geosciences

MDPI

Review

The Hell Creek Formation, Montana: A Stratigraphic Review and Revision Based on a Sequence Stratigraphic Approach

Denver Fowler [1,2]

[1] Badlands Dinosaur Museum, Dickinson Museum Center, Dickinson, ND 58601, USA; Denver.fowler@dickinsongov.com
[2] Museum of the Rockies, Montana State University, Bozeman, MT 59717, USA

Received: 12 September 2020; Accepted: 30 October 2020; Published: date

Supporting Information

1. Methods: Lithofacies Descriptions

Facies descriptions follow methodology laid out in Miall (1985). Descriptions mostly follow those of Flight (2004) for the Bearpaw Shale and Fox Hills Sandstone. Additional lithofacies are described for the Colgate sandstone, ?Battle Formation, an undivided Hell Creek Formation, and the lowermost 5–10 m of the Fort Union Formation. It was desirable to stay as close to Flight's (2004) definitions as possible in order to facilitate cross comparison between measured sections and interpretation; however I have also chosen to remain true to the intentions of Brown (1906) in keeping the Basal Sandstone (and associated basal scour) as the first unit of the Hell Creek Formation, rather than the tidal flats identified by Flight (2004). This analysis is not as concerned with the nature of the basal contacts as much as internal stratigraphy within the Hell Creek Formation itself, hence some of the stratal and facies relationships described by Flight (2004) were not directly observed by myself, but I have included them here to ease comparisons.

1.1. Bearpaw Shale

The Bearpaw Shale is the basalmost formation considered in this study; as such only the uppermost 10–20 m have been observed in outcrop. In this upper 20 m or so, the Bearpaw Shale generally coarsens upwards, predominantly comprising shale with occasional interbedded sandstone. All lithofacies display sheet-like geometries.

Geomorphologically, shale units form low, rounded hills, conspicuously different from the cliff forming lithologies of the overlying units. Beds of pale grey to tan, fine grained silty sandstone, up to 1 m thick, become increasingly common in the upper 5–10 m of the formation, where they are interbedded with shale. Sandstones are massive, planar bedded or occasionally hummocky-cross-stratified, weather a pale grey color, and form steeper slopes than the underlying shale. Sandy units within the Bearpaw eventually grade into the overlying Fox Hills Sandstone.

1.1.1. Massive to laminated mudstone (Mml)

Lithofacies Mml is a massive to laminated fissile shale, typically mid-dark grey, weathering to dark grey with occasional zones of iron oxidation.

- Hydrodynamic interpretation

Mml is interpreted as representing deposition by fine grains of sediment falling out of suspension in quiet water (Boggs, 2001).

- Facies associations

Mml typically grades vertically into facies Sh or Sm, but may abruptly overlie Sh or Sm. At some localities Mml is erosively overlain by Se of the Basal Sand or Jen Rex Sand of the Hell Creek

Formation. Flight (2004) states that Se of the Colgate Sandstone may also overlie Mml of the Bearpaw. Although probable, this was not observed in any sections which I measured.

- Depositional process

The gradational contact of overlying facies Sh or Sm is indicative of hemipelagic deposition gradually coming under the influence of higher energy deposition, indicative of shallowing water depth. At localities where Sh or Sm are abruptly overlain by Mml, this is taken to indicate a change from higher energy deposition back to hemipelagic deposition.

1.1.2. Horizontally stratified silty sandstone (Sh)

Lithofacies Sh is a light grey colored, poorly consolidated siltstone or silty sandstone. Grain size is silt-sized to very fine sand. Horizontally stratified beds are usually less than 30 cm in thickness and coarsen upwards. Adapted from Flight (2004).

- Hydrodynamic interpretation

Sh is interpreted as representing upper or lower flow regime deposition, where flows are shallow or of low enough velocity as to not form ripples (Boggs, 2001; Flight, 2004).

- Facies associations

Sh either abruptly overlies Mml, or the contact is gradational. Sh is overlain abruptly by Mml, or gradationally coarsens into Shcs, or Sm of the Fox Hills Formation.

It is noted here that this transitional facies is variably considered as either part of the Bearpaw Shale or Fox Hills Sandstone, depending on which state or region is being studied (e.g., see Jensen and Varnes, 1964; Landman and Waage, 1993; Landman and Cobban, 2003).

- Depositional process

A gradational contact of Sh over Mml is indicative of hemipelagic deposition gradually coming under the influence of higher energy deposition, indicative of shallowing water depth. An abrupt contact may be more indicative of deposition during storm events (Carr et al., 2003; Flight, 2004). At localities where Sh or Sm are abruptly overlain by Mml, this is taken to indicate a change from higher energy deposition back to hemipelagic deposition.

1.1.3. Massive silty sandstone (Sm)

Lithofacies Sm is a light grey colored, poorly consolidated siltstone or silty sandstone. Grain size is silt-sized to very fine sand. Bedding is massive and up to 1–2 meters in thickness. Adapted from Flight (2004).

- Hydrodynamic interpretation

Lack of sedimentary structures in Sm is interpreted as representing either bioturbation by burrowing organisms; rapid deposition; or homogeneity of grain size and sediment type (Flight, 2004).

- Facies associations

Sm either abruptly overlies Mml, or the contact is gradational. Sm is overlain abruptly by Mml, or gradationally coarsens into Shcs, or Sm of the Fox Hills Formation.

It is noted here that this transitional facies is variably considered as either part of the Bearpaw Shale or Fox Hills Sandstone, depending on which state or region is being studied (e.g., see Landman and Waage, 1993; Landman and Cobban, 2003).

- Depositional process

A gradational contact of Sm over Mml is indicative of hemipelagic deposition gradually coming under the influence of higher energy deposition, indicative of shallowing water depth. At localities where Sm is abruptly overlain by Mml, this is taken to indicate a change from higher energy deposition back to hemipelagic deposition.

1.2. Fox Hills Sandstone (excluding the Colgate Sandstone)

The Fox Hills Sandstone is a complex unit that generally coarsens upwards and exhibits a sheet-like geometry with considerable variation in thickness. Lithologies are typically fine grained sandstones (hummocky cross-stratified, trough cross-bedded, planar bedded, ripple cross laminated, and massively bedded) with less common interbedded mudstone. Flight (2004) notes a number of facies which can be medium or coarse grained, but I did not observe medium or coarse grained sand within the Fox Hills Formation, although sandstones of the overlying Hell Creek Formation are commonly medium grained at their bases, fining upwards. This is corroborated in the definition of the Fox Hills Sandstone given by Jensen and Varnes (1964) who suggest the unit comprises only lower to upper fine sand.

The Fox Hills Sandstone is conspicuous in outcrop by its yellow-orange coloration (Figure 4–6); generally distinct from the more pale grey sandstones of the underlying Bearpaw Shale, or overlying Colgate Sandstone and Hell Creek Formation (although the latter are often tan colored).

The gradational transition from the Bearpaw Shale to Fox Hills Sandstone has led to variable lithostratigraphic definitions of the position of the contact (e.g., Landman and Waage, 1993; Landman and Cobban, 2003). For consistency, here the basalmost bed of the Fox Hills Sandstone follows Flight (2004) as being either the first amalgamated hummocky cross-stratified sandstone (in contrast to the isolated units of the Bearpaw Shale), first massive sandstone, or first trough cross-stratified sandstone. Typically the Fox Hills Sandstone is 4–6 m thick, but can reach up to 15 m thick locally (Flight, 2004). Massive bedding and hummocky cross stratification is more common near the base of the formation, with trough cross bedding and ripple cross lamination more common higher up. *Thalassinoides* and *Planolites* burrows are recorded in trough cross-stratified sands by Flight (2004). Large carbonate-concretions are common throughout (Jensen and Varnes, 1964), but especially in the upper part of the unit, which is typically capped by prominent bench-forming cemented sandstones.

1.2.1. Hummocky cross-stratified sandstone (Shcs)

Lithofacies Shcs comprises hummocky cross-stratified well -sorted, well-cemented, fine-grained tan-colored sandstone. Adapted from Flight (2004).

- Hydrodynamic interpretation

Hummocky cross-stratification forms under oscillatory flow conditions, generally taken to represent deposition during storm events (Harms et al., 1975; Dott and Bourgeios, 1982).

- Facies associations

Flight (2004) records that facies Shcs is gradationally overlain by St, Sm, Sr, and Sl, or abruptly overlain by Mml of the Bearpaw Shale. Shcs gradationally overlies Sm, or abruptly overlies Mml of the Bearpaw Shale.

- Depositional process

Shcs is interpreted as representing deposition during storm events (Harms et al., 1975; Dott and Bourgeios, 1982). Flight (2004) reports that the larger bedform size and bedset thickness of Shcs in the Fox Hills Formation (compared to the Bearpaw Shale) indicates that it was deposited under higher energy conditions (note that Shcs was not noted in the Bearpaw Shale by me here).

1.2.2. Massive sandstone (Sm)

Lithofacies Sm is a tan to orange colored well-sorted fine-grained sandstone. Bedding is massive and up to 1–5 meters in thickness. Adapted from Flight (2004).

- Hydrodynamic interpretation

Lack of sedimentary structures in Sm is interpreted as representing either bioturbation by burrowing organisms; rapid deposition; or homogeneity of grain size and sediment type (Flight, 2004).

- Facies associations

Sm gradationally overlies Shcs, St, or Sl of the Fox Hills Formation, or Mml of the Bearpaw Shale. Sm is overlain gradationally by Shs, St, Sl, Sr, and Mm of the Fox Hills Formation, or is overlain abruptly by Mml of the Bearpaw Shale. Sm may be erosively overlain by Se of either the Colgate Sandstone or Hell Creek Formation.

- Depositional process

Sm is considered as representing a transitional unit from other sand bodies (St, Hhcs, Sr) which have more defined structure, suggesting that lack of structure in Sm may not be primary. Structure may have been eliminated by bioturbation (Flight, 2004).

1.2.3. Trough cross-stratified sandstone (St)

Trough cross stratified sandstone (St) is recorded as present in the Fox Hills Sandstone by Flight (2004) and Jensen and Varnes (1964), but was not personally noted by myself as the emphasis of my work is not focused on the Fox Hills Formation; this account is therefore based on the observations of these authors. Lithofacies St is a light gray to tan colored well-sorted, poorly to moderately cemented medium grained sandstone. Troughs are 1–2 m wide and ~0.5 m in height. Bed sets are up to 8 m in thickness. invertebrate feeding traces *Thalassenoides*, *Planolites*, and *Ophiomorpha* are reported as occasionally present by Flight (2004).

- Hydrodynamic interpretation

Trough cross stratification represents dune migration in a lower flow regime with a unidirectional current (Boggs, 2001).

- Facies associations

Flight (2004) observes that St gradationally overlies Shcs, Sm, Sr, or Mm of the Fox Hills Formation, or abruptly overlies Mml of the Bearpaw Formation. St is interbedded or overlain gradationally by Sm, Sr, and Mm, or abruptly by Se of the Hell Creek Formation. Flight (2004) suggests that St might also be gradational above to Fml of the Hell Creek Formation, but this is not shown in any of her measured sections (in her appendix), and is probably not possible based on the depositional hiatus that exists between the Fox Hills and Hell Creek formations; given that this relationship is not shown in any of the measured sections, then I suspect that this is a misstatement, rather than misidentification of Hell Creek Basal Sand as Fox Hills Formation.

- Depositional process

St represents higher energy deposition than Shcs and Sr. Unlike St of the Hell Creek Formation, St of the Fox Hills is not associated with channel forms, and tends to be found at the top of coarsening upward sequence. In comparison, St of the Hell Creek Formation is associated with large channel forms, and is typically the basal unit in a fining upward sequence that ends with a terrestrial mudstone.

1.2.4. Ripple cross-laminated sandstone (Sr)

Lithofacies Sr is a yellow colored well-sorted fine-grained sandstone with asymmetric ripples. Beds are typically ~0.2 m in thickness, but observed up to 0.5 m.

- Hydrodynamic interpretation

Sr is interpreted as forming in a lower flow regime.

- Facies associations

Sr gradationally overlies Shcs, Sm, or Mm of the Fox Hills Formation, or Mml of the Bearpaw Shale (Flight, 2004). Sr is overlain gradationally or interbedded with Sm and Mm, or abruptly overlain by St of the Fox Hills Formation; Fsm of the Colgate Sandstone, or erosively overlain by Se of either the Colgate Sandstone or Hell Creek Formation.

Flight (2004) states that this facies is not abundant in the Fox Hills Formation. My own observation is that is encountered commonly as the uppermost facies of the Fox Hills Formation. Often it is Sr that forms the concreted bench-forming horizon commonly encountered at the upper contact of the Fox Hills Formation.

- Depositional process

Sr represents lower energy or shallower deposition than St within the lower flow regime. Prominence of Sr in the uppermost Fox Hills Formation might be expected as the unit overall records shallowing depositional conditions as it coarsens upwards from the conformable underlying Bearpaw Shale.

1.2.5. Massive mudstone (Mm)

Mm is a massive dark brown or grey, well-sorted, poorly-consolidated silty mudstone. It is a very minor facies, rarely encountered in the Fox Hills Formation. Where it occurs it is limited to beds 10cm or less in thickness, lenticular, and laterally discontinuous over more than a few meters (Flight, 2004).

- Hydrodynamic interpretation

Mm is interpreted as representing deposition by fine grains of sediment falling out of suspension in quiet water (Boggs, 2001). Lack of primary structure may indicate reworking or rapid deposition.

- Facies associations

Mm typically is interbedded with St, Sm, or Sr (Flight, 2004).

- Depositional process

The fine grain size of Mm suggests deposition in low energy setting. This probably occurs within typical Fox Hills depositional cycles as high energy conditions, progress to waning flow, and eventual quiet water conditions whereupon mud can settle out of suspension.

1.2.6. Low angle planar sandstone (Sl)

Flight (2004) notes that lithofacies Sl is rarely observed in the field and combines her own notes with those of Shoup (2001). As the emphasis of my own project does not concern the Fox Hills Formation, I include it here only out of completeness. Sl is a light tan to grey, low angle planar laminated well-sorted medium to coarse grained sandstone.

- Hydrodynamic interpretation

Sl is interpreted as representing upper flow regime deposition, where flows are shallow or of low enough velocity as to not form ripples (Boggs, 2001; Flight, 2004).

- Facies associations

Sl grades upwards intp Sm, or is abruptly overlain by Se or St of the Hell Creek Formation. Sl grades from Sm or Shcs below (Flight, 2004).

- Depositional process

Sl represents swash and backwash; higher energy conditions than observed in Shcs, St, Sr, and probably Sm (Boggs, 2001; Flight, 2004).

1.3. Colgate Sandstone

The Colgate Sandstone is most easily distinguished from the underlying Fox Hills Sandstone by its grey to white weathering color, and greenish-grey fresh surfaces (Main manuscript Figure 7; Calvert, 1912; Thom and Dobbin, 1924; Murphy et al., 2002, although see below). Where present, the Colgate Sandstone rests on an erosive scour that is typically shallow (0–2 m), but sometimes incises up to 25 m into the Fox Hills Sandstone, or even into the underlying Bearpaw Shale (Flight, 2004; Behringer, 2008). A coarse grained basal lag was recorded by Wheeler (1983) although this is rarely encountered (Flight, 2004; Behringer, 2008). Otherwise, the Colgate Sandstone is a micaceous, clay-rich fine grained sandstone, with occasional thin interbedded mudstones, and rare, laterally restricted coals. Bedding is typically massive, occasionally planar, although trough cross stratification is visible in particularly thick sections. Total thickness of the Colgate Sandstone varies, and is typically 2–5 m, but up to 15m in geographically restricted areas (see main manuscript; Flight, 2004).

Sandstone facies of the Colgate sandstone (Sm, St, Sh) are not typically laterally extensive and the unit exhibits mostly restricted channelized geometry (Flight, 2004; Behringer, 2008). The Colgate Sandstone is generally poorly cemented, and large concretions are notably absent, unlike the underlying Fox Hills Sandstone and overlying Basal Sand of the Hell Creek Formation (which may aid in distinguishing the Colgate Sandstone from these units; although note that Waage, 1968, suggests calcareous concretions are present in Colgate Sandstone exposures of South Dakota, none were observed by myself in Montana). *Skolithos* burrows are recorded in sandstones by Flight (2004). Although the bold white weathered color is considered characteristic of the Colgate Sandstone (Calvert, 1912; c; Waage, 1968; Murphy et al., 2002; Flight, 2004; Behringer, 2008), this is variable geographically, and not commonly seen in the Hell Creek type area (Jensen and Varnes, 1964), although it is conspicuous at the northern edge of "Best Butte" (see section description or the Marina

Road exposures). The Colgate Sandstone typically exhibits conspicuous dual color banding (Main manuscript; Figures 5,7,8), with a lower pale tan unit, and a less colorful but brighter pale grey upper unit. The upper unit exhibits more thin interbedded mudstones than the lower unit, and it is the upper unit that sometimes weathers to a bold white color (Main manuscript, Figure 7). In a fresh surface, the contact between the two bands is marked by a thin (~1–2 mm) iron-rich horizon, while the initial 2–3 cm above the contact are notably gleyed (main manuscript, Figure 9).

The Colgate Sandstone fines rapidly or abruptly in the upper 1–2 meters into a grey siltstone (Fsm) which in all observed sections is overlain by an organic-rich horizon (C1). These two lithofacies are included here within the Colgate Sandstone, mainly due to the transitional contact of Sm with Fsm making separation difficult. Previous authors (e.g., Dobbin and Reeside, 1929; Flight, 2004; Behringer, 2008) have included these units as the basalmost facies of the Hell Creek Formation. but again, the transitional nature of Sm to Fsm makes this undesirable. Further discussion of this issue occurs in the main manuscript.

1.3.1. Erosional scour (Se)

The basal contact of the Colgate Sandstone is marked by an erosive scour that is typically shallow (0–2 m), but sometimes incises up to 25 m into the Fox Hills Sandstone, or even into the underlying Bearpaw Shale (Flight, 2004; Behringer, 2008).

- Hydrodynamic interpretation

Se is interpreted as representing a scour formed by current activity removing underlying sediment.

- Facies associations

Se is very rarely overlain by a coarse grained basal lag (recorded by Wheeler, 1983; but not observed here, nor by Flight, 2004; or Behringer, 2008). Typically Se is overlain by Sm or St of the Colgate Sandstone. Where sandstone facies of the Colgate Sandstone are absent, Se is either overlain by Fsm of the Colgate Sandstone, or probably compounded with Se at the base of the Hell Creek Formation.

- Depositional process

Flight (2004) and Behringer (2008) suggest the erosive scour represents a broad incised valley formed by fall in accommodation (in this case, linked to sealevel fall). Evidence in support of this diagnosis includes depth (up to 25 m); lateral continuity of the erosive scour; a non-Waltheran facies shift from marine Bearpaw Shale to estuarine deposits of the Colgate Sandstone, and onlap of the Colgate Sandstone to incised valley walls (Flight, 2004; Behringer, 2008).

1.3.2. Massive sandstone (Sm)

Sm is the most characteristic facies of the Colgate Sandstone, being a greenish-grey, well-sorted, fine to medium grained, micaceous, clay-rich, fining upward sandstone that weathers to a grey or notably conspicuous white color. Bedding is massive, although faint remains of primary bedding are sometimes visible. Sm occasionally exhibits the U-shaped burrow trace fossil *Skolithos* (Flight, 2004).

- Hydrodynamic interpretation

Due to the presence of *Skolithos*, massive bedding is likely to be the result of biogenic reworking destroying primary structures. However, see depositional process.

- Facies associations

Sm overlies Se of the Colgate Sandstone or is transitional from St. Sm is overlain either gradationally or abruptly by Fsm of the Colgate Sandstone, or is erosively overlain by Se of the Hell Creek Formation.

- Depositional process

Without primary structure, it is difficult to ascertain a depositional process for Sm specifically. Massively bedded sandstones may form from sediment gravity flows (Miall, 1996); however, lack of primary structures may also be due to biogenic reworking. The presence of faint vestiges of primary structures is also suggestive that the Colgate Sandstone may have originally had primary structure. It has been suggested that lack of primary structure may be the result of the Colgate Sandstone being composed of a large proportion of lithic fragments, the feldspars of which have been altered diagenetically into clay (explaining the high clay content of this unit, despite the fine to medium sand grain size; Dobbin and Reeside, 1929; Waage, 1968). Flight (2004) notes that other than the lack of structure, the similarity of Sm to St suggests a similar depositional process; ie. that Sm represents fluvial deposition in estuarine, delta mouth-bar, or other marginal marine setting. The upper transition to Fsm (then Fc) represents a decrease in energy and a change in depositional environment to tidal flats.

1.3.3. Trough cross-stratified sandstone (St)

I did not personally observe lithofacies St, but it is included here as it was noted as present at one locality (westernmost Garfield County) by Flight (2004; upon which this account is based) and is important for interpretation of the Colgate Sandstone. St is a well-sorted, fine to medium grained, micaceous, clay-rich sandstone that weathers to a grey or notably conspicuous white color. Troughs are 1–2 m wide and 0.5–1 m deep. St occasionally exhibits the U-shaped burrow trace fossil *Skolithos* (Flight, 2004).

- Hydrodynamic interpretation

Trough cross stratification represents sand transported in traction currents, forming dunes which migrate in a lower flow regime with a unidirectional current (Miall, 1998; Boggs, 2001).

- Facies associations

Flight (2004) states that in the one section in which she observed it, St directly superposed Se and was overlain by Sm.

- Depositional process

Skolithos-dominated ichnofacies are indicative of medium to high-energy wave-dominated foreshore, estuarine, and delta mouth-bars (Buatois and Mangano, 2004). As trough cross-stratification is indicative of unidirectional current, this suggests St represents estuarine, delta mouth-bar, or other marginal marine fluvial deposition. Flight (2004) suggests that the vertical transition from St to Sm may represent change from unidirectional to variable currents (ie. perhaps more tidal or wave-based influence), but I do not see any reason to think that Sm is not simply the result of increased biogenic disruption on St.

1.3.4. Planar horizontally bedded sandstone (Sh)

I did not personally observe lithofacies Sh, but it is included here as it was noted as present at one locality (north of Winnett, Petroleum County) by Flight (2004; upon which this account is based). Sh is a well-sorted, fine to medium grained, micaceous, clay-rich sandstone that weathers to a grey or notably conspicuous white color. Troughs are 1–2 m wide and 0.5–1 m deep. The U-shaped burrow trace fossil *Skolithos* is abundant (Flight, 2004).

- Hydrodynamic interpretation

Planar horizontally bedded sandstone can be deposited under two different conditions (Miall, 1996); within an upper flow regime at the transition from subcritical to supercritical flow for fine to medium grained sand; and in coarse to very coarse sand at low flow speeds (rarely preserved).

- Facies associations

Flight (2004) states that in the single section in which she observed it, Sh is transitional from Sm below, subsequently being abruptly overlain by Fml of her lower Hell Creek Formation. I find the suggestion that Fml overlies Sh to be unlikely as this suggests absence of both Se and the basal sand. Indeed, consultation of the Flight (2004) appendix (containing the measured sections) demonstrates that Fml identified by Flight (2004) is the facies I identify here as Fsm and C1 of the Colgate Sandstone (grey siltstone overlain by an organic rich purple mudstone).

- Depositional process

Skolithos-dominated ichnofacies are indicative of medium to high-energy wave-dominated foreshore, estuarine, and delta mouth-bars (Buatois and Mangano, 2004). Transition from Sm to Sh suggests an increase in energy from probable lower flow regime (Sm), to higher flow regime (Sh). The overlying contact with transitional facies Fsc represents decrease in energy to a tidal flat setting.

1.3.5. Massive mudstone (Mm)

Massively bedded silty mudstone lenses occur interbedded within the Colgate Sandstone. These mudstones are dark brown or grey, well sorted and poorly consolidated. Bed thicknesses are 5 cm or less and are not laterally extensive, typically 10 m or less. I did not observe this facies in the field and its inclusion here follows Flight (2004), who records it at one locality.

- Hydrodynamic interpretation

Mm was deposited as suspension dropout in quiet water.

- Facies associations

Flight records a single locality where Mm occurs interbedded within Sm or Sh. The contacts between lithofacies are undulatory, but with no ripples.

- Depositional process

Thin interbeds of Mm within sandstone facies with undulatory contacts is similar to descriptions of flaser or wavy bedding (Martin, 2000). This is generally taken to represent deposition under periods of intermittent flow, from slackwater (mud deposition) to a stronger current (sand or silt) most notably in a tidally-influenced setting (Martin, 2000; Boggs, 2001).

1.3.6. Massive to laminated siltstone (Fsm)

The first of my new lithofacies of the Colgate Sandstone is a massive siltstone or mudstone (Fsm) which in association with the overlying organic rich mudstone (C1), usually forms the uppermost bed of the Colgate Sandstone. This unit was assigned (in part) to Fml of the lower Hell Creek Formation by Flight (2004), but I move it into the Colgate Sandstone, because at some localities Sm of the Colgate sandstone fines upwards into Fsm, suggesting that it should be considered part of the Colgate depositional cycle.

Fsm is a medium to pale grey, well sorted siltstone. Bedding is massive, with beds up to 50 cm thick, although typically closer to 10cm, and sometimes as little as 2–5 cm. Flight (2004) suggests that Fsm (her Fml) may reach up to 3 m in thickness at some localities (in combination with the overlying lithofacies C1). Root traces are present which may penetrate completely through Fsm into the underlying Sm (Flight, 2004). Flight (2004) records occasional *Skolithos* burrows occurring in lower parts of Fsm. Fsm occurs with sheet-like geometry as a single horizon at or near the top of the Colgate depositional cycle. Fsm is sometimes present even if underlying Colgate Sandstone St, Sm, or Sh are absent.

- Hydrodynamic interpretation

Massive to laminated silt or mudstone represents deposition from suspension or weak traction currents (Miall, 1996). It is possible that massive bedding is a result of rapid deposition of uniform grain size, or a sediment gravity flow. However, presence of laminae in some sections, and presence of rootlets and *Skolithos* traces (Flight, 2004) suggest that any lack of primary structures is due to secondary biogenic reworking.

- Facies associations

Fsm overlies Sm abruptly or gradationally. It can also occur in the absence of sandstone facies, therefore directly overlying Sm or Sr of the Fox Hills Formation; in this situation there is no evidence of an erosive scour (Se) of the Colgate Sandstone. Fsm is overlain abruptly by the organic rich horizon C1.

- Depositional process

The transitional or abrupt contact between underlying Sm and Fsm suggests decrease in energy combined with flooding. Presence of *Skolithos* in lower parts of Fsm, being replaced by root traces is consistent with a decrease in energy being associated with a change from fluvial or estuarine conditions to tidal flat (Flight, 2004).

1.3.7. Coal or organic-rich shale (C1 and C2)

The second of my new lithofacies of the Colgate Sandstone refers to two separate organic rich lithofacies both included as classification code C (Miall, 1985).

The first lithofacies (C1) is a purple, or reddish brown siltstone or silty mudstone almost always encountered as the uppermost unit of the Colgate Sandstone. Bedding is massive or laminated, and sheet-like in geometry. The unit rarely exceeds 40 cm in thickness, but is typically much less (<10 cm) and can be as little as 1cm. Bed thickness is generally related to thickness of the Colgate Sandstone overall; in areas where the Colgate Sandstone is thick, unit thicknesses of lithofacies Fsm and C1 also tend to be thicker. The unit is organic rich with plant detritus, although fragments are small enough such that the type of plant cannot be discerned.

The second use of lithofacies C2 refers to a more typical coal which is rarely encountered interbedded within Sm. Flight (2004) does not record the presence of coal within the Colgate, but coals are present (albeit very rarely) as thin (<50cm) lenses (main manuscript, Fig. 8) within massively bedded sandstone. Lenticular coals have not been observed more than ~10 m in width, and were only observed at Crooked Creek, north of the small town of Winnett (Petroleum County, ~120 km west of Jordan; main manuscript, Figure 1).

- Hydrodynamic interpretation

Massive to laminated silt or mudstone represents deposition from suspension or weak traction currents (Miall, 1996).

Coal deposition occurs in quiet water settings.

- Facies associations

C1 overlies Fsm abruptly, and is overlain by Se, Sihs, Sm, or St of the Hell Creek Formation. C2 occurs as laterally discontinuous interbeds within Sm of the Colgate Sandstone.

- Depositional process

Presence of organic fragments, in combination with rootlet traces into and through the underlying Fsm supports interpretation of Fsm through C1 as tidal flats.

C2 represents accumulation and burial of peat or a concentration of woody materials in a quiet water setting. However, as lenticular interbeds of coal within Sm, C2 probably does not represent extensive coal swamps; rather coal beds are either reworked from elsewhere, or represent quiet water deposition in abandoned chutes or ox-bows.

1.4. ?Battle Formation

An unusual set of lithofacies up to 10 m in thickness occurs between the underlying Colgate Sandstone (C1), and erosively overlying Basal Sand of the Hell Creek Formation (Se, followed by Sm, Shcs, or St). The set of lithofacies comprise a basal pale colored siltstone (seatearth, Fr), an organic rich silt or sandstone (C), and mauve or green-grey banded mudstone (Fml).

These lithofacies were assigned (in part) to Fml of the lower Hell Creek Formation by Flight (2004). However, here I very tentatively refer them to the Battle Formation (otherwise only recorded in southern Alberta and Saskatchewan). This referral is based on lithological similarity to description of the Battle Formation given by Irish (1970), and the occurrence of palynomorphs which have correlated with the Battle Formation in Alberta and Saskatchewan (Lerbekmo, 2009).

These facies show similarity to the organic rich C1 facies as defined above as the uppermost facies of the underlying Colgate Sandstone. However, I chose to include C1 within the Colgate Sandstone (rather than the Battle Formation) as C1 is encountered overlying Fsm of the Colgate Formation in sections where neither the sandstone facies of the Colgate Sandstone, nor the Battle Formation facies are present. In the future it might be desirable to remove both Fsm and C1 from the Colgate Sandstone and place them within the Battle Formation, although definition of the boundary between these units is not clear, and I am unable to find good photographs; for example, it is not clear if the basal bed of the Battle Formation is one of the organic-rich horizons, or the underlying pale siltstone (Irish, 1970; Eberth and Braman, 2012).

It is necessary to separate these possible Battle Formation facies mainly due to the confusion that their inclusion in either the Colgate or Hell Creek formations might cause concerning the age of these units and their contacts. I also consider that the basal unit of the Hell Creek Formation should be maintained as the Basal Sandstone as originally defined by Brown (1907), and consistent with current understanding of depositional cyclicity.

I have only encountered these probable Battle Formation facies in the area around Hell Creek itself, most easily observable at Manaige Spring (see main manuscript), but also in the cliffs visible on both sides of the usually flooded tributary of Hell Creek itself ("Battle Butte"). Combined thickness of the Battle Formation lithofacies is 10 m at Manaige Spring, but thins northwards such that it is only ~ 5 m thick at Battle Butte (~ 1 km north of Manaige Spring), and absent at "Best Butte" (~3 km NE of Manaige Spring; see main manuscript). I suspect that this represents considerable northwards thinning and hence consider the Battle Formation as lenticular in geometry.

These facies descriptions are only preliminary as a more detailed investigation of these specific beds has not been conducted.

1.4.1. Seatearth (Fr)

A conspicuous pale cream-colored silt or silty mudstone which is massively bedded, up to 30 cm thick, well sorted and poorly consolidated. This facies was only observed at two localities where it has a sheet-like geometry. The facies was not analysed closely enough to ascertain if rootlets were present.

- Hydrodynamic interpretation

Massive silt or mudstone represents deposition from suspension or weak traction currents (Miall, 1996). It is possible that massive bedding is a result of rapid deposition of uniform grain size, or a sediment gravity flow.

- Facies associations

Fr abruptly overlies C1 of the Colgate Sandstone and abruptly underlies C of the Battle Formation.

- Depositional process

Based on its position underlying the organic rich horizon C, lithofacies Fr is tentatively interpreted as a seatearth.

1.4.2. Organic-rich silt, silty mud, or sandstone (C)

lithofacies C is a dark brown to black, organic rich horizon with grain size varying from silt or silty mud, to fine sandstone. The most easily observable section exposing this facies at Manaige Spring on the Hell Creek Marina road (see main manuscript), where C is a massive to laminated silt or silty mud. However, ~2 km to the east in Jordan Coulee (47°34′2″ N, 106°55′39″ W; NAD27CONUS), C is a fine grained silty sandstone. Large cm-scale fragments of wood are occasionally present, especially so when C is a sandstone. C reaches a maximum thickness of ~30 cm and has a sheet-like geometry.

- Hydrodynamic interpretation

Massive to laminated silt or mudstone represents deposition from suspension or weak traction currents (Miall, 1996). The more sandy occurrence of this facies represents deposition in higher energy conditions.

- Facies associations

C abruptly overlies Fr, and is abruptly overlain by Fml of the Battle Formation.

- Depositional process

Presence of organic fragments, in combination with rootlet traces into and through the underlying Fsm supports interpretation of Fsm through C1 as tidal flats.

1.4.3. Massive mudstone (Fml)

Fml is a massively bedded mudstone. It is variable in coloration, although generally dominated by mauve purple and green-grey bands. It has only been observed in detail at the Manaige Spring locality where it is ~11 m thick, but is also visible northwards along the east and west valley walls of Hell Creek itself where it is eroded by incision by the overlying Se of the Hell Creek Formation. This limited exposure suggests a sheet-like geometry.

- Hydrodynamic interpretation

Mm was deposited as suspension dropout in quiet water.

- Facies associations

Mm abruptly overlies C of the Battle Formation and is erosively overlain by Se, Sm, Sihs, or St of the Hell Creek Formation.

- Depositional process

The abrupt contact of Mm with underlying C suggests a change from tidal flat to floodplain deposition. The erosive contact of Se (then Sm, Shcs, or St) of the Hell Creek Formation suggests an increase in energy; in the case of Sm or St to a fluvial channel; in the case of Shcs, fluctuating flow strength possibly indicative of tidal influence or seasonal variation.

1.5. Hell Creek Formation

The ~80–90 m thick Hell Creek Formation consists of seven lithofacies comprising an erosional scour (Se), Inclined heterolithic strata (Sihs), trough cross-bedded (St), massive (Sm), and ripple cross-laminated sandstones (Sr), massive to laminated siltstones and mudstones (Fml), and organic rich facies (C). Lithofacies are for the most part fluvial in origin, although there is some indication of possible marine or tidal influence in basal beds. Here I differ from Flight (2004) in that I do not consider the Basal Sandstone as a subdivision separate from the rest of the Hell Creek Formation.

A detailed overview of the Hell Creek Formation is given in the main manuscript.

1.5.1. Erosional scour (Se)

Erosional scours can be found within the Hell Creek Formation at the bases of the four major amalgamated sandstone units (Basal Sand; Jen Rex Sand; Apex Sand; Ten Meter Sand; Hartman et al., 2014), but also at the bases of isolated channels.

Normally the basal contact of the Hell Creek Formation with the underlying unit (various) is not strongly erosive (main manuscript Figure 4, 5, 10), but is occasionally up to 5m depth (main manuscript, Figure 10). However, scouring is relatively rare and very localized in nature, perhaps explaining how it was not observed by Flight (2004), although it was mentioned by Brown (1907; 1914) and Jensen and Varnes (1964), who suggested incisions up to 10 m are known. The exceptionally thick Basal Sand at the type section (Hartman et al., 2014; as reinterpreted here) represents at least ~15 m of relief.

The base of the Jen Rex Sand is usually marked by an erosive scour, with depth variation highly localized, typically from 0–5 m, but up to 15 m (Flight, 2004). The scour at the base of the Apex Sand usually shows very little relief but has been observed to incise up to 5 m into the Middle Hell Creek Formation, to the top of the Null Coal (East Gilbert Creek; see main manuscript). Typically, the least relief is seen for Se at the base of the 10 m sand, which was only observed with any notable incision at the south side of East Gilbert Creek where it incises ~10 m into the top of the Apex Sand.

At some localities, Se is overlain by a lag of gravel to cobble-sized clasts. This has been observed for both the basal Se and that of the Jen Rex Sand. Even in the absence of a conglomerate, Se is commonly overlain by a lag deposit of dinosaur bones.

- Hydrodynamic interpretation

Se is interpreted as representing a scour formed by current activity removing underlying sediment.

- Facies associations

At the basal contact, since the depth of Se can be up to 25m, then it can erosively overlie any of the facies down to Mml of the Bearpaw Shale. I have not personally observed this relationship however; the deepest incision of Se that I have observed is at the new type section where Se erosively overlies Sm of the Bearpaw Shale.

Se is typically overlain by a medium grained sandstone of the Hell Creek Formation, either Sm or St. More rarely, Se is overlain by Sihs (only observed at the basal contact; Flight, 2004).

- Depositional process

Erosive scours can represent major regional events, or localized channel scouring. Regional erosive scours (present at the bases of major amalgamated sandstone units) are evidence of stillstand or fall in accommodation, and may represent significant periods of time (tens of thousands to millions of years). Localized scouring at the bases of isolated channels is representative of an order of magnitude less time, centuries to thousands of years.

1.5.2. Inclined Heterolithic Strata (Sihs)

Flight (2004) describes Inclined Heterolithic Strata (IHS) as a relatively common lithofacies (Sihs) encountered as part of the Basal Sand, although no convincing photograph is provided. However, Sihs is recorded at Site #10 of Flight (2004; Figure 13 and appendices), which is the same as what I call "best butte" (see main manuscript). I did not have the opportunity to measure a section at best butte, but I did take a series of photographs (see main manuscript). The facies described by Flight (2004) as IHS are low angle inclined beds which occur overlying Sm at the top of the first package of sandstones (immediately overlying C1 of the Colgate Sandstone), alternating in lithology between sandstone and mudstone; consistent with description of IHS given by Thomas et al. (1987).

The following description is adapted from Flight (2004). Sihs comprises shallowly inclined beds of sandstone and mudstone with sporadic, often large iron concretions. Sand beds are typically ~30 cm thick, well sorted, fine grained, and exhibit ripples and occasional flaser bedding. Bimodal current direction was recorded at one section (best butte) by Flight (2004). Mudstone beds are ~5–10 cm thick, dark brown to black (this coloration is not immediately obvious based on photographs of best butte) and contain plant fossils.

Sihs is recorded only as a component lithofacies of the Basal Sand, and is not observed higher up in the Hell Creek Formation (e.g., Jen Rex Sand, Apex Sand, 10 Meter Sand). Sihs is not laterally extensive, even within the Basal Sand, and should be considered as channelized geometry.

- Hydrodynamic interpretation

Alternating beds of sandstone and mudstone indicate cyclic deposition between higher energy flow (sand) to suspension fallout (mud; Thomas et al., 1987).

- Facies associations

Other than the alternating beds that define the lithofacies, Sihs gradationally overlies Sm, and is gradationally overlain by St or Fml of the Hell Creek Formation.

- Depositional process

IHS represents environments that experience cyclic variation in depositional conditions. As such, IHS is often considered as indicative of tidally influenced deposition (Thomas, 1987). This was contested by Eberth (2005) who suggested that IHS encountered far inland from the shoreline may instead be indicative of seasonal variation in climate, or other forcing factors.

1.5.3. Trough cross-stratified sandstone (St)

St is a well-sorted, medium to fine-grained, clay-rich sandstone that weathers to a grey or tan color, often in a distinctive rilled pattern. Bedsets were observed up to 25 m thick, comprised of individual beds typically 1–2 m in thickness. Troughs are typically 1–2 m wide, but up to 5m (Flight, 2004) and 0.5–2 m deep. Bedsets and individual beds fine upwards. St contains calcareously cemented concretions, which are frequent and sometimes large, on the scale of meters. St can be of either channelized or sheet-like geometry. Channelized geometry is more commonly observed in the Basal Sand or Jen Rex Sand in the lower half of the Hell Creek Formation. St is broadly equivalent to the "cross-stratified sandstone" facies of Fastovsky (1987).

Conglomerate lags are occasionally observed within the lower 2–3 m of the Basal Sand and Jen Rex Sand, but have not been observed in stratigraphically higher amalgamated sandstones. Conglomerates comprise weathered bone and mudstone clasts typically <2cm in diameter, but occasionally up to 10 cm.

- Hydrodynamic interpretation

Trough cross stratification represents sand transported in traction currents, forming dunes which migrate in a lower flow regime with a unidirectional current (Miall, 1998; Boggs, 2001).

- Facies associations

St abruptly overlies Se, Sm, Sihs, Sr, or Fml. St is overlain often gradationally by Sm, Sr, Fml or (rarely) abruptly by Se.

- Depositional process

Transition from St to Sr or Sm represents decrease in energy, but within a channel environment. Transition from St to Fml represents decrease in energy and a change from traction-based transport in a channel to suspension fallout in a floodplain environment.

1.5.4. Massive sandstone (Sm)

Sm is a medium to fine-grained, clay-rich massively bedded sandstone that weathers to a grey or tan color, often in a distinctive rilled pattern. Bedsets are up 10m, with individual beds 1–3 m thick, fining upwards. Sm contains calcareously cemented concretions, which are frequent and sometimes large, on the scale of meters. Smaller (up to ~25cm) spherical or irregular iron concretions are also common, although notably much more rare or absent in the upper half of the Hell Creek Formation. Sm can be of either channelized or sheet-like geometry. Channelized geometry is more commonly observed in the Basal Sand or Jen Rex Sand in the lower half of the Hell Creek Formation.

- Hydrodynamic interpretation

Lack of sedimentary structures in Sm is interpreted as representing either bioturbation by burrowing organisms; rapid deposition; or homogeneity of grain size and sediment type (Miall, 1998; Boggs, 2001). However, vestiges of primary structure (typically cross-bedding) are sometimes visible, especially when iron staining or small nodules are present.

- Facies associations

Sm gradationally overlies St, or abruptly overlies Se or Fml. St is overlain often gradationally by Sm, Sr, Fml or (rarely) abruptly by Se.

- Depositional process

Similar to Sm of the Colgate Sandstone, it is possible that lack of primary structure may be the result of diagenesis, due to feldspathic degradation into clay (Dobbin and Reeside, 1929; Waage, 1968). Presence of root casts noted by Flight (2004) may indicate that bioturbation is at least in part responsible for the lack of primary structures.

Transition from St to Sm represents decrease in energy, but within a channel environment. Transition from Sm to Fml represents decrease in energy and a change from traction-based transport in a channel to suspension fallout in a floodplain environment.

1.5.5. Ripple cross-laminated sandstone (Sr)

Lithofacies Sr is a grey to tan colored well-sorted fine-grained sandstone with ripple cross lamination. Ripples are asymmetric, up to 5cm in height and <10cm wavelength. Beds are typically quite thin ~0.2 m or less in thickness. Sr is most conspicuous in the broken edges of large concretions where they are emphasized by slight variation in resistance to erosion between laminae.

- Hydrodynamic interpretation

Sr is interpreted as forming in a lower flow regime. Asymmetrical ripples are indicative of unidirectional current.

- Facies associations

Sr gradationally overlies Sm, or St of the Hell Creek Formation. It is gradationally overlain by St, Sm, or Fml.

- Depositional process

Sr represents lower energy or shallower deposition than St or Sm within the lower flow regime.

1.5.6. Massive to laminated mudstone or siltstone (Fml)

Lithofacies Fml (mostly equivalent to the “siltstone” facies of Fastovksy, 1987) makes up the majority of the thickness of the Hell Creek Formation, comprising massive or laminated grey, grey-green, grey-blue, purple and brown mudstones, silty mudstones, and occasional siltstones. Fml are low-chroma colors, described as "somber" by Brown (1907), and alternations of different color beds leads to banding in outcrop. Beds are variable in thickness, up to 3m, but typically less. High smectite content in some beds (particularly dark grey, and grey-green) leads to "popcorn" weathering. Where present, laminations are planar. Slickensides are common. Rootlets and organic debris are common, but mostly restricted to dark grey or brown mudstones. Iron concentrations, staining, and gypsum crystals are common.

- Hydrodynamic interpretation

Fml was deposited as suspension dropout in quiet water.

- Facies associations

Fml gradationally overlies Sm, Sr, or St of the Hell Creek Formation. It is gradationally overlain by C, or abruptly overlain by St, or Sm.

- Depositional process

Transition from Sm to Fml represents decrease in energy and a change from traction-based transport in a channel to suspension fallout in a floodplain environment, probably due to periodic sheetwash flooding (Fastovsky, 1987). An abrupt transition from Fml to Se, Sm, or St represents an increase in energy from floodplain suspension fallout to traction transport in a channel.

1.5.7. Coal or organic-rich shale (C)

Lithofacies C is usually represented by red-brown fissile laminated silty mudstones, very rich in organic debris (mostly equivalent to the "facies of organic accumulation" of Fastovksy, 1987). Laminations are planar. Bed thickness is typically ~20 cm but can be up to 50 cm. Beds are lenticular and typically laterally persistent only ~100 m, although they may form clusters of lenticular beds at particular horizons. Some C facies are more laterally persistent and may extend over a kilometre.

Thin coals comprised of a greater proportion of organic debris are generally absent from the Hell Creek Formation in Montana. An exception is the Null Coal which occurs at the top of the middle depositional sequence. This unit is ~50 cm thick in western McCone County, but thins slightly to the east, the lower part changing from a true coal to a red organic rich shale. This is determinable by the presence of two persistent ash horizons the lower of which is preserved within a coal in McCone County, but in a red organic rich shale in eastern Garfield County.

- Hydrodynamic interpretation

Organic rich shale facies of C was deposited as suspension dropout in quiet water. Coal deposition occurs in quiet water settings.

- Facies associations

C gradationally overlies Fml, and is abruptly overlain by Se, St, Sm, or Fml. Although not observed directly, the Null Coal probably grades laterally into red fissile shale.

- Depositional process

C represents accumulation and burial of peat or a concentration of woody materials in a quiet water setting. Although rare in the Hell Creek, lateral persistence over ~20–30 km of (for example) the Null Coal shows that some coal horizons represent extensive coal swamps; rather than lenticular localized concentrations, perhaps representing quiet water deposition in abandoned chutes or ox-bows. Laterally persistent coal organic rich horizons were interpreted as representing widespread paludal conditions by Fastovsky and McSweeney (1987).

1.6. Fort Union Formation

The Fort Union Formation is not the main emphasis of this study, however, facies in the lowermost Fort Union Formation are included here as they represent the first ~5–10 m of sediment above the formational contact, coincident with the K-Pg boundary. These described facies comprise an erosional scour (Se), Trough cross-bedded sandstone (St), laminated siltstone and mudstone (Fl), Massive mudstone (Fm) and Coal (C). Unlike most other formational contacts in this study, that of the Hell Creek and Fort Union formations is usually non-erosive, recording a transition from massive mudstone (Fml) of the uppermost Hell Creek Formation to coal (C) of the Fort Union Formation.

1.6.1. Erosional scour (Se)

Erosional scours can be found at the bases of major sandstone units within the lowermost Fort Union Formation. Relief is generally 1–2 m or less; however a notable deep incision occurs at Bug Creek in McCone County, where Paleogene channels incise at least ~30 m into the Hell Creek Formation (Lofgren, 1995), and at Penick Coulee in Garfield County where incision is at least ~10 m into the Hell Creek Formation (see main manuscript).

- Hydrodynamic interpretation

Se is interpreted as representing a scour formed by current activity removing underlying sediment.

- Facies associations

Se erosively overlies C, or Fml of the Hell Creek Formation, and C, Fm or Fl of the Fort Union Formation. Se is typically overlain by St.

- Depositional process

Erosive scours can represent major regional events, or localized channel scouring. Regional erosive scours (present at the bases of major amalgamated sandstone units) are evidence of stillstand or fall in accommodation, and may represent significant periods of time (tens of thousands to millions of years). Localized scouring at the bases of isolated channels is representative of an order of magnitude less time, centuries to thousands of years.

1.6.2. Trough cross-stratified sandstone (St)

St is a well-sorted, medium to fine grained sandstone that weathers to a yellow or brown color of notably higher chroma than sandstones of the underlying Hell Creek Formation. Bedsets were observed up to 30 m thick, comprised of individual beds typically 1–2 m in thickness, fining upwards. Troughs are typically 1–2 m wide, and 0.5–2 m deep. St can be of either channelized or sheet-like geometry.

- Hydrodynamic interpretation

Trough cross stratification represents sand transported in traction currents, forming dunes which migrate in a lower flow regime with a unidirectional current (Miall, 1998; Boggs, 2001).

- Facies associations

St abruptly overlies Se, or Fl (of either the Fort Union or Hell Creek Formation). St is overlain gradationally by Fl.

- Depositional process

Transition from Fl to St represents an increase in energy, from quiet water floodplain deposition to a fluvial channel environment. Transition from St to Fl represents gradual decrease in energy and a change from traction-based transport in a channel to suspension fallout in a floodplain environment.

1.6.3. Laminated siltstone or mudstone (Fl)

Lithofacies Fl of the lowermost Fort Union Formation is a distinctive banded siltstone or mudstone. These beds are high chroma shades of yellow, brown, tan, and brownish grey, in notable contrast to the low chroma Fml of the Hell Creek Formation. Fl is typically finely laminated (1–3mm thickness), exhibits conspicuous iron staining (especially in the more pale colored bands), and was described as "variegated" by Archibald (1982) and Fastovsky (1987). Plant detritus is occasionally abundant, along with occasional rootlets. Individual bands are typically up to 50 cm in thickness. Packages of banded facies can be up to 5 m thick, and are sheet-like in geometry, being laterally extensive over kilometers.

- Hydrodynamic interpretation

Fl was deposited as suspension dropout in quiet water.

- Facies associations

Fl abruptly overlies C of the Fort Union Formation, gradationally overlies Sm, Sr, or St of the Hell Creek Formation. Fl is abruptly overlain by C, St, or Sm.

- Depositional process

Fl represents low energy floodplain deposition; banded siltstones are considered to represent paludal deposition on a floodplain with overall high water tables, supported by the presence of articulated remains of aquatic vertebrates (Fastovsky, 1987).

1.6.4. Massive mudstone (Fm)

Lithofacies Fm is less commonly encountered in the lowermost Fort Union Formation than Fl. Fm is a massively bedded high-chroma brown mudstone. Beds are often quite thick, up to 3 m, but more typically ~ 1 m.

- Hydrodynamic interpretation

Fm was deposited as suspension dropout in quiet water.

- Facies associations

Fm gradationally overlies St, or abruptly overlies C or Fl of the Fort Union Formation. It is abruptly overlain by C, St or Fl.

- Depositional process

Transition from Sm to Fm represents decrease in energy and a change from traction-based transport in a channel to suspension fallout in a floodplain environment, probably due to periodic sheetwash flooding. An abrupt transition from Fm to Se, Sm, or St represents an increase in energy from floodplain suspension fallout to traction transport in a channel.

1.6.5. Coal (C)

One of the most conspicuous changes from the Hell Creek Formation to the Fort Union Formation is that the lower part of the Fort Union contains a large number of thick coals (lithofacies C). Coals are well developed and typically 0.5–2 m in thickness, and sometimes up to 3m. Many contain cream to pink colored ash horizons that have been dated most recently by Sprain et al. (2015). Some coal horizons are lenticular, but many are laterally extensive over a kilometer or more.

- Hydrodynamic interpretation

Coal deposition occurs in quiet water settings.

- Facies associations

C abruptly overlies Fml of the Hell Creek Formation or Fml of the Fort Union Formation. C is abruptly overlain by Se, St, or Fml.

- Depositional process

C represents accumulation and burial of peat or a concentration of woody materials in a quiet water setting. Many lower Fort Union Formation coal horizons extend laterally over many kilometers, suggesting extensive coal swamp environments were present.

References cited (part 1)

1. Archibald, J. D. 1982. A study of Mammalia and geology across the Cretaceous-Tertiary boundary in Garfield County, Montana. University of California Publications in the Geological Sciences 122:1–286.
2. Behringer, D. H. 2008. Geometry, genesis and sequence stratigraphic framework of the Colgate Sandstone Member of the Fox Hills, Garfield County, MT. M.S., Montana State University, Bozeman, Montana, 134 pp.
3. Boggs, S. 2001. Principles of Sedimentology and Stratigraphy. Prentice Hall, Upper Saddle River, N.J., 568 pp.
4. Brown, B. 1907. The Hell Creek beds of the Upper Cretaceous of Montana : their relation to contiguous deposits, with faunal and floral lists, and a discussion of their correlation. Bulletin of the American Museum of Natural History 823–845.

5. Buatois, L. A., and M. G. Mángano. 2004. Animal-substrate interactions in freshwater environments: applications of ichnology in facies and sequence stratigraphic analysis of fluvio-lacustrine successions. Geological Society, London, Special Publications 228:311–333.
6. Calvert, W. R., C. F. Bowen, F. A. Herald, J. H. Hance, E. Stebinger, and A. L. Beekly. 1912. Geology of Certain Lignite Fields in Eastern Montana. US Government Printing Office, pp.
7. Carr, I. D., R. L. Gawthorpe, C. A. Jackson, I. R. Sharp, and A. Sadek. 2003. Sedimentology and sequence stratigraphy of early syn-rift tidal sediments: the Nukhul Formation, Suez Rift, Egypt. Journal of Sedimentary Research 73:407–420.
8. Dobbin, C. E., and J. B. Reeside. 1929. The Contact of the Fox Hills and Lance Formations. US Government Printing Office, pp.
9. Eberth, D. A. 2005. The geology. Dinosaur Provincial Park: A Spectacular Ancient Ecosystem Revealed 54–82.
10. Eberth, D. A., and D. R. Braman. 2012. A revised stratigraphy and depositional history for the Horseshoe Canyon Formation (Upper Cretaceous), southern Alberta plains. Canadian Journal of Earth Sciences 49:1053–1086.
11. Fastovsky, D. E. 1987. Paleoenvironments of Vertebrate-Bearing Strata during the Cretaceous-Paleogene Transition, Eastern Montana and Western North Dakota. PALAIOS 2:282.
12. Fastovsky, D.E. 1987. Paleoenvironments of vertebrate-bearing strata during the Cretaceous-Paleogene transition, eastern Montana and western North Dakota. PALAIOS 2, 282–295. https://doi.org/10.2307/3514678
13. Flight, J. N. 2004. Sequence stratigraphic analysis of the Fox Hills and Hell Creek Fms (Maastrichtian), Eastern Montana and its relationship to dinosaur paleontology. MS, Montana State University, Bozeman, Montana, 164 pp.
14. Hartman, J. H., R. D. Butler, M. W. Weiler, and K. K. Schumaker. 2014. Context, naming, and formal designation of the Cretaceous Hell Creek Formation lectostratotype, Garfield County, Montana. Geological Society of America Special Papers 503:89–121.
15. Irish, E. J. W. 1970. The Edmonton Group of South-Central Alberta. Bulletin of Canadian Petroleum Geology 18:125–155.
16. Jensen, F. S., and H. D. Varnes. 1964. Geology of the Fort Peck Area, Garfield, McCone and Valley Counties, Montana. US Govt. Print. Off., 49 pp.
17. Landman, N. H., and K. M. (Karl M. Waagé. 1993. Scaphitid ammonites of the Upper Cretaceous (Maastrichtian) Fox Hills Formation in South Dakota and Wyoming. Bulletin of the American Museum of Natural History 215:1–257.
18. Landman, N. H., and W. A. Cobban. 2003. Ammonites from the upper part of the Pierre Shale and Fox Hills Formation of Colorado. American Museum Novitates 1–45.
19. Lofgren, D. L. 1995. The Bug Creek Problem and the Cretaceous-Tertiary Transition at McGuire Creek, Montana. University of California Press, 204 pp.
20. Martin, A. J. 2000. Flaser and wavy bedding in ephemeral streams: a modern and an ancient example. Sedimentary Geology 136:1–5.
21. Miall, A.D. 1985. Architectural-element analysis: a new method of facies analysis applied to fluvial deposits. Earth-Science Reviews 22, 261–308.
22. Miall, A.D., 1996. The geology of fluvial deposits. Springer Verlag, Berlin, Germany.

23. Murphy, E. C., J. W. Hoganson, and K. R. Johnson. 2002. Lithostratigraphy of the Hell Creek Formation in North Dakota. Geological Society of America Special Papers 361:9–34.
24. 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 53:123–179.
25. Thom, W. T., and C. E. Dobbin. 1924. Stratigraphy of Cretaceous-Eocene transition beds in eastern Montana and the Dakotas. Geological Society of America Bulletin 35:481–506.
26. Waagé, K.M. 1968. The Type Fox Hills Formation, Cretaceous (Maestrichtian), South Dakota. Bulletin of the Peabody Museum of Natural History 27, 1–175.
27. Wheeler, K.L. 1983. Maestrichtian shoreline sedimentation in northeastern Montana (M.S. thesis). University of Iowa, Iowa City, IA.

2. Methods: Terrestrial Sequence Stratigraphy

Sequence stratigraphy interprets sedimentological responses to cycles of accommodation and sediment supply that are subject to primary allogenic and autogenic controls (including eustasy, climate, basin subsidence, and source area tectonism). Strata are arranged into depositional sequences originally defined as "a relatively conformable succession of genetically related strata bounded by unconformities or their correlative conformities" (Mitchum et al., 1977: p. 53). A revised definition is offered by Catuneanu et al. (2009: p. 19) as "a succession of strata deposited during a full cycle of change in accommodation or sediment supply". This removes the need for a depositional sequence to specifically be bound by unconformities, and intentionally excludes reference to the controversial term "base-level" (Catuneanu et al., 2009).

Cyclic patterns have long been recognized in terrestrial deposition, but their study through sequence stratigraphic methods is relatively new. Since the foundational work of Vail and colleagues (1977), most sequence stratigraphy has focused on the influence of relative changes in sea level on marine depositional systems. Terrestrial sequence stratigraphy has been studied to a much lesser degree. Nevertheless, cycles of accommodation and sediment supply have been proposed as explanation for channel stacking patterns of multistory amalgamated channel sandstones, and isolated channels within floodplain dominated mudstone successions (Posamentier and Vail, 1988; Miall, 1991; Legaretta et al., 1993; Schumm, 1993; Wright and Marriot, 1993; Shanley and McCabe, 1993; 1994; Aitken and Flint, 1994; Kamola and Van Wagoner, 1995; McCarthy and Plint, 1998; Marriot, 1999; Posamentier and Allen, 1999; Catuneanu, 2006, Catuneanu et al., 2009, Blum et al., 2013; Campo et al., 2016; Amorosi et al., 2017). Other recent work has emphasized the importance of both the frequency and maturity of paleosols (Bown and Kraus, 1987; Kraus, 1987; 1999; 2002; Cleveland et al., 2007) and trace fossils (Buatois and Mangano, 2004) in interpreting cyclic deposition. However, there is controversy over the appropriate application of sequence stratigraphic methods and terminology to terrestrial depositional cycles.

In terrestrial systems, conventional thought states that the influence of eustatic sealevel decreases upstream; however, it has become a point of discussion as to how far upstream this influence extends. Catuneanu (2006) represents a typical viewpoint that sealevel might influence deposition in low-relief systems up to about 250 km inland from the shoreline, although significantly less in fluvial systems where barriers exist. However, in the extremely low-relief Amazon River Basin, Quaternary sealevel change has been shown to have affected valley incision and sedimentation up to 1500 km inland (Irion et al., 2009). Another study on the Amazon River Basin documented tidal effects on sedimentation occurring over 1000 km inland (Kosuth et al., 2009).

Due to difficulty linking sealevel change with terrestrial depositional cycles, then terminology that is linked to sealevel and shoreline trajectories (e.g., Falling Stage, Lowstand, Transgressive, and Highstand Systems Tracts; FSST, LST, TST, HST, respectively) may not be applicable to inland terrestrial deposits without demonstrating regional correlation to paralic and marine sediments.

Further, terrestrial sedimentation cyclicity is likely caused by a balance of allogenic and autogenic factors (eustasy, climate, basin subsidence and source area tectonism), rather than only sealevel. Consequently, recent terrestrial sequence stratigraphic models instead use the neutral terminology of High- and Low-Accommodation Systems Tracts (HAST and LAST, respectively; Schumm, 1993; Tandon and Gibling, 1994; Shanley and McCabe, 1994; Holbrook, 1996; Legarreta and Uliana, 1998; Miall, 2002; Catuneanu, 2006; Catuneanu et al., 2009).

Cycles of sedimentation in terrestrial deposits tend to follow a pattern of stacked sequences comprising a sequence boundary, overlain by a LAST, and subsequent HAST. Sequence boundaries are created by periods of zero or negative accommodation (i.e. loss), represented by non-deposition or erosion, hence a surface of subaerial unconformity or disconformity (Type 1 sequence boundaries; Posamentier and Allen, 1999; Catuneanu et al., 2006). These can take the form of erosive scours (sometimes forming incised valleys or a regional flattened "peneplanation surface") or correlative development of mature interfluve paleosols (Wright and Marriot, 1993; Kraus, 1999, 2002; Miall, 2010). Alternatively, sequence boundaries may form by compounded "cut and cover", where rivers quickly erode then deposit channel facies, without a prolonged nor laterally extensive subaerial exposure (Strong and Paola, 2008; Holbrook, 2010; Gibling et al., 2011; Holbrook and Bhattacharya, 2012; Miall, 2010). Under this model, repeated "cut and cover" events overlap laterally to produce amalgamated channel deposits (either sheet-like or confined within a valley) identical to previous models with the conceptual difference that the underlying sequence boundary surface of erosion may be more strongly diachronous (Gibling et al., 2011). Regardless, sequence boundaries are usually placed at the base of the LAST, representing a period of low accommodation where floodplain aggradation rates were slow. Thus LAST is typically characterized by laterally extensive amalgamated channel complexes, and / or incised valley-fills. In HAST, accommodation is created and filled rapidly, leading to thick successions of aggrading overbank fines with only weakly developed paleosols on the floodplain, and isolated rather than amalgamated channels. The terrestrial equivalent of a marine maximum flooding surface (i.e. maximum basinal subsidence) may be represented by extensive coal seams and / or lacustrine sediments (Catuneanu and Sweet, 1999). During later HAST, as the rate of accommodation diminishes, floodplain aggradation decreases, and more strongly developed soils may form including a more mature paleosol at the top of the HAST (Kraus, 1987, 1999, 2002). However, preservation may be limited because of potential erosion of the subsequent sequence boundary, or that aggradation rates of the following LAST are so low that sediment reworking by channel combing is intense.

An increasing amount of literature utilizes terrestrial sequence stratigraphic methods to identify cyclic depositional sequences in ancient fluvial systems (e.g., Aitken and Flint, 1994; Kamola and Van Wagoner, 1995; Eberth et al., 2001; Plint et al., 2001; Zerfass et al., 2003, Catuneanu et al., 2006; Cleveland et al., 2007; Roca and Nadon, 2007). Examples from retroarc foreland basins (Laramide and Sevier synorogenic systems) of the Upper Cretaceous of the Western Interior of the United States include the Campanian Two Medicine Formation, Montana (Rogers, 1994;1995;1998; Shelton, 2007); Maastrichtian upper Bearpaw through basal Hell Creek Formation, Montana (Flight, 2004; Behringer, 2008); Campanian to Paleocene strata of the Bighorn Basin, Wyoming (Mitchell, 2002); the Maastrichtian Ferris Formation, Wyoming, (Wroblewski, 2006); Cenomanian Dakota Sandstone, Utah (Antia and Fielding, 2011), Campanian to Paleocene Mesaverde Group, Utah (Olsen et al., 1995), and Maastrichtian Javelina Formation, Texas (Atchley et al., 2004). Of particular interest are cyclic depositional models that have been developed over the past 20 years in Alberta, as these relate to depositional systems very similar to the Hell Creek Formation. Here, depositional sequences and sequence boundaries of distal floodplain and marine intertonguing sediments of the Belly River Group (Eberth, 1990; 1996; 2005; Eberth and Hamblin, 1993; Eberth et al., 1994; Eberth, 2005) and Edmonton Group (Catuneanu and Sweet, 1999; Straight and Eberth, 2002; Chen et al., 2005) have been correlated with the contemporaneous inland Wapiti Formation (Fanti and Catuneanu, 2010). This provides a case study of development of an initial model in a relatively restricted area, can eventually be applied as a regional model, including to units that are entirely terrestrial with no marine tongues.

It should probably be noted that opposition is building towards accommodation-based models of terrestrial sequence stratigraphy (Strong and Paola, 2008; chapter 6 in Miall, 2014). Whether or not the accommodation paradigm will remain valid is unclear in the long term. Debate mostly concerns the causative nature of sequence boundaries; whether they truly represent variation in accommodation, or whether simple changes in climate (etc) may cause non-erosional sequence boundaries; a major criticism leveled at accommodation-based models seems to stem from a perceived necessity for sequence boundaries to be represented by incision and subaerial erosion surfaces (chapter 6 in Miall, 2014). Much of the debate concerns terminology, where the word "sequence" is considered by some to be only appropriate for cyclicity attributable to sealevel, which is itself synonymized with baselevel by some workers. Even the word "accommodation" is entrenched in terminology used for categorizing depositional cycles in terrestrial settings (LAST, HAST; Catuneanu et al. 2009), despite this cyclicity not being necessarily tied to a single forcing mechanism. However, there is no widely accepted alternative terminology; "transgressive/regressive systems tracts" (e.g., Miall, 2014) are undesirable as this terminology is attached to recognition of shoreline movement that may not be demonstrable for most units.

References cited (part 2)

1. Aitken, J. F., and S. S. Flint. 1994. High-frequency sequences and the nature of incised-valley fills in fluvial systems of the Breathitt Group (Pennsylvanian), Appalachian foreland basin, eastern Kentucky. 353–368.
2. Amorosi, A., Bruno, L., Cleveland, D.M., Morelli, A., Hong, W. 2017. Paleosols and associated channel-belt sand bodies from a continuously subsiding late Quaternary system (Po Basin, Italy): New insights into continental sequence stratigraphy. GSA Bulletin 129, 449–463. https://doi.org/10.1130/B31575.1
3. Antia, J., and C. R. Fielding. 2011. Sequence stratigraphy of a condensed low-accommodation succession: Lower Upper Cretaceous Dakota Sandstone, Henry Mountains, southeastern Utah. AAPG Bulletin 95:413–447.
4. Atchley, S. C., L. C. Nordt, and S. I. Dworkin. 2004. Eustatic Control on Alluvial Sequence Stratigraphy: A Possible Example from the Cretaceous-Tertiary Transition of the Tornillo Basin, Big Bend National Park, West Texas, U.S.A. Journal of Sedimentary Research 74:391–404.
5. Behringer, D. H. 2008. Geometry, genesis and sequence stratigraphic framework of the Colgate Sandstone Member of the Fox Hills, Garfield County, MT. M.S., Montana State University, Bozeman, Montana, 134 pp.
6. Blum, M., Martin, J., Milliken, K., Garvin, M. 2013. Paleovalley systems: Insights from Quaternary analogs and experiments. Earth-Science Reviews 116, 128–169. https://doi.org/10.1016/j.earscirev.2012.09.003
7. Bown, T. M., and M. J. Kraus. 1987. Integration of channel and floodplain suites; I, Developmental sequence and lateral relations of alluvial Paleosols. Journal of Sedimentary Research 57:587–601.
8. Buatois, L. A., and M. G. Mángano. 2004. Animal-substrate interactions in freshwater environments: applications of ichnology in facies and sequence stratigraphic analysis of fluvio-lacustrine successions. Geological Society, London, Special Publications 228:311–333.
9. Campo, B., Amorosi, A., Bruno, L. 2016. Contrasting alluvial architecture of Late Pleistocene and Holocene deposits along a 120-km transect from the central Po Plain (northern Italy). Sedimentary Geology 341, 265–275. https://doi.org/10.1016/j.sedgeo.2016.04.013
10. Catuneanu, O. 2006. Principles of Sequence Stratigraphy. Elsevier Science, Amsterdam, 375 pp.
11. Catuneanu, O., and A. R. Sweet. 1999. Maastrichtian-Paleocene foreland-basin stratigraphies, western Canada: a reciprocal sequence architecture. Canadian Journal of Earth Sciences 36:685–703.

12. Catuneanu, O., M. A. Khalifa, and H. A. Wanas. 2006. Sequence stratigraphy of the Lower Cenomanian Bahariya Formation, Bahariya Oasis, Western Desert, Egypt. Sedimentary Geology 190:121–137.
13. Catuneanu, O., V. Abreu, J. P. Bhattacharya, M. D. Blum, R. W. Dalrymple, P. G. Eriksson, C. R. Fielding, W. L. Fisher, W. E. Galloway, M. R. Gibling, K. A. Giles, J. M. Holbrook, R. Jordan, C. G. S. C. Kendall, B. Macurda, O. J. Martinsen, A. D. Miall, J. E. Neal, D. Nummedal, L. Pomar, H. W. Posamentier, B. R. Pratt, J. F. Sarg, K. W. Shanley, R. J. Steel, A. Strasser, M. E. Tucker, and C. Winker. 2009. Towards the standardization of sequence stratigraphy. Earth-Science Reviews 92:1–33.
14. Chen, D., C. W. Langenberg, and A. P. Beaton. 2005. Horseshoe Canyon-Bearpaw Transition and Correlation of Associated Coal Zones across the Alberta Plains. Alberta Energy and Utilities Board : Alberta Geological Survey, Edmonton, Alberta, 22 pp.
15. Cleveland, D. M., S. C. Atchley, and L. C. Nordt. 2007. Continental Sequence Stratigraphy of the Upper Triassic (Norian–Rhaetian) Chinle Strata, Northern New Mexico, U.S.A.: Allocyclic and Autocyclic Origins of Paleosol-Bearing Alluvial Successions. Journal of Sedimentary Research 77:909–924.
16. Eberth, D. A. 1990. Stratigraphy and sedimentology of vertebrate microfossil sites in the uppermost Judith River Formation (Campanian), Dinosaur Provincial Park, Alberta, Canada. Palaeogeography, Palaeoclimatology, Palaeoecology 78:1–36.
17. Eberth, D. A. 1996. Origin and significance of mud-filled incised valleys (Upper Cretaceous) in southern Alberta, Canada. Sedimentology 43:459–477.
18. Eberth, D. A. 2005. The geology, in: Currie, P.J., Koppelhus, E.B. (Eds.), Dinosaur Provincial Park: A Spectacular Ancient Ecosystem Revealed. Indiana University Press, Bloomington, Indiana, pp. 54–82.
19. Eberth, D. A., and A. P. Hamblin. 1993. Tectonic, stratigraphic, and sedimentologic significance of a regional discontinuity in the upper Judith River Group (Belly River wedge) of southern Alberta, Saskatchewan, and northern Montana. Canadian Journal of Earth Sciences 30:174–200.
20. Eberth, D. A., D. Brinkman, and S. M. Kwasniowski. 1994. Sequence Stratigraphy, Depositional Environments and Paleoecology of the Judith River Group (Upper Cretaceous), Southern Alberta. Society of Petroleum Geologists Field guide PR-3, Calgary, Alberta, 69 pp.
21. Eberth, D. A., D. B. Brinkman, P.-J. Chen, F.-T. Yuan, S.-Z. Wu, G. Li, and X.-S. Cheng. 2001. Sequence stratigraphy, paleoclimate patterns, and vertebrate fossil preservation in Jurassic–Cretaceous strata of the Junggar Basin, Xinjiang Autonomous Region, People's Republic of China. Canadian Journal of Earth Sciences 38:1627–1644.
22. Fanti, F., and O. Catuneanu. 2010. Fluvial Sequence Stratigraphy: The Wapiti Formation, West-Central Alberta, Canada. Journal of Sedimentary Research 80:320–338.
23. Flight, J. N. 2004. Sequence stratigraphic analysis of the Fox Hills and Hell Creek Fms (Maastrichtian), Eastern Montana and its relationship to dinosaur paleontology. MS, Montana State University, Bozeman, Montana, 164 pp.
24. Gibling, M. R., C. R. Fielding, and R. Sinha. 2011. Alluvial valleys and alluvial sequences: towards a geomorphic assessment. From River to Rock Record: The Preservation of Fluvial Sediments and Their Subsequent Interpretation. SK Davidson, S. Leleu, and CP North (eds.). Society for Sedimentary Geology, Special Publication 97:423–447.
25. Holbrook, J. M. 1996. Complex fluvial response to low gradients at maximum regression; a genetic link between smooth sequence-boundary morphology and architecture of overlying sheet sandstone. Journal of Sedimentary Research 66:713–722.

26. Holbrook, J. M., and J. P. Bhattacharya. 2012. Reappraisal of the sequence boundary in time and space: Case and considerations for an SU (subaerial unconformity) that is not a sediment bypass surface, a time barrier, or an unconformity. Earth-Science Reviews 113:271–302.
27. Irion, G., J. Müller, J. O. Morais, G. Keim, J. N. de Mello, and W. J. Junk. 2009. The impact of Quaternary sea level changes on the evolution of the Amazonian lowland. Hydrological Processes 23:3168–3172.
28. Kamola, D. L., and J. C. Van Wagoner. 1995. Stratigraphy and Facies Architecture of Parasequences with Examples from the Spring Canyon Member, Blackhawk Formation, Utah. American Association of Petroleum Geologists, Memoir 64:27–54.
29. Kosuth, P., J. Callède, A. Laraque, N. Filizola, J. L. Guyot, P. Seyler, J. M. Fritsch, and V. Guimarães. 2009. Sea-tide effects on flows in the lower reaches of the Amazon River. Hydrological Processes 23:3141–3150.
30. Kraus, M. J. 1987. Integration of channel and floodplain suites; II, Vertical relations of alluvial Paleosols. Journal of Sedimentary Research 57:602–612.
31. Kraus, M. J. 1999. Paleosols in clastic sedimentary rocks: their geologic applications. Earth-Science Reviews 47:41–70.
32. Kraus, M. J. 2002. Basin-Scale Changes in Floodplain Paleosols: Implications for Interpreting Alluvial Architecture. Journal of Sedimentary Research 72:500–509.Legarreta, L., and M. A. Uliana. 1998. Anatomy of hinterland depositional sequences: Upper Cretaceous fluvial strata, Neuquen basin, west-central Argentina; pp. 83–92 in K. W. Shanley and P. McCabe (eds.), Relative role of eustasy, climate and tectonism in continental rocks., . Special Publication vol. 59. SEPM.
33. Legarreta, L., M. A. Uliana, C. A. Larotonda, and G. R. Meconi. 1993. Approaches to nonmarine sequence stratigraphy – theoretical models and examples from Argentine basins. Proceedings of Institut Francais Du Petrole, Conference on Exploration and Production: Subsurface Reservoir Characterization from Surface Observations, April 12-17, 1992 125–143.
34. Marriott, S. B. 1999. The use of Models in the Interpretation of the Effects of Base-Level Change on Alluvial Architecture; pp. 269–281 in N. D. Smith and J. Rogers (eds.), Fluvial Sedimentology VI. Blackwell Publishing Ltd.
35. McCarthy, P. J., and A. G. Plint. 1998. Recognition of interfluve sequence boundaries: Integrating paleopedology and sequence stratigraphy. Geology 26:387–390.
36. Miall, A. D. 2010. The Geology of Stratigraphic Sequences. Springer Science & Business Media, 522 pp.
37. Miall, A. D. 2014. Fluvial depositional systems. Springer, New York. 316 pp.
38. Miall, A. D. 1991. Stratigraphic Sequences and Their Chronostratigraphic Correlation. Journal of Sedimentary Petrology 61.
39. Miall, A. D. 2002. Architecture and sequence stratigraphy of Pleistocene fluvial systems in the Malay Basin, based on seismic time-slice analysis. American Association of Petroleum Geologists Bulletin 86:1201–1206.
40. Miall, A. D., O. Catuneanu, B. K. Vakarelov, and R. Post. 2008. Chapter 9 The Western Interior Basin; pp. 329–362 in Andrew D. Miall (ed.), Sedimentary Basins of the World. vol. Volume 5. Elsevier.
41. Mitchell, J. H. 2002. Sedimentary record of Late Cretaceous through Paleocene evolution of the Bighorn Basin, Wyoming. M.S., University of Montana, Missoula pp.
42. Mitchum Jr., R. M., P. R. Vail, and S. Thompson. 1977. Seismic stratigraphy and global changes of sea-level, Part 2: The depositional sequence as a basic unit for stratigraphic analysis; pp. 53–62 in Seismic Stratigraphy - Applications to hydrocarbon exploration. American Association of Petroleum Geologists, Tulsa, Oklahoma.

43. Olsen, T., R. Steel, K. Hogseth, T. Skar, and S. L. Roe. 1995. Sequential architecture in a fluvial succession; sequence stratigraphy in the Upper Cretaceous Mesaverde Group, Prince Canyon, Utah. Journal of Sedimentary Research 65:265–280.
44. Plint, A. G., P. J. McCarthy, and U. F. Faccini. 2001. Nonmarine sequence stratigraphy: Updip expression of sequence boundaries and systems tracts in a high-resolution framework, Cenomanian Dunvegan Formation, Alberta foreland basin, Canada. AAPG Bulletin 85:1967–2001.
45. Posamentier, H. W., and P. R. Vail. 1988. Eustatic controls on clastic deposition II—sequence and systems tract models. SEPM Special Publication 42:125–154.
46. Posamentier, H. W., and G. P. Allen. 1999. Siliciclastic Sequence Stratigraphy: Concepts and Applications. SEPM (Society for Sedimentary Geology), 210 pp.
47. Roca, X., and G. C. Nadon. 2007. Tectonic Control on the Sequence Stratigraphy of Nonmarine Retroarc Foreland Basin Fills: Insights from the Upper Jurassic of Central Utah, U.S.A. Journal of Sedimentary Research 77:239–255.
48. Rogers, R. R. 1994. Nature and origin of through-going discontinuities in nonmarine foreland basin strata, Upper Cretaceous, Montana: Implications for sequence analysis. Geology 22:1119–1122.
49. Rogers, R. R. 1995. Sequence stratigraphy and vertebrate taphonomy of the Upper Cretaceous Two Medicine and Judith River Formations, Montana. Ph.D, University of Chicago, Chicago, Illinois, 400 pp.
50. Rogers, R. R. 1998. Sequence analysis of the Upper Cretaceous Two Medicine and Judith River formations, Montana; nonmarine response to the Claggett and Bearpaw marine cycles. Journal of Sedimentary Research 68:615–631.
51. Schumm, S. A. 1993. River response to baselevel change: implications for sequence stratigraphy. Journal of Geology 279–294.
52. Shanley, K. W., and P. J. McCabe. 1994. Perspectives on the Sequence Stratigraphy of Continental Strata. AAPG Bulletin 78:544–568.
53. Shanley, K. W., and P. J. McCabe. 2009. Alluvial Architecture in a Sequence Stratigraphic Framework: A Case History from the Upper Cretaceous of Southern Utah, USA; pp. 21–55 in S. S. Flint and I. D. Bryant (eds.), The Geological Modelling of Hydrocarbon Reservoirs and Outcrop Analogues. Blackwell Publishing Ltd.
54. Shelton, J. A. 2007. Application of sequence stratigraphy to the nonmarine Upper Cretaceous Two Medicine Formation, Willow Creek anticline, northwestern Montana. M.S., Montana State University, Bozeman, Montana, 238 pp.
55. Straight, W. H., and D. A. Eberth. 2002. Testing the Utility of Vertebrate Remains in Recognizing Patterns in Fluvial Deposits: An Example from the Lower Horseshoe Canyon Formation, Alberta. PALAIOS 17:472–490.
56. Strong, N., and C. Paola. 2008. Valleys that never were: time surfaces versus stratigraphic surfaces. Journal of Sedimentary Research 78:579–593.
57. Tandon, S. K., and M. R. Gibling. 1994. Calcrete and coal in late Carboniferous cyclothems of Nova Scotia, Canada: Climate and sea-level changes linked. Geology 22:755–758.
58. Vail, P. R., R. M. Mitchum Jr., and S. Thompson. 1977. Seismic stratigraphy and global changes of sea level, part 3: relative changes of sea level from coastal onlap; pp. 63–81 in Seismic Stratigraphy - Applications to hydrocarbon exploration. American Association of Petroleum Geologists, Tulsa, Oklahoma.

59. Wright, V.P., Marriott, S.B., 1993. The sequence stratigraphy of fluvial depositional systems: the role of floodplain sediment storage. Sedimentary Geology 86, 203–210. https://doi.org/10.1016/0037-0738(93)90022-W
60. Wroblewski, A. F.-J. 2006. Relative influences of tectonism, climate, and sea level on valley incision and sedimentary fill: new insights from Upper Cretaceous and Paleocene examples. SEPM Special Publication 85:309–326.
61. Zerfass, H., E. L. Lavina, C. L. Schultz, A. J. V. Garcia, U. F. Faccini, and F. Chemale Jr. 2003. Sequence stratigraphy of continental Triassic strata of southernmost Brazil: a contribution to Southwestern Gondwana palaeogeography and palaeoclimate. Sedimentary Geology 161:85–105.