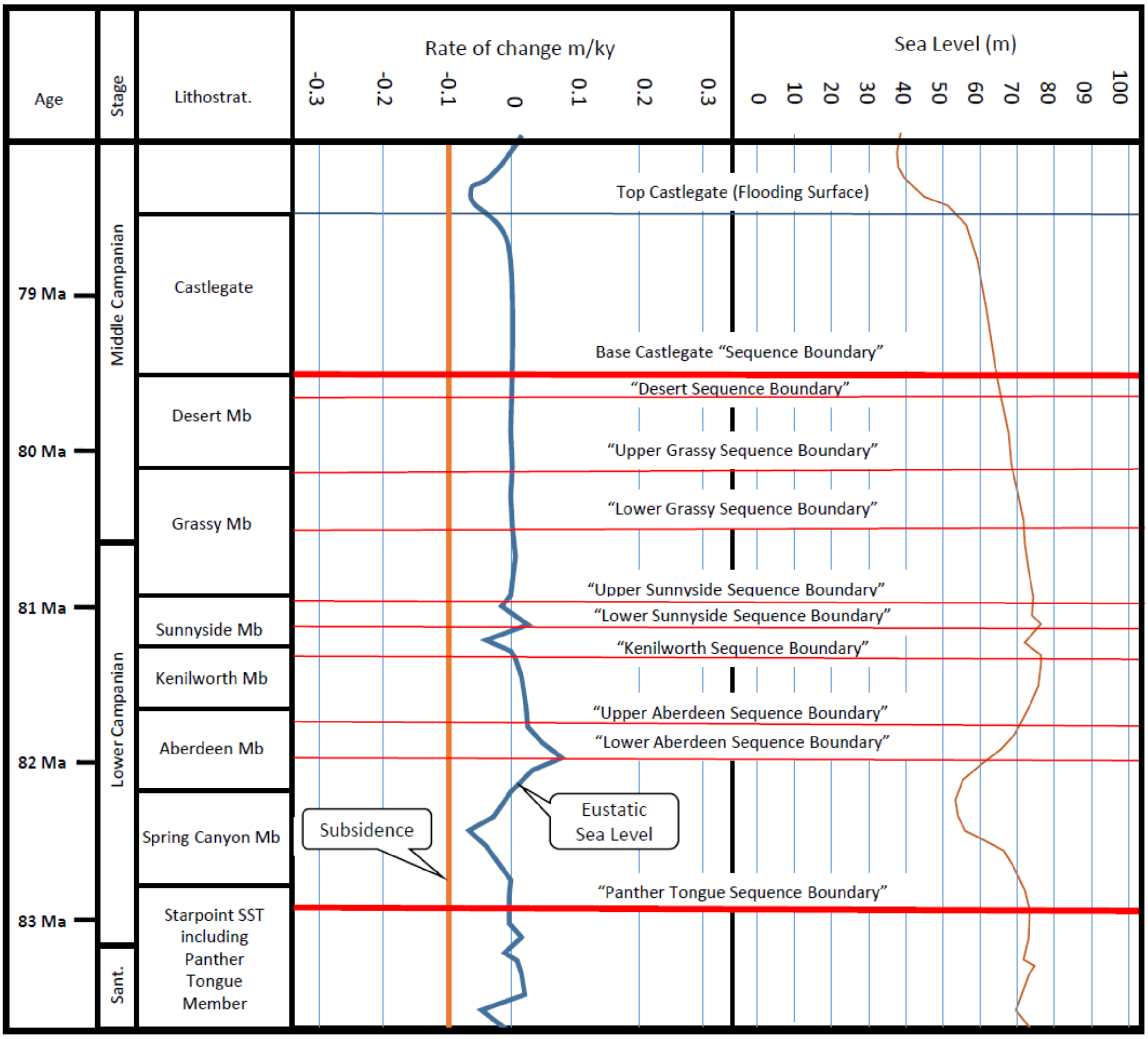


Fig 10. Stratigraphy of the Book Cliffs succession with most recent eustatic sea-level curve of Kominz et al. (2008). Comparison of the rate of eustatic sea-level change and the rate of subsidence suggests that at no point during the deposition of the succession was there a "relative fall" so no type-1 sequence boundaries should be expected.