Stratigraphic Analysis and Regional Correlation of Isolated, Top-Truncated Shallow Marine Sandstone Bodies within the Upper Cretaceous Frontier Formation, Bighorn and Washakie Counties, Wyoming

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STRATIGRAPHIC ANALYSIS AND REGIONAL CORRELATION OF ISOLATED,
TOP-TRUNCATED SHALLOW MARINE SANDSTONE BODIES WITHIN THE
UPPER CRETAEOUS FRONTIER FORMATION, BIGHORN AND WASHAKIE
COUNTIES, WYOMING

by

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A THESIS

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A detailed sedimentologic and stratigraphic analysis facilitated interpretations of depositional environment, sequence stratigraphy, and sandstone body geometry for isolated, top-truncated, shallow marine sandstone bodies of the Upper Cretaceous (Cenomanian-Turonian) Frontier Formation, northeast Bighorn Basin, Wyoming. The Frontier Formation interval is ~160 meters thick and was deposited as a complex clastic wedge that prograded into Cretaceous Western Interior Seaway (KWIS). The vertical interval comprises several incomplete coarsening-upward cycles, composed of basal offshore marine and prodeltaic shales progressively overlain by proximal shallow marine/fluvial facies that are capped by pebble lags. Sedimentary structures, vertical stacking patterns, and lateral variability within these cycles record multiple southward progradational episodes of tide- and wave- influenced, fluvially-dominated deltas. Subsurface correlation of sandstone bodies reveals dip elongate, strike restricted, lensoid, digitate, linear, and lobate geometries, supporting the deltaic interpretation. A sequence stratigraphic analysis of outcrop sections divides the coarsening-upward cycles into multiple parasequences and identifies two types of key stratigraphic surface
(transgressive surfaces of erosion, sequence boundaries). Transgressive surfaces of erosion occur as low-relief, laterally extensive pebble lag horizons that top-truncate parasequences, generating mudstone-encased, isolated sandstone bodies. Sequence boundaries are placed at the base of shallow marine sandstones (Peay Member), as well as at the erosional contact between fluvial and shallow marine facies (Torchlight Member). Sequence boundary placement suggests shoreline advancement basinward during relative sea-level lowstand. Relative sea-level transgressive-regressive cycles observed within parasequences were generated from the interplay between allogenic forces (tectonics, climate, eustacy). This study proposes a depositional model explaining the dispersal of southward-deflected, isolated shallow marine deposits 10’s to 100’s of kilometers basinward of contemporaneous shorelines. The interaction between fresh and saline water, pressure gradients, and the Coriolis Effect generated shore-parallel, southward-deflected geostrophic currents that dispersed sediments south, parallel to the KWIS western paleoshoreline. Additionally, this study highlights multiple member-scale lateral pinch-outs and intramember-scale heterogeneities in sandstone bodies. Such findings will assist in future hydrocarbon exploration efforts.
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INTRODUCTION

A multitude of elongate, laterally restricted sandstone bodies encased in marine mudstones have been identified within the Upper Cretaceous (Cenomanian-Maastrichtian) stratigraphic record of the Western Cordilleran Foreland Basin of continental North America. These bodies are believed to have been sourced predominantly from the Sevier Orogenic Highlands to the west and accumulated in the Cretaceous Western Interior Seaway (KWIS). Some of these 20 – 40 m thick, elongate (tens of km) sandstone bodies are believed to represent deltaic progradation into distal basinal locations in response to sea level lowstand conditions (Posamentier & Morris, 2000; Bhattacharya & Willis, 2001). The low gradient sea floor facilitated long-distance progradation of relatively thin deltaic sandstones (Posamentier & Morris, 2000). Subsequent transgressive ravinement truncated the accumulations, removing up to 20 meters of nearshore and terrestrial (fluvial) facies in some cases (Weimer, 1988; Hwang & Heller, 2002). This resulted in the stratigraphic record being dominated by mudstone-encased shallow marine sandstone bodies, isolated tens of kilometers from contemporary shorelines. Relative sea level fluctuations, generated from allogenic controls (climate, tectonics, eustacy) are believed responsible for this cyclic depositional pattern within the stratigraphic record of the basin (Miller et al., 2003; Catuneanu, 2006; Van den Berg van Saporoea & Potsma, 2008).

Historically, these shoreline-detached, isolated sandstone bodies encased in marine mudrocks have been profitable for hydrocarbon exploration, including those
within the Frontier Formation, the subject of this study. Understanding the origins of these enigmatic sandstone bodies has often proved difficult; however, leading to an array of hypotheses as to their depositional environment. Past analyses of the Frontier Formation have invoked several depositional environments, including marine/tidal sand ridges, reworked offshore bar complexes, storm-influenced sand sheets, barrier island bars, and bayhead deltas/estuarine incised valley fill deposits (Barlow & Haun, 1966; Tillman & Almon, 1979; Winn, 1991; Merewether et al., 1998). Recent studies of the Frontier Formation within the Powder River Basin have applied sequence stratigraphic methodologies to better interpret possible depositional mechanisms. The majority of these studies conclude that the isolated bodies represent prograding shallow marine deltaic deposits formed under low accommodation conditions (Willis et al., 1999; Bhattacharya & Willis, 2001; Gani & Bhattacharya, 2007; Lee et al., 2007; Vakarelov & Bhattacharya, 2009). Sequence stratigraphic interpretation of low accommodation settings is challenging because of the susceptibility of sandstone bodies to significant transgressive ravinement; however, resulting in the removal of nearshore marine and fluvial sediments (Bhattacharya & Willis, 2001; Bhattacharya, 2006; Porebski & Steel, 2006; Hampson et al., 2008a). The genetic linkage of these shallow marine sediments with their contemporary shoreline deposits often cannot be resolved satisfactorily, making the identification of a formative depositional environment difficult (Van Wagoner et al., 1990; Kamola & Van Wagoner, 1995).
OBJECTIVES & SIGNIFICANCE

The purpose of this study is to develop and refine sequence stratigraphic and depositional models for the Frontier Formation in the northeast Bighorn Basin, Wyoming by performing a detailed three-dimensional analysis of vertical and lateral facies patterns, internal stratal architecture, and sandstone body geometries. Such an analysis will improve upon the regional sequence stratigraphic context for not only the entire formation, but also for morphologically similar units both within the KWIS and throughout the geologic record. Additionally, by providing insights into the geometry, stratigraphic context, and dispersal patterns of these Cretaceous sandstone bodies, this study will also provide information relevant to future hydrocarbon exploration activity within the region.

GEOLOGIC SETTING

The Upper Cretaceous (Cenomanian-Turonian) Frontier Formation was formed as a complex series of eastward prograding clastic wedges shed into the western KWIS and sourced from the Sevier Orogenic Belt to the west. Sediment accumulation occurred basinward of the Sevier Foreland Basin depocenter (foredeep) on a gently eastward-dipping sea floor under low accommodation conditions (Fig. 1) (Posamentier & Morris, 2000).

Figure 2, based on Clark (2010), illustrates a west-east geochronologic, biostratigraphic, and lithostratigraphic correlation of the Frontier Formation clastic wedge across Wyoming. The Frontier Formation is represented stratigraphically as
numerous sandstone bodies that were deposited intermittently between the Cenomanian and Early Coniacian, separated by finer-grained intervals, and with several depositional hiatuses. These sandstone bodies accumulated during a long-term (second-order) rise in global sea-level, upon which was superimposed several shorter-term (third-order) sea-level lows (Kauffman & Caldwell, 1993). Episodes of short-term sea-level fall allowed for the eastward progradation of shallow marine sediments into distal portions of the basin. A general west-to-east transition from continental to shallow marine facies is observed across Wyoming (Cobban &

**Figure 1:** A). Paleogeographic reconstruction of the western interior of North America during the Late Cretaceous (Cenomanian-Coniacian). As shown, several deltas were sourced from the Sevier Orogenic Belt and deposited into the Cretaceous Western Interior Seaway (KWIS). Those deltas include the Frontier (F), Vernal (V), Last Chance (LC), and Notom (N). B). Present-day Wyoming with partitioned basins. The area of interest for this study is within the eastern Bighorn Basin (yellow) in north-central Wyoming. Modified after Clark (2010).
Reeside, 1952, Fig. 2). Western basins (Green River, Wind River) in Wyoming contain abundant fluvial channel sandstone bodies, conglomerates and coals (Cobban & Reeside, 1952). Eastward, the Bighorn and Powder River basins are dominated by shallow marine sandstones in the stratigraphic succession (Cobban & Reeside, 1952). Ultimately, the succession thins to the east as individual sandstone bodies pinch out, becoming isolated in marine shales (Cobban & Reeside, 1952).

In the northeast Bighorn Basin, the Frontier Formation conformably overlies the Mowry Shale and is conformably overlain by the Cody Shale (Cobban & Reeside, 1952, Fig. 3). Previous studies have placed the Mowry-Frontier contact at the Clay Spur Bentonite (Hintze, 1914; Kirschbaum et al., 2009). The Clay Spur Bentonite is not ubiquitous across the study area; however, and other bentonitic beds occur lower in the Mowry Shale. A more reliable, and mappable criterion for the Mowry/Frontier contact is given by a distinct, laterally continuous change from light gray porcellaneous siltstones and sandstones (Mowry) to dark grey/black mudstones (Frontier) observed everywhere in outcrop, and recognizable in subsurface wireline logs. The Frontier Formation is herein divided into six members, most of which are top-bounded by abrupt upward transitions from shallow marine sandstones to marine mudstones. Stratigraphically, from oldest to youngest, these units are named the Stucco, Peay, Potato Ridge, Alkali, Torchlight, and Spence members (Fig. 4). These names are modified after Clark (2010), and include some newly-defined members so as to provide a complete subdivision of the Frontier Formation, using names that are acceptable according to the North American Stratigraphic Code (NACSN, 1983) and
are currently vacant. A basal interval (30 – 40 m thick) consisting of dark gray shales that coarsen up into interbedded siltstone and sandstone is herein named the Stucco Member (Figs. 3, 4). The Peay Member (Hintze, 1914) is a sandstone unit that forms ridges and cliffs, overlying the basal shales and coarsening-upward siltstone-sandstone interbeds (Figs. 3, 4). It is here proposed that a regionally-extensive, coarsening-up interval 1 – 5 m thick between the top of the Peay Member and ‘X’ Bentonite be named the Potato Ridge Member. The Alkali Member, informally proposed by Clark (2010), occupies the stratigraphic interval between the base of the ‘X’ Bentonite and the base of the cliff-forming sandstone of the Torchlight Member (Fig. 4). The Torchlight Member (Hintze, 1914) is a prominently-outcropping sandstone that gradationally overlies the Alkali Member and is capped by the laterally persistent Torchlight Conglomerate (Figs. 3, 4, 8f). Finally, it is proposed that a set of coarsening up intervals above the Torchlight Member, previously included in the Cody Shale, are re-defined as an uppermost member of the Frontier Formation, and named the Spence Member (Figs. 3, 4).

According to Clark (2010), the Frontier Formation is biostratigraphically constrained by ammonites (*Acanthoceras amphibolum*, *Dunveganoceras pondi*, and *Baculites yokoyamai*), inoceramids, and bentonites (Clay Spur, X, and Upper Bed) (Fig. 2). Clark (2010) summarizes literature concerning the $^{40}$Ar/$^{39}$Ar dates for each
Figure 2: Biostratigraphic, lithostratigraphic, and chronostratigraphic correlation of the Frontier Formation along a west-east transect through Wyoming. Correlation of individual sandstone intervals of the Frontier Formation between basins (Green River, Bighorn, Powder River) is constrained by bentonites, as well as the first occurrences of specific inoceramids and ammonites. Modified from Clark (2010).

of the relevant bentonites. The Clay Spur Bentonite has an age of 97.17 +/- 0.69 Ma (Obradovich, 1993), the X Bentonite is placed at 94.96 +/- 0.5 Ma (Cobban et al., 2006), while the exact age of the Upper Bed Bentonite is unresolved (Clark, 2010).

Within the Torchlight Member, the first appearances of *Acanthoceras amphibolum* and *Dunveganoceras pondi* are dated at 94.93 +/- 0.53 Ma and 94.63 +/- 0.61 Ma, respectively, while the first appearance of *Baculites yokoyamai* (Spence Member) is placed near the Turonian-Coniacian boundary (89.3 Ma: Obradovich, 1993).

Therefore, the Frontier Formation within the northeast Bighorn Basin was deposited
within the Cenomanian-Late Turonian, with a 4 m.y. disconformity occurring between the Torchlight and Spence Members (Kirschbaum, 2009; Clark, 2010).

Figure 3: Photographs showing the contacts between several members of the Frontier Formation. Displayed contacts are laterally consistent and extensive throughout the study area. A) Contact between the porcellaneous, light gray shales of the Mowy (below) and the dark gray/black mudstones of the basal Frontier (Stucco Member, outcrop Section 17). B) The upper contact of the Peay Member sandstone with the Potato Ridge Member, and the contact between the Potato Ridge and Alkali Members at Section 1. C) A lithologic and color (orange-brown fine-grained sandstones to gray mudstones) change, marking the interpreted upper contact of the Frontier Formation (Spence Member) with the overlying Cody Shale (CKC Section 1).
Figure 4: Composite log of the Frontier Formation broadly representing 20 measured outcrop sections throughout the northeast Bighorn Basin. Thicknesses of each member are averages and do not represent the true total thickness at any one locality. Facies, sedimentary structures, bioturbation (BI), and trace and body fossils are shown. Red arrows denote stratigraphically important bentonite beds.
**Figure 5:** Locations of twenty measured outcrop sections northwest of and east of Greybull, Wyoming. Sections located southeast of those in Clark (2010) (CKC-CRF Sections). Correlation of sections facilitates north-south and east-west cross-sections (Appendix 1A-B) of the Frontier Formation. Sections extend approximately 30 km northwest and 15 km east of Greybull. (TCA – Tin Can Alley).
METHODS

A detailed sedimentologic and ichnologic analysis was performed along a ~30 km, northwest-southeast trending outcrop belt of the Frontier Formation within the northeast Bighorn Basin. Twenty outcrop sections were measured from south of those in Clark (2010) (Alkali Anticline) in the northwest to the Greybull River Cliffs and Potato Ridge in the southeast (Fig. 5). Sections were spaced approximately 1 km apart so as to facilitate a high-resolution analysis of the outcrop belt. Sedimentologic and ichnologic data, including fossils (body and trace), sedimentary structures, vertical and lateral bedding trends, grain-size trends, lithological contacts, body thicknesses and paleocurrent data were collected, forming the basis for facies and depositional environmental analyses. Observed ichnologic data were interpreted following the methodology presented in Clark (2010), where bioturbation intensity is given a value based upon the degree of observed sediment destratification (Bann et al., 2004). Values of zero are indicative of an absence of bioturbation, while values of six are associated with complete sediment reworking by biogenic processes (Bann et al, 2004).

Northwest-southeast (depositional dip) and east-west (depositional strike) cross-sections were constructed from the measured outcrop sections (including those in Clark, 2010) so as to reconstruct the three-dimensional facies and body geometry variations. A regionally extensive, sheet-like pebble lag at the top of the Torchlight Member sandstone (Torchlight Conglomerate) was chosen as the cross-section datum. Age control from laterally extensive synchronous horizons (Clay Spur and X
Bentonites), as well as the verification of vertical stacking trends and lateral variations of facies and body geometries between adjacent outcrop sections aided in the correlation of key geologic surfaces and sediment bodies.

Well logs from drill holes located throughout the eastern Bighorn Basin (Bighorn and Washakie Counties) (Fig. 6) were acquired from the Wyoming Oil and Gas Conservation Commission and used to facilitate regional sandstone body geometry interpretations through the construction of well log cross-sections and isopach maps. Five cross-sections oriented north-south (three) and east-west (two) were constructed from the regional correlation of gamma ray logs. As with surface data cross-sections, subsurface cross-sections were correlated and analyzed using the Torchlight Conglomerate datum. Using the PETRA computer software, isopach maps of the four main sandstone bodies within the study area (Peay, Potato Ridge, Torchlight, Spence) were created from the correlation of sandstone and bentonite intervals from gamma ray, neutron porosity, and resistivity logs.

**FACIES ANALYSIS**

The typical facies assemblage observed throughout the Frontier Formation consists of a coarsening-upward sequence of basal dark gray shales, interbedded siltstones and sandstones (sandstone ratio increases up-section), thickly-bedded, sharply-based amalgamated sandstones, and a laterally extensive, cycle-capping pebble lag. Partial to complete expressions of this assemblage occur repetitively
Figure 6: Location map of surface and subsurface data points and wireline log-based cross-sections throughout Bighorn and Washakie Counties, eastern Bighorn Basin, Wyoming.
Figure 7: Photographs showing characteristics of Facies A-D observed throughout the study area. A). Dark gray/black shale of Stucco Member, near the contact of the Mowry Shale (Facies A, Outcrop Section 17). B). Dark gray/black mudstone and siltstone with thin (cm’s) sandstone interbeds (arrow) (Facies B). This facies occurs stratigraphically above Facies A, but below Facies C. (Stucco Member, Outcrop Section 11). C). Interbedded sandstone with thin siltstone partings (Facies C), occurring stratigraphically between Facies B and D (Stucco Member, Carcass Gully Outcrop Section). D). Contact between Facies C below and the thickly-bedded sandstone with minor siltstone interbeds (Peay Member, Facies D, Tin Can Alley Outcrop Section). E). Cross-sectional view of thin rippled intervals within sandstones (arrows) of Facies D (Bighorn River North Outcrop Section). F). Plan view of thin rippled intervals (Part E) showing interference ripples (arrow) and the horizontal trace *Gyrochorte* (*Gy.*) (Peay Member, Bighorn River North Outcrop Section).
throughout the Frontier Formation. Evidence for wave, current, outflow, and unidirectional paleocurrent trends with tidal, wave, and fluvial influences points to a broadly deltaic environment of deposition for the various intervals. Following is a detailed analysis of facies composing the coarsening-upward assemblages, which amplifies and modifies that presented by Clark (2010).

**Facies A**

*Description*

Facies A is composed entirely of black to dark gray claystones and siltstones, with interbedded bentonitic intervals (Fig. 7a). The claystones and siltstones are fissile (shales) with fine laminations, with the clay to silt ratio decreasing stratigraphically up-section. Occasional pockets of yellow sulfurous staining (probably jarosite and/or other sulfates) and organic-rich intervals occur throughout this facies. The observed bentonites are either pale yellow or light gray in color, depending on whether the exposure is fresh or weathered, respectively. Deeply weathered bentonites exhibit a ‘popcorn’ texture at surface, while physically unaltered specimens are blocky in character. Throughout the study area, Facies A has a bioturbation index (BI) rating of 0, indicating an absence of bioturbation. The intervals represented by Facies A are approximately 5-10 m thick, showing lateral continuity in successive outcrop sections. Individual bentonitic intervals range in thickness from 20 – 80 cm, with thicker units being regionally correlateable. A sharp, relatively planar lower contact at the base of Facies A is observed. The occurrence of
thin (cm’s), fine grained, laterally discontinuous sandstone stringers marks the
gradational upper contact of Facies A with Facies B.

Interpretation

The dominance of black to dark grey claystones and siltstones indicates
deposition in offshore environments. Clay- and silt-sized particles were likely
entrained in buoyant hypopycncal plumes and transported 100’s of kilometers from a
terrestrial source (Wright, 1977; Bhattacharya & Willis, 1991). Following the
velocity decrease of the plume, entrained sediments were deposited slowly, but
steadily, generating the observed laterally continuous accumulations of clay and silt.
Anoxic and reducing conditions are inferred at the time of deposition with the
occurrence of sulfides, a lack of bioturbation (BI = 0) and high organic carbon values.
An increase in silt abundance up-section, with respect to clay-sized particles
represents deposition more proximal to the terrestrial source. Interbedded bentonitic
intervals represent the accumulation of ash derived from volcanic activity. In contrast
to thinner bentonitic intervals, thicker accumulations (Clay Spur & X Bentonites) are
regionally extensive and widespread as large volumes of volcanic ash settled to the
sea floor in open marine, offshore settings.
Facies B

Description

Facies B consists primarily of siltstones (80 - 90 %), with a minor constituent of thinly-bedded sandstones (10 – 20 %) (Fig. 7b). Siltstones are dark gray to black in color with occasional yellow sulfurous patches and organic matter dispersed throughout. Physically, the siltstones are fissile and contain fine laminations. Sandstones are very fine to fine-grained, consisting mostly of quartz, lithic grains, and mud laminae. Observed sedimentary structures within the sandstones include asymmetric ripple cross-lamination with occasional organic-rich mud drapes and flat-to-low angle cross-bedding. Bioturbation is not present within the siltstones (BI = 0), while sandstones exhibit an overall bioturbation index of 1 – 2 (BI = 2 – 4 locally). Common traces include Planolites, Diplocraterion, and sediment swimming traces (navichnia). Individual sandstone bodies occur as several centimeter (1 – 5 cm) thick laterally discontinuous stringers with sharp upper and lower contacts. Thicker beds within the succession often display increased lateral continuity with respect to thinner beds. Vertically, the thin sandstone stringers increase in abundance and thickness up-section within Facies B, resulting in a sediment package that is laterally persistent and consistently recurs as a 3 – 15 m thick interval throughout the study area. Overall, Facies B displays gradational lower and upper contacts with Facies A and C, respectively.
**Interpretation**

The occurrence of thin sandstone interbeds, as well as an increased abundance of siltstone with respect to claystone indicates deposition in a more proximal environment than Facies A. The characteristically sharp-based, very-fine to fine grained sandstones with unidirectional current and combined flow ripple cross-laminations are interpreted to have originated as storm-flow tempestite deposits (Aigner & Reineck, 1982; Bhattacharya & MacEachern, 2009). The thin-bedded nature of sandstone bodies likely indicates the distal portions of such storm-flow deposits (Aigner & Reineck, 1982). Low levels of observed bioturbation (BI = 0 mudstones/siltstones; BI = 1-2 sandstones) indicate a highly stressed environment. Anoxic conditions are inferred during the deposition of shales with no bioturbation and the occurrence of dispersed sulfides. The relatively uncommon *Planolites*, *Diplocraterion*, and sediment swimming traces within the sandstone beds represent trophic generalists that were able to exploit brief periods of bottom water oxygenation following tempestite deposition (MacEachern et al., 2005; MacEachern & Bann, 2008). The presence of sediment swimming traces suggests a substrate that was regularly thixotropic (fluid mud) (Bhattacharya & MacEachern, 2009). Sandstone beds increase in abundance, thickness, and lateral continuity up-section, indicating gradual transition to an increasingly proximal depositional environment. The above evidence, in combination with enclosing facies (Table 1), is consistent with Facies B representing deposition in a prodeltaic environment below storm wave base (Bhattacharya & Walker, 1991; Bhattacharya & MacEachern, 2009).
Facies C

Description

Facies C contains sandstones that are interbedded with thin siltstone beds (Fig. 7c). The siltstones are characteristically dark gray to black in color, fissile, finely laminated with finely divided woody/coaly organic debris, as well as intermittent sulfurous patches. Sandstone beds are fine-grained and composed of quartz, lithic grains, and black chert pebbles that occur throughout, but increasing upsection. Sedimentary structures commonly observed within individual sandstone beds include hummocky cross-stratification (HCS), asymmetric ripple cross-lamination, symmetrical ripple cross-lamination and form sets, interference ripples, combined flow ripple cross-lamination (in places showing strongly aggradational stratification style), flat-to-low angle cross-bedding, and syneresis cracks. Bioturbation is absent within the siltstones (BI = 0), while sandstone beds exhibit moderate sediment reworking (BI = 2 – 4). Abundance of traces is highly variable from bed to bed, with some horizons displaying intense bioturbation, often by only one or two ichnotaxa. Such ichnogenera include Planolites, Thalassinoides, Diplocraterion, Gyrochorte, Rhizocorallium, Ophiomorpha, Asterosoma, Lockeia, fugichnia, Teichichnus, Phycosiphon, and Cylindrichnus. Individual sandstones commonly range from 50 – 80 cm thick, but occasionally exceed 1 m as sandstone bodies thicken up-section. Sandstone thickening occurs at the expense of the interbedded siltstone as it is visibly less common up-section. Laterally, bodies are more continuous with respect to Facies B, but still locally pinch out, generating lensoid geometries. Sharp, planar, and
undulating contacts are commonly observed between sandstones and siltstones. Overall, Facies C repeatedly occurs throughout the Frontier Formation stratigraphic succession, ranging from 1 – 10 m thick. When correlated within the Peay Member, this unit is laterally extensive, gradationally transitioning into Facies D (above) and from Facies B (below). Anomalous thinning occurs near Lovell Draw (Appendix 1A) with thickening down depositional dip along the Bighorn River cliffs in Greybull within the Peay Member. Here, the thickening and thinning trends do not occur as a result of the deposition of overlying Facies D, as overlying facies also co-vary in a similar fashion.

**Interpretation**

The occurrence of thicker, more abundant and laterally continuous sandstone bodies indicates an increasingly proximal depositional environment, with respect to Facies B. Facies C contains multiple features that suggest an influence from river input. Sandstone bodies display characteristics (unidirectional combined flow/current ripples, sharp/planar/swaley contacts, flat- to low-angle cross-bedding) of unidirectional and combined flow, typical of storm outflow deposits (Arnott & Southard, 1990; Southard et al., 1990; Dumas et al., 2005). Siltstone intervals containing phytodetrital deposits that lack bioturbation and sedimentary structure likely developed from high fluvial runoff events (freshets) that transported
Figure 8: Photographs showing details of Facies E-I observed throughout the study area. **A).** Massively-bedded, amalgamated sandstones with dispersed boulder-sized secondary iron concretions (Facies E, Peay Member, Outcrop Section 9). **B).** Brown, fissile siltstone with abundant plant debris (arrow, Facies G), separating Facies F (below) from Facies H (above) (Torchlight Member, Outcrop Section 1). **C).** Flat- to low-angle cross-stratification (arrow) commonly observed within fine-medium grained sandstones of Facies F at the base of the Torchlight Member (Outcrop Section 1). **D).** Trough cross-stratification (arrow) within medium-coarse grained sandstones of Facies H (Torchlight Member, Outcrop Section 1). **E).** In situ pebble lag (arrow) consisting of chert and petrified wood clasts, with dispersed bone and tooth fragments throughout (Facies I, on top of the Peay Member, Outcrop Section 1). **F).** In situ pebble-cobble lag (arrow) on top of the Torchlight Member, consisting of chert, andesite porphyry, and quartzite clasts (Facies I, Outcrop Section 1).
terrestrially-derived organic matter seaward (MacEachern et al., 2005; MacEachern & Bann, 2008). Low to moderate bioturbation (BI = 2-3) levels representing a proximal expression of the *Cruziana* Ichnofacies, suggesting a nearby fluvial influence (MacEachern et al., 2005; MacEachern & Bann, 2008). Such events introduce zones of fresh water near the sediment-water interface, creating brackish conditions and a stressful environment for marine organisms. Bioturbation likely occurred between periods of high fluvial discharge during which the substrate was not reworked.

Syneresis cracks form under such brackish water conditions as clay particles flocculate, forming shrinkage structures, further suggesting a nearby fluvial influence (Wheeler & Quinlan, 1951; Burst, 1965; Plummer & Gostin, 1981). Additionally, the occurrence of hummocky and swaley cross-stratification, as well as wave ripples show sediment reworking by high energy oscillatory currents associated with storm wave action (Hunter & Clifton, 1982; Arnott & Southard, 1990; Southard et al., 1990; Dumas et al., 2005; Dumas & Arnott, 2006). As such, the documented characteristics of Facies C are indicative of deposition on a distal delta to medial front under the influence of waves, storms, and river outflow above storm wave base. This facies is comparable to thinly- to thickly-interbedded siltstones/sandstones interpreted as distal to medial delta front deposits within the broadly time-equivalent Ferron Sandstone of south-central Utah (Fielding, 2010).
**Facies D**

*Description*

Facies D consists of fine-grained sandstone (~ 95 %) with interbedded siltstone partings (~ 5 %) (Figs. 7d-f). Siltstones are fissile and dark gray (fresh) to dark brown-orange (weathered) in color and contain finely divided plant debris, siderite nodules, and sulfur staining. Sandstone beds are mostly fine-grained with significant quartz and lithic components. Black chert pebbles are dispersed throughout, with an increase in abundance up-section. Sedimentary structures observed within the siltstones include asymmetric ripple cross-lamination, climbing ripple cross-lamination, and convolute bedding. Sandstone beds commonly contain HCS, flat-to-low angle cross-stratification, asymmetric and symmetric ripple cross-lamination, interference ripples, syneresis cracks and locally small-scale cross-bedding. Bioturbation within the siltstones is uncommon, and *Planolites* is the only observed ichnogenus. A BI of 2 – 3 is typical within individual sandstone beds. Traces include *Diplocraterion, Planolites, Thalassinoides, Ophiomorpha, Gyrochorte* and unnamed arthropod claw marks. The ichnogenera assemblage has low diversity, with few commonly recurring traces. Overall, a low abundance of traces is suggested from the observation of minimal biogenic activity. Individual sandstone beds exhibit mostly sharp, scoured, undulating, and planar basal and upper contacts with adjacent sandstone beds and siltstone intervals. Beds are commonly 1.5 – 2.5 m thick, thicken up-section, and are laterally extensive throughout the study area. Facies D intervals form gently-dipping clinoform sets with beds extending over large distances (~ 1 km).
before lapping down tangentially onto a basal surface composed of Facies C. Overall, Facies D is typically 10 – 15 m thick, with thinner intervals at Lovell Draw and thicker accumulations down depositional dip in the Peay Member along the Bighorn River cliff in Greybull (Appendix 1A).

Interpretation

Abundant large-scale HCS and undulating bedding within the sandstone bodies of Facies D is indicative of a high-energy environment dominated by oscillatory wave flow and combined current-wave motion, perhaps during major storm/outflow events (Hunter & Clifton, 1982; Arnott & Southard, 1990; Southard et al., 1990; Dumas et al., 2005; Dumas & Arnott, 2006). Gently-dipping, elongate clinoform sets suggest deposition under low accommodation settings on a low depositional gradient. While a fluvial influence is suggested with the occurrence of unidirectional climbing/current ripples, syneresis cracks, and interbedded organic siltstones, oscillatory wave action was increasingly responsible for reworking the sediment, excising and creating the observed decline in siltstone partings up-section (Hunter & Clifton, 1982; Arnott & Southard, 1990; Southard et al., 1990; Dumas et al., 2005; Dumas & Arnott, 2006). Most bioturbation (vertical traces with minor occurrences of horizontal traces) is observed in distinctive bedding intervals, while the remainder of the sandstone body remains largely undisturbed. Organisms occupy the substrate along bedding planes usually during fair weather conditions, between periods of deposition (Bann & Fielding, 2004; MacEachern et al., 2005; MacEachern
& Bann, 2008). Traces commonly occur in accumulations with symmetrical ripples, interference ripples, and hummocky cross-stratification. Such bioturbation, referable to an impoverished expression of the *Cruziana/Skolithos* Ichnofacies is indicative of turbid conditions associated with a constant reworking of substrates in high energy environments (MacEachern et al., 2005; MacEachern & Bann, 2008). As such, Facies D is interpreted to record increasingly proximal, delta front environments between storm and fair weather wave base. Facies D closely resembles amalgamated sandstones in the Ferron Sandstone of south-central Utah interpreted by Fielding (2010) as proximal delta front deposits.

**Facies E**

*Description*

Facies E is dominated by a coarsening-upward succession of fine- to medium-grained sandstones consisting of a mixture of well-rounded quartz and lithic grains (Fig. 8a). Well-rounded chert pebbles are scattered throughout, increasing in abundance up-section. Sandstone beds display massive and flaggy bedding with the latter resulting from extensive weathering via prolonged exposure. Observed sedimentary features include abundant HCS, swaley cross-stratification (SCS), low angle to flat cross-bedding, macroform inclined bedding, small scale cross-bedding, asymmetric and symmetric ripple cross-lamination, interference ripples, syneresis cracks, and large secondary siderite nodules. Bioturbation is exceptionally rare within Facies E, which is assigned a BI of 0 – 1, with only *Planolites, Diplocraterion,* and
Thalassinoides ichnogenera present. According to the type log (Fig. 4), individual sandstone bodies are amalgamated to form a composite tabular, elongate, massively-bedded sandstone interval (10 – 35 m) across the study area. Within the Peay Member, the thinnest intervals were observed at Lovell Draw, with thicker accumulations occurring down depositional dip along the Bighorn River cliffs in Greybull. Basal and upper contacts between amalgamated sandstone units are sharp. Additionally, Facies E forms a gradational basal contact with the underlying Facies D and is sharply overlain by a pebble lag conglomerate (Facies I).

Interpretation

The occurrences of medium- to thick-bedded, sharply-based, tabular, amalgamated sandstone bodies with unidirectional cross-bedding (south-south-eastward) and macroform inclined bedding represent progradation of bedforms down a gentle depositional slope. A lack of interbedded mudstones and siltstone within quartz- and lithic-grained sandstone bodies containing HCS, SCS, and symmetrical ripples indicates a significant amount of storm and wave oscillatory influence in relatively shallow water depths (Hunter & Clifton, 1982; Southard et al., 1990; Dumas et al., 2005). Additionally, the overall coarsening up-section trend from fine- to medium-grained sandstones, as well as the presence of dispersed well-rounded chert pebbles supports the interpretation of a high-energy environment with an increased proximity to the shoreline. An abundance of syneresis cracks within lower portions of Facies E indicates a freshwater influence during deposition (Wheeler &
Quinlan, 1951; Burst, 1965; Plummer & Gostin, 1981). Absent to minimal bioturbation levels (BI = 0 – 1), represented by a very impoverished Skolithos Ichnofacies suite sparsely occupy distinct horizons within Facies E. As such, it is interpreted that observed bioturbation was generated by trophic generalists during brief periods of fair weather in an environment that was otherwise too stressed to support bottom-dwelling life (Bann & Fielding, 2004; MacEachern et al., 2005; MacEachern & Bann, 2008). The above characteristics of Facies E suggest a south-southeast prograding deltaic mouth bar depositional environment above fair weather wave base, under the constant influence of wave and current modification.

**Facies F**

*Description*

Only occurring in the Torchlight Member, Facies F consists of a fine-grained sandstone that is dominated by quartz and lithic grains (Figs. 8b, c). Well-rounded chert pebbles are locally dispersed throughout the facies. Flat-to-low angle bedding is the dominant physical sedimentary structure. Unidirectional cross-bedding is locally preserved. Facies F is sparsely bioturbated (rare fugichnia) and is assigned a BI of 0 - 1. The lower contact (Facies C, Fig. 4) is not readily observable, while the upper contact is sharp and erosional (Facies G or H, Fig. 4), having regional significance. Overall, the interval ranges between 2 and 6 meters thick and is more consistently preserved throughout northern portions of the study area in the vicinity of Alkali
Anticline (Clark, 2010). In southern localities, the stratigraphic interval occupied by Facies F occurs as the sandy remnants of an easily-weathered lithology in outcrop.

Figure 9: Photographs of common physical sedimentary structures and features observed through the Frontier Formation interval. A). Syneresis cracks on a horizontal bedding plain displaying the hallmark trilette arm pattern (arrow) (Peay Member, Facies D, Bighorn River North Outcrop Section). B). Aggrading symmetrical wave ripples (arrow) within a siltstone parting of Facies D (Peay
Member, Tin Can Alley Outcrop Section). C. Horizontal bedding plane surface of Facies D showing tuning fork bifurcation (arrow), of symmetrical wave ripple crests. The vertical burrow, Diplocraterion (Di.), is present sparsely (Peay Member, Bighorn River North Outcrop Section). D. Small-scale trough cross-stratification (arrow) within Facies E of the Peay Member (Outcrop Section 11). E. Dispersed coaly plant debris (arrow) within the thickly interbedded sandstones and siltstones of Facies C (Peay Member, Bighorn River North Outcrop Section). F. Small-scale hummocky cross-stratification (HCS; arrow) within the thickly interbedded sandstones of Facies C (Peay Member, Bighorn River South Outcrop Section).

**Interpretation**

Flat-to-low angle cross-bedded sandstone that lacks any observable bioturbation is interpreted as representing deposition in a high energy environment. Individual bedsets were deposited during high discharge events probably associated with storms. Flat-to-low angle cross-stratification implies the constant reworking of sediments following deposition. The regionally persistent sharp upper contact is indicative of significant widespread erosion before the accumulation of overlying facies (Facies G or Facies H). While the lower contact is not readily observable, Facies F is interpreted to be genetically related to underlying facies (Facies C, Fig. 4) culminating in a coarsening upward stratigraphic cycle (Van Wagoner et al., 1990; Kamola & Van Wagoner, 1995). A lack of bioturbation, plant debris, trough cross-bedding, and siltstone partings suggests the accumulation of Facies F occurred in an environment different from that of a delta front (Facies D, E). As such, the aforementioned characteristics of Facies F suggest a high energy, shallow water, upper shoreface depositional environment.
Facies G

Description

Facies G is a localized accumulation of gray (fresh) to brown (weathered) siltstone with abundant plant fragments dispersed throughout (Fig. 8b). The siltstone displays planar laminations and is fissile in character. Evidence for biogenic sediment reworking is lacking and a BI of 0 is assigned. Only observed in Section 1 (Appendix 1A), Facies G is 40 centimeters thick, while extending approximately a few tens of meters laterally before being erosionally truncated. The lower contact with Facies F is sharp while the upper contact with Facies H is undulating and erosional. Overall, Facies G exhibits a discontinuous lensoid geometry in the north-south trending outcrop.

Interpretation

These unbioturbated siltstones containing abundant plant debris are interpreted to represent alluvial or coastal flood plain deposits. The fact that such terrestrial sediments overlie shallow marine deposits implies a significant erosional discontinuity with the underlying facies (Facies F). Furthermore, over much of the outcrop belt, Facies G is absent, and Facies F is directly and erosionally overlain by fluvial channel deposits (Facies H – see below). The erosional juxtaposition of flood plain deposits above shallow marine accumulations suggests that regional fluvial downcutting most likely removed significant portions of such sediments from the stratigraphic record.
**Facies H**

*Description*

Facies H consists entirely of medium- to coarse-grained, lithic, poorly cemented sandstone that exhibits an increase in grain-size stratigraphically up-section (Fig. 8b, d). The sandstone commonly contains well-rounded chert pebbles dispersed along bedding planes throughout, with an increase in abundance up-section. Chert pebbles, as well as coarse-grained sandstones also occur along the basal contact with Facies F. South-southeast-oriented trough cross-bedding is the predominant physical sedimentary structure observed throughout, with a minor bidirectional component to paleoflow occurring at several localities. Some bed tops are covered by symmetrical wave ripples, in places with interference patterns. Planar to low-angle cross-bedding is present locally. The BI for Facies H is 0 as bioturbation is absent throughout. Petrified trunks of fossil trees were found locally, as were molds after bivalve shells. Regionally, individual sharp-based sandstone beds coalesce to form multilateral, multistory, tabular, sheet-like geometries, typically ranging 3 – 7 meters thick. Individual sandstone beds are sharp-based. Overall, Facies H has both sharp upper and lower contacts with enclosing facies. The lower contact with Facies F or G (where present) is erosional, occurring as a regionally traceable erosional surface. The upper contact with Facies I is erosional, with an observed low angle relief surface.
Interpretation

Bimodal trough cross-beds in multilateral/multistory sandstone bodies (Facies H) that overlie a regional erosional surface are interpreted to represent the accretion and accumulation of subaqueous barforms and bedforms in rivers with tidal influence (Dalrymple et al., 1992; Shanley et al., 1992; Dalrymple & Choi, 2007; Fischbein et al., 2009). The regional erosional surface does not exhibit significant incisional relief and does not facilitate an interpretation of incised valley formation. Rather, the erosion surface has a broadly planar and concordant cross-sectional geometry. Accumulations of chert pebbles at the erosional base of Facies H, as well as along individual bedding planes indicates a high energy environment capable of physically scouring underlying sediments and transporting coarse-grained/pebble-sized sediments. A lack of bioturbation (BI = 0) can be attributed to both high energy and brackish-to-fresh water conditions within the fluvial environment. Observation of bimodal trough cross-bedding, as well as the occurrence of bivalve molds in the upper portions of Facies H may suggest a coastal influence. The juxtaposition of erosionally-based, multilateral/multistory, trough cross-bedded sandstone bodies above marine shoreface sands indicates that Facies H was formed above a surface of regional downcutting.
Facies I

Description

Facies I is a suite of pebble-cobble conglomerate beds preserved at a variety of stratigraphic levels throughout the Frontier Formation. The thickest accumulation occurs above the Torchlight Member (Torchlight Conglomerate: Fig. 8f), although very coarse-grained sandstones/pebble to cobble conglomerates also occur within the Peay and Alkali Members (Fig 8e). The Torchlight Conglomerate is a clast-supported accumulation of well-rounded chert, quartzite and andesitic porphyry pebbles and cobbles, with an additional population of granodiorite, diorite, and petrified wood (very rare) clasts. Within the Peay and Alkali Members, Facies I is both matrix and clast-supported, the matrix dominated by very coarse quartz grains with a major lithic component, and the gravel population is solely composed of well-rounded black chert clasts. Bone fragments, crocodile teeth, fish vertebrae, and unidentified teeth were also observed within a conglomerate bed at the top of the Peay Member. In situ exposures of the Torchlight Conglomerate are relatively uncommon as the conglomerate is weakly cemented. Thus, Facies I often occurs as scattered pebbles and cobbles covering the ground surface adjacent to outcrop of the Torchlight Member. Where in situ, the Torchlight Conglomerate lacks physical sedimentary features and displays a fining upward trend from basal cobbles to pebbles and granules up-section. Above the Peay Sandstone, the very coarse sandstone/pebble lag often displays symmetric ripples with interference patterns. Facies I is devoid of bioturbation (BI = 0) throughout. Regionally, the multiple occurrences of Facies H
(Peay, Torchlight) are laterally extensive and display sheet-like geometries. Thicknesses vary throughout the members, ranging between 5 and 80 cm. Overall, the lower contacts of Facies I are erosional, but generally planar.

*Interpretation*

Juxtaposed erosionally above shallow marine-to-fluvial deposits, chert and andesite-rich pebble/cobble accumulations are interpreted to have formed during regional transgressions (Weimer, 1988; Hwang & Heller, 2002). Such low-relief and consistently widespread deposits represent regional events that effectively truncated underlying strata in a planar-to-subhorizontal fashion (Martinsen, 2003a). The occurrence of wave and interference ripples on top of coarse-grained sandstone-to-pebble/cobble lags indicates that high energy wave action scoured the underlying sediments, winnowing away fine-grained sediments (Weimer, 1988; Hwang & Heller, 2002). Localities displaying reverse-graded lag deposits overlain by offshore mudstones imply a period of high energy wave ravinement that subsequently waned through time. As such, the aforementioned characteristics of Facies H are interpreted to represent depositional hiatuses during widespread sea level transgressions.

**FACIES STACKING PATTERNS AND LATERAL VARIATIONS**

The following section provides a brief description of each member of the Frontier Formation in the study area, in ascending order, concerning vertical stacking patterns and lateral variations.
Stucco Member

Vertical Trends

Consisting of a coarsening-upward interval, the Stucco Member interval lies stratigraphically between the Mowry/Frontier contact and the base of Facies D (amalgamated sandstones) of the Peay Member (Fig. 4). The vertical succession consists of basal offshore marine mudstones (Facies A), interbedded prodeltaic mudstones/siltstones and sandstones (Facies B), and distal delta front hummocky cross-stratified sandstones interbedded with siltstones (Facies C). The sandstone-to-siltstone ratio gradually increases up-section as sandstone bodies thicken at the expense of siltstone interbeds. A genetically-related (Waltherian) succession is interpreted as the observed contacts between facies are gradational.

Lateral Variations

The Stucco Member displays lateral continuity along both depositional dip and strike (Appendix 1A, B). Where observed, the entire succession ranges between 30 – 40 meters thick, between the basal Mowry/Frontier contact and the upper contact with Facies D of the Peay Member. The basal Mowry/Frontier contact is laterally extensive, as it is observed throughout much of the study area (Appendix 1A, B). Facies within the Peay Member (mentioned below) do not downcut into the Stucco Member, preserving the regional consistency of the interval.
**Peay Member**

*Vertical Trends*

A detailed facies analysis of the Peay Member from 20 measured outcrop sections reveals a shoaling and coarsening upward trend throughout the vertical facies assemblage. The vertical trend consists of middle delta front hummocky and swaley cross-stratified sandstones with thin siltstone partings (Facies D), proximal delta front/mouth bar trough cross-stratified sandstones (Facies E), and coarse sandstone/pebble lag (Facies I) (Fig. 4). With the exception of the erosional basal contact of Facies I, contacts between facies are gradational, suggesting a genetic depositional relationship and a single shallowing-upward trend through the Peay Member.

*Lateral Variations*

The Peay Member displays thickening and thinning trends along both north-south and east-west outcrop trends (Appendix 1A, B). Observed thicknesses range from 35 m – 110 m along the north-south transect, and 25 m – 110 m along the east-west transect. Thickness variations predominantly occur within Facies D-E, with the thickest accumulations occurring along the Bighorn River cliffs in Greybull (north-south; east-west transects) (S 13-15, TCA, Fig. 5, Appendix 1A, B). Thinner intervals of the Peay Member (~35 – 40 m) were observed in proximity to Lovell Draw (S 4-8, Fig. 5; north-south transect). The Peay also thins in a west-east direction from Greybull (110 m) to Potato Ridge (25 m) forming a series of three sandstone benches.
(Facies C) as Facies D and E pinch out (S 13-15, TCA, Potato Ridge, Fig. 5, Appendix 1B). Facies I is observed regularly above Facies E throughout the study area as a low-relief deposit with little thickness variation (< 0.50 m).

**Potato Ridge Member**

*Vertical Trends*

Stratigraphically, the Potato Ridge Member lies above Facies I of the Peay Member (Fig. 4). Observed facies from measured outcrop sections include the basal offshore marine mudstones (Facies A), interbedded prodeltaic mudstones and sandstones (Facies B), distal delta front hummocky cross-stratified sandstones interbedded with siltstones (Facies C), and a thin pebble lag (Facies I) (Fig. 4). Facies A passes gradationally into Facies B and C, whereas Facies I locally shows a sharp, erosional contact with the sandstone of Facies B/C. Ultimately, the Potato Ridge vertical succession is overlain stratigraphically by the “X” Bentonite (Fig. 4). Pervasive mining of the “X” Bentonite limits the extent of accessible exposure the Potato Ridge Member.

*Lateral Variations*

The Potato Ridge Member vertical succession is laterally consistent within measured outcrop sections throughout the study area (Appendix 1A, B). Thicknesses obtained from outcrop sections along the north-south transect ranged between 3 and 8 meters (Appendix 1A). The interval is not exposed within east-west transect sections
due to extensive mining activity. However, given the vertical interval separating the Peay and Alkali Members along the east-west cross-section (Appendix 1B), Potato Ridge Member thicknesses are likely consistent throughout the outcrop study area.

**Alkali Member**

*Vertical Trends*

The Alkali Member is an approximately 40 – 60 meter thick interval consisting of numerous (4 – 7) coarsening upward cycles (Fig. 4). These cycles range from 5 – 20 meters thick and commonly consist of a basal offshore marine shale (Facies A), interbedded prodeltaic mudstones/siltstones and sandstones (Facies B), hummocky cross-stratified sandstones with interbedded siltstone intervals (Facies C), capped by a thin pebble lag (Facies I) (Fig. 4). Facies A – C contain gradational contacts, while Facies I erosionally overlies Facies C. The Alkali Member interval overlies the “X” Bentonite, and overlain by the Torchlight Member (Fig. 4).

*Lateral Variations*

Outcrops exposing the Alkali Member were measured along both the north-south and east-west transects (Appendix 1A, B). Individual sandstone body thicknesses and occurrences vary throughout with no observable trends. Pebble lags (Facies I) are correlatable throughout the study area, but are not as persistent as the lag above the Peay Member. Overall, the interval varies in thickness along the north-south cross-section. Thick (30 – 40 m) and thin (10 – 20 m) intervals occur in
geographic locations similar to thick and thin Peay Member deposits, respectively (Appendix 1A, B). However, accurate thickness measurements are difficult to obtain as the Alkali Member interval is extensively altered due to bentonite mining activity within the study area. As such, the lateral continuity and variation of individual thin coarsening-up intervals is relatively poorly-resolved as outcrop sections containing the Alkali Member are often spaced several kilometers apart, prohibiting any detailed regional correlation.

**Torchlight Member**

*Vertical Trends*

Throughout the study area, the Torchlight Member consists of a coarsening-upward interval of medium-to-coarse-grained sandstones. From base to top in a vertical stratigraphic section, the observed facies include flat-to-low angle cross-bedded sandstones (Facies F), multilateral and multistory trough cross-stratified sandstones (Facies H), and an andesitic and chert large pebble-to-cobble lag (Facies I) (Fig. 4). Throughout much of the region, Facies H erosionally overlies Facies F. However, a thin, lensoid-shaped occurrence of siltstone (Facies G) occurs locally along the contact.

*Lateral Variations*

The basal erosional contact of Facies H is consistent regionally along both of the north-south and east-west transects (Appendix 1A, B). Several of the measured
outcrop sections reveal that Facies H rests upon marine strata (Facies F), where Facies G has been removed by erosion (Appendix 1A). Additionally, Facies H erosionally rests upon the distal deltaic facies of the Alkali Member locally (Facies C, Appendix 1A, B). Facies I forms a laterally extensive event throughout the region, occurring as a low-relief, relatively planar horizon (Fig. 4). Overall, the Torchlight Member consistently ranges between 10 – 15 meters thick along depositional dip and strike (Appendix 1A, B).

**Spence Member**

*Vertical Trends*

Two distinct shoaling and coarsening up cycles are present within the Spence Member over much of the study area. The facies assemblage for the cycle consists of a combination of interbedded prodeltaic mudstones/siltstones and sandstones (Facies B), distal delta front hummocky cross-stratified sandstones and interbedded siltstone intervals (Facies C), and a pebble lag (Facies I) (Fig. 4). A distinct horizon immediately above the second shoaling-upward cycle contains boulder-sized calcareous septarian nodules with the ammonite *Dunveganoceras pondii* (Kirschbaum et al., 2009) (Fig. 2). Contacts between Facies B and C are gradational, while the basal surface of Facies I is erosional (Fig. 4).
Lateral Variations

The Spence Member is poorly exposed as two minor benches in the measured outcrop sections along both the north-south and east-west transects (Appendix 1A, B). Facies I is not aerially extensive, with exposure of the lag occurring only near the northern extremity of the north-south outcrop cross-section (Appendix 1A). However, a thin sandstone interval (Facies C) and the distinct septarian nodule horizon are persistent throughout the study area along both cross-sectional transects. The interval exhibits a consistent regional thickness, ranging between 20 and 25 meters (Appendix 1A, B).

Discussion
Depositional Environment

Vertical trends and lateral variations in the facies assemblages observed throughout the Frontier Formation (Stucco, Peay, Potato Ridge, Alkali, Torchlight, and Spence Members) constitute evidence for repeated shallow marine deltaic progradational events. It is common for shallow marine deposits to display a combination of wave, storm, tidal current, river-derived current, and oceanic current physical processes, with one process often dominating (Hampson et al., 2008a). Frontier Formation accumulations are interpreted to represent wave- and tidally-influenced, fluvially-dominated deltaic deposits. Physical sedimentary structures and plan body geometries that formed under the influence of fluvial effluent are abundant. Thinly-interbedded sandstones within thick offshore marine deposits (Facies B)
display current ripples, combined-flow ripples, and sharp bedding surfaces that are indicative of deposition under unidirectional flow regimes. Depauperate trace fossil suites, syneresis cracks (Fig. 7A), and the dispersal of organic siltstone interbeds throughout the stratigraphic sections also support a fluvial influence. Hummocky cross-stratified sandstones (Fig. 9F), small scale trough and flat- to low-angle cross-bedded sandstones that coincide with decreasing siltstone/sandstone ratios up-section are indicative of storm and fair weather wave-reworked sediments (Figs. 7C, 8D, 9D). Observed plan geometries (e.g. Peay Sandstone, Fig. 13) of sandstone bodies are digitate and lobate, indicative of fluvially-dominated deltaic environments. The preservation of bimodal cross-bedding orientations in the Peay and Torchlight Members also suggests a tidal influence upon deposition at times (Fig. 10).

Gently southward-dipping clinoforms within the Peay Member sandstones, as well as paleocurrent data derived from current ripple laminations and trough cross-bedding indicate southward delta progradation and fluvial (Torchlight) paleoflow direction (Fig. 10). Fluvially-derived sediments were deposited as small scale cross-bedded, shallow marine deltaic mouth bars (Facies E; Peay Member) that prograded into the KWIS. The southward direction indicated by paleocurrent and clinoform directions was parallel to the regional paleoshoreline. Such longshore progradation could result from onshore and longshore fair weather wave-driven and geostrophic currents, associated with a counterclockwise gyre that existed within the KWIS during the Late Cretaceous (Slingerland et al., 1996), similar to the model derived for the Ferron Sandstone in Fielding (2010).
The Stucco and Peay Members in combination display the most complete upward shoaling and upward coarsening vertical facies succession within the Frontier Formation (Figs. 4). Regional erosion is observed within the Torchlight Member with the juxtaposition of fluvial sandstone deposits over nearshore and offshore marine sediments (Fig. 4, Appendix 1A, B). Additionally, outcrop Section 1 (Fig. 5) contains a laterally discontinuous occurrence of fluvial floodplain siltstones (Fig. 4). As such, the upper Torchlight may be a genetically-unrelated vertical succession as the erosion of underlying sediments by fluvial activity that may indicate unrepresented geologic time (cf. Van Wagoner et al., 1990; Kamola & Van Wagoner, 1995). As the Potato Ridge, Alkali, and Spence Members also exhibit vertical successions comparable to the Peay, they most likely represent distal and off-flank equivalents of prograding deltas. A further analysis of regional progradation patterns of all Frontier Formation Members is given below.

**SUBSURFACE ANALYSIS**

A regional subsurface correlation of the Frontier Formation throughout the eastern Bighorn Basin was performed to interpret lateral and vertical variations in sandstone body geometry and to evaluate depositional trends. Analysis of measured outcrop sections formed the basis for interpreting and correlating key stratigraphic horizons of the Frontier Formation into the subsurface. The northernmost (Section 1) and southernmost (Bighorn River South) measured outcrop sections along the
Figure 10: Paleoflow and sediment dispersal patterns of the Peay and Torchlight sandstone bodies. A). Photograph of a Peay Sandstone cliff line west of the MiSwaco Bentonite Plant northwest of Greybull, Wyoming. B). Rose diagrams containing paleocurrent data gathered from twenty measured outcrop sections for both the Peay and Torchlight sandstones. Paleocurrent data predominantly suggest southward sediment dispersal with a bimodal component. C). Outline of bedding features observed along the cliff line in Fig. 10A. Black arrows are pointing at gently-inclined clinoform surfaces that are dipping southward, corresponding to the regional sediment dispersal pattern interpreted from paleocurrent data in Fig. 10B. The gentle inclination of clinoforms also suggests deposition under shallow water low accommodation settings.
depositional dip cross-section were used to calibrate nearby subsurface gamma ray logs (Figs. 11, 12) (Well API # 4900320303 – A-A’: 4900320450 – B-B’). Regional correlations given by Kirschbaum et al. (2009) also served as a correlation guide for the region. As with the outcrop transects, cross-sections are hung from the Torchlight Conglomerate Datum. The interval of interest includes the six Frontier Formation Members (Stucco, Peay, Potato Ridge, Alkali, Torchlight, Spence) and their corresponding sandstone units, stratigraphically enclosed between the Mowry Shale below and the Cody Shale above.

**Mowry Shale**

The Mowry/Frontier contact directly corresponds to the M100 surface of Kirschbaum et al. (2009: their Figure 7, Well API # 4900320888). This surface is interpreted as the subsurface gamma ray expression of the Clay Spur Bentonite and/or the contact between silicified siltstones and sandstones of the Mowry Shale with fissile dark gray shales of the basal Stucco Member. This surface is characterized by a sharp increase in gamma ray values at the base of the Stucco Member that is readily observed within a majority of the gamma ray logs used in this analysis (Appendix 2A-E).

**Stucco Member**

In Well API# 4900320303 (A-A’; Appendix 2A), the Stucco Member interval lies between the Mowry/Frontier contact (see above) and the base of the massive
Peay Member sandstone at depth 900 m (Fig. 11). The top boundary is not correlatable to any surface interpreted in Kirschbaum et al. (2009). Overall, the Stucco Member succession displays a partial funnel shape, with moderately high gamma ray values at the base, while slowly decreasing upward, suggesting a coarsening-upward component. This gamma ray log pattern is equivalent to Facies A, B, and C observed in outcrop (Well API# 4900320303; Fig. 11). Thicknesses range between 30 and 40 meters and are consistent throughout all subsurface correlations (Appendix 2A – E). Isopach maps were not generated for the Stucco Member as it lacks regionally significant and traceable sandstone bodies.

**Peay Member**

In Well API# 4900320303 (A-A’; Appendix 2A), the top of the Peay Member is placed at a depth of 866 meters below the surface above an upward decreasing trend in gamma ray log values (Fig. 11), resulting in a regionally consistent, funnel-shaped log pattern across much of the eastern Bighorn Basin. This surface directly correlates to F500 in Kirschbaum et al. (2009: their Figure 7, Well API # 4900320303) and is the gamma ray log equivalent to the planar, low relief pebble lag at the top of the Peay Member in measured outcrop sections. The thickest accumulations of the Peay Member (55 – 70 m) occur near Greybull (B-B’) and extend northwest along cross-section A-A’ (Appendix 2A). A regional thinning trend of the entire interval (30 – 46 m) is observed in the subsurface southeast of Greybull near Manderson along cross-section B-B’ (Appendix 2B). Additionally, thinning of
the interval is observed along transect E-E’, immediately west-southwest of Greybull (Appendix 2E).

Isopach maps generated from well log and outcrop intersections display trends in thickness variation of the Peay Member sandstone body throughout the northeastern Bighorn Basin (Fig. 13). Extending northwest of Greybull, a northwest-southeast trend of thick sandstone (24 – 34 m) coincides with the overall increase in the Peay interval thickness (Fig. 13). An abrupt east-to-west decrease in body thickness is apparent perpendicular to this trend, where massive sandstones display an interfingering relationship with enclosing mudstone-dominated strata before ultimately pinching out after approximately 15 kilometers (E-E’) (Fig. 13). Thick sandstone accumulations are absent from southern and western portions of the study area, averaging < 3 – 11 meters. Additionally, outcrop observations reveal an anomalous southward thinning and abrupt thickening of the Peay Sandstone northwest of Greybull near Lovell Draw (A-A’) (Fig. 13). Overall, the Peay Sandstone exhibits a northwest-southeast elongate, east-west restricted digitate geometry (Fig. 13).

**Potato Ridge Member**

Regional correlation of the Potato Ridge Member is aided by the laterally continuous key stratigraphic surface, F400, of Kirschbaum et al. (2009: their Figure 7, Well API #4900320303). This horizon (top Potato Ridge Member) is present above a broadly coarsening-up trend observed in subsurface well logs occurring at 856 meters
Figure 11: Calibration of measured Outcrop Section 1 with the southern-most gamma ray log along subsurface cross-section A-A’, near Alkali Anticline. Calibrations aided in the subsurface correlation of the Frontier Formation interval north of Alkali Anticline.
Figure 12: Calibration of Bighorn River South outcrop section with subsurface data. Well API # 4900329624 is placed within subsurface cross-section B-B’. This calibration diagram aided in the correlation of Frontier Formation intervals in the southern portions of the eastern Bighorn Basin.
below the surface (Well API # 4900320303) and is expressed in outcrop as a pebble lag-bearing sandstone that caps a coarsening-upward succession (Fig. 11). Above the Potato Ridge Member, a thick bentonitic interval that corresponds to the “X” Bentonite in outcrop is manifested in well logs as a regionally continuous, abrupt increase in gamma ray values (Appendix 2A-E). As such, the Potato Ridge Member is defined stratigraphically as the interval located between the top of the Peay Member and the base of the “X” Bentonite (Figs. 4, 11). The interval thickens to the south and southwest of Greybull, with the thickest intervals reaching 46 to 61 meters (B-B’). In Well API # 4904320721, the Potato Ridge Member is expressed as a cylindrically-shaped, sharp-based low gamma ray response (Appendix 2B). Ultimately, the interval thins south of Cottonwood Creek (Appendix 2B-E). West of Cottonwood Creek, wire line logs display a series of three successive intervals of upward-decreasing gamma ray values, culminating in a funnel shape trend (C-C’). North of Greybull, the interval dramatically thins (Well API # 4900320303) to approximately 3 – 6 meters, consistent with nearby measured outcrop sections (Fig. 11).

A thickness maximum of the Potato Ridge sandstone is preserved in southern portions of the eastern Bighorn Basin. Coinciding with thick intervals observed in well logs near the Cottonwood Creek oil field, the isopach map illustrates an approximate east-to-west elongate trend for substantial sandstone accumulations (18 – 46 m) (Fig. 13). Massive sandstone bodies observed near Cottonwood Creek split westward into three distinctive units along subsurface cross-sections C-C’ and D-D’.
As shown in well log cross-sections, sandstone body thinning occurs north and south of the main accumulation.

**Figure 13:** Isopach maps of Frontier Formation sandstone bodies in the northeast Bighorn Basin. **A). Peay Sandstone.** Accumulations display a north-south elongate, east-west thinning trend, characteristic of a southward-directed digitate system. A down-dip thinning-thickening trend observed (white arrow) corresponds to the outcrop trend passing through an off-flank portion of a digitate delta. **B). Potato Ridge Sandstone.** A southward shift in the depocenter is suggested for the post-Peay
Potato Ridge Sandstone. An east-west elongate sandstone body geometry is observed from subsurface correlations. Additionally, compensational stacking is observed with respect to the Peay Sandstone. **C). Torchlight Sandstone.** In conjunction with wireline log interpretations, a northwest-southeast trending channel body is interpreted (arrow). As such, widespread coastal marine and fluvial deposition observed within the Torchlight Sandstone represents a basin-ward shift in sedimentation, as well as compensational stacking with respect to the Peay and Potato Ridge bodies. **D). Spence Sandstone.** Two isolated, eastward-directed lobes are apparent, again exhibiting compensational stacking with respect to underlying strata.

area (Fig. 13). Measured outcrop sections within the northwestern portions of the study area contain a correlative interval with thin (cm’s thick) sandstone accumulation (A-A’) (Appendix 1A). As such, the Potato Ridge Member sandstone body exhibits an overall east-west elongate, north-south laterally-restricted lensoid geometry (Fig. 13).

**Alkali Member**

The Alkali Member is the interval between the “X” Bentonite and the Torchlight Sandstone, as defined by Clark (2010). Analysis of wireline logs from Well API # 4900320303 reveals two distinctive upward decreasing gamma ray log successions (A₁ = upper; A₂ = lower) (Fig. 11). These successions are correlatable along cross-section A-A’ north of Alkali Anticline. However, the regional continuity of A₁ and A₂ is difficult to ascertain and they do not directly correspond to surfaces illustrated in Kirschbaum et al. (2009). Where present, thicknesses for the successions vary throughout the study area. Both reach maximum thicknesses along cross-section A-A’ north (A₁; 18 – 26 m : A₂; 21 – 32 m) of Alkali Anticline. In southern and western portions beyond cross-section A-A’, A₁ is not readily recognizable, while the
A₂ horizon is traceable throughout the eastern Bighorn Basin. The A₂ succession displays a minor thickness increase in the southwest part of the study area along cross-section C-C’. Wells API # 4904320447 and 4904320206 exhibit a blocky gamma ray pattern (low gamma values) in the same stratigraphic interval as A₂ throughout the study area that is interpreted as the equivalent horizon observed throughout the study area (Appendix 2C). Isopach maps were not generated for the Alkali Member sandstones because of their variable patterns and the difficulty of regional correlation.

Extensive sandstone accumulations in both Alkali Member successions are not present in the subsurface cross-sections. Thinly-bedded, north-south and east-west laterally-restricted, isolated bodies are evident, mainly in the northwestern portions of the study area (A-A’). The thickest observed accumulations (~ 12 meters) occur near to (A₂) and north of (A₁) Alkali Anticline. However, throughout cross-section A-A’, the majority of body thicknesses are much less, ranging between 1 and 3 meters.

**Torchlight Member**

Serving as the regional datum for the outcrop and subsurface cross-sections, the top of the Torchlight Member coincides with the F300 surface of Kirschbaum et al. (2009: their Figure 7, Well API# 4900320303), as well as the Torchlight Conglomerate observed in measured sections (Fig. 11). The Torchlight horizon occurs as a planar, low relief surface throughout much of the eastern Bighorn Basin, occurring at a depth of 770 meters in Well API# 4900320303 (Fig. 11). This surface
locally occurs in conjunction with an abrupt increase in gamma ray values, which may represent a localized bentonite horizon. Gamma ray logs commonly appear as funnel-shaped (upward-decreasing gamma ray values) or blocky and cylindrical (no upward gamma ray trend). The thickest accumulations (45 – 61 m) occur southeast of Greybull, near Manderson (B-B’) (Appendix 2B). Cylindrical-shaped, sharply based gamma ray responses correspond to the increase in interval thickness, as observed in wells API # 4900320994 and 4904320622 (Appendix 2B). The Torchlight interval thins to the north near Greybull and along cross-section A-A’ (9 – 18 m), as well as towards the south and southwestern portions of the eastern Bighorn Basin. Western portions of the study area display 2-3 small-scale upward-decreasing gamma ray cycles (C-C’) (Appendix 2C). Additional thickening (20 – 25 m) occurs east-to-west along cross-section E-E’, immediately west of Greybull (Appendix 2E).

Significant Torchlight sandstone body accumulations observed in cross-sections B-B’ (Well API# 4900320994; 4900320622, Appendix 2B) and E-E’ (Well API # 4900320450, Appendix 2E) directly correspond to the overall interval thickness increases near Manderson (arrow) and west of Greybull (Fig. 13). Isopach maps highlight individual body accumulations, with the greatest thicknesses ranging between 30 – 35 meters (Fig. 13). Sandstones thin to the north and east, as well as to the south and west of Manderson (Fig. 13). The isopach map illustrates an overall northwest-southeast elongate, northeast-southwest laterally-restricted, linear geometry for the Torchlight Sandstone throughout the eastern Bighorn Basin (Fig. 13).
**Spence Member**

The Spence Member stratigraphic surface used in regional correlation directly corresponds to F200 of Kirschbaum et al. (2009: their Figure 7), occurring at the top of a package of 2 – 3 coarsening-upward successions preserved above the Torchlight Member (Fig. 11). In southern portions of the eastern Bighorn Basin, this horizon is highlighted by the abrupt upward change to very high gamma ray values, suggesting the presence of a bentonite interval (eg: API # 4904320721; 4904320657; Appendix 2D – E). Overall, gamma ray log trends are highly variable, with funnel, symmetrical, and asymmetrical shapes all preserved. The Spence Member succession ranges between 35 - 40 meters thick throughout the study area. In Well API # 4904320422, an increase in the sand to mud ratio occurs to the southwest of Greybull as indicated by a higher proportion of low gamma ray values (D-D’) (Appendix 2D).

As many as three sandstone bodies associated with three small-scale upward-decreasing gamma ray log cycles occur within the Spence Member. Such bodies display a thin (3 – 6 m), lensoid character in subsurface correlations. The thickest accumulations (6 – 15 m) occur in the southwest portion of the study area, coinciding with the overall increase in sandstone body thickness shown in the Spence Member isopach map (Fig. 13). While cross-sections A-A’, C-C’, and D-D’ contain individual sandstone intervals characterized by lensoid geometries, the isopach map indicates an overall thin, possibly lobate geometry for the entire Spence Member vertical succession (Fig. 13).
Discussion

Upward declining, funnel-shaped gamma ray log profiles commonly occur throughout the subsurface intersections of the Stucco, Peay, Potato Ridge, Alkali, Torchlight, and Spence Members (Appendix 2A-E). Cant (1992) interprets this type of trend as recording abruptly topped, coarsening upward succession representing deposition in crevasse splay, distributary mouth bar, clastic strand plain, barrier island, or shallow marine sand sheet environments. Additional identified gamma ray log trends include

![Gamma Ray Log Trends Diagram](image)

**Figure 14:** Upward trends in gamma ray logs. Funnel-shaped, serrated (non-trending), symmetrical, and asymmetrical trends are all observed throughout the Frontier Formation interval. Depositional environment interpretations after Cant (1992).
serrated (non-trending) (Potato Ridge, Torchlight), symmetrical, and asymmetrical shapes (Appendix 2A-E). Sharp-based serrated trends are interpreted as originating in aeolian, braided fluvial, and submarine canyon fill environments (Fig. 14; Cant, 1992). With a rounded top and base, symmetrical gamma log patterns likely develop from sandy offshore bars and transgressive shelf sands (Fig. 14; Cant, 1992). Sharply-based, asymmetric gamma ray responses likely represent a fining up succession of fluvial point bars, tidal point bars, deep sea channel deposits, and transgressive shelf sands (Fig. 14; Cant, 1992).

Lateral and vertical variations in facies assemblages observed in measured outcrop sections, as well as correlation between outcrops and wireline logs serve as a direct control for interpreting gamma ray log trends (Appendix 1A, B; Figs. 11, 12). Upward declining, funnel-shaped trends in the subsurface Peay Member directly correspond to interpreted prograding delta front to distributary mouth bar deposits at outcrop. Detailed facies analyses also lead to a similar progradational delta front to distributary mouth bar interpretation for such upward-decreasing gamma trends within the Potato Ridge, Alkali, Torchlight, and Spence Members. Sharp-based serrated trends within the Torchlight sandstone most likely reflect coastal fluvial deposits, similar to facies observations in measured outcrop sections. Given the observed facies assemblage of surrounding strata (Peay, Torchlight), serrated trends within thick Potato Ridge intervals indicate a probable fluvial influence at the associated localities. Full exposure of the Spence Member was limited within the study area, prohibiting an appropriately detailed facies analysis. As such, further
facies analysis of the Spence Member concerning vertical and lateral distributions within measured outcrop sections must occur before interpreting subsurface gamma ray log trends beyond generalizations such as those presented in Cant (1992).

A combination of shoaling-upward successions in outcrop (offshore marine shales to proximal delta front sandstones) and subsurface (funnel-shaped gamma ray logs) cross-sections, lateral facies variations, and paleocurrent data form the basis for a regional interpretation of depositional systems and sediment dispersal trends. Isopach maps and subsurface cross-sections predominantly display linear to lobate plan geometries for sandstone bodies within the Peay, Potato Ridge, Torchlight, and Spence Members (Fig. 13). Paleocurrent data (Peay, Torchlight Members) and gently-dipping clinoforms (Peay Member) illustrate a south-southeast progradation direction, possibly resulting from a deflected asymmetric delta planform similar to the interpretation of the Ferron Sandstone, south-central Utah (Fielding, 2010; Figs. 10, 13). Such trends do occur in the stratigraphic record along the western margin of the KWIS, particularly within the Notom Delta Ferron Sandstone model proposed by Fielding (2010). This model differs from the asymmetric delta model proposed by Bhattacharya & Willis (2001) in that significant accumulations of sandy sediments occur in downdrift areas, whereas alongshore directed currents deposit beach ridges on updrift locations (Fielding, 2010). Deposition of the modern Po River Delta is invoked as a modern analogue to the deposition of the Peay and Torchlight Members (Fig. 15b, Cattaneo et al., 2003). Subaqueous shallow marine sandstones are deflected and prograde southward from eastward-protruding terrestrial fluvio-deltaic facies (Fig
15b, Cattaneo et al., 2003). The resultant planform geometry for the shallow marine sandstone bodies are depositional dip elongate, laterally-restricted, and lobate, similar to those observed within the Frontier Formation (Peay & Torchlight Members; Fig 15b, Cattaneo et al., 2003). Additionally, the anomalous down-dip thinning and thickening trend observed in the Peay Sandstone isopach map (Fig. 13, arrow) may represent a transect intersecting off-flank portions of the delta lobe or possible differential erosion from deep-seated tectonic events (Rio Thrust; Stone, 2004).

Figure 15a: Several major delta progradational events (Peay, Potato Ridge, Torchlight, Spence) occurred in the low accommodation settings of the KWIS in response to sea-level fluctuations. Sandstone bodies display depositional dip elongate, laterally restricted, lobate geometries. Southward deflection of sediments (Peay & Torchlight Members) resulted from the interaction of sediment input with a counterclockwise circulation gyre within the KWIS. Upon entering the KWIS, fresh water sources that delivered sediments basinward did not mix with saline sea water. This relation, coupled with the Coriolis Effect, deflected deltas to the right (western sources deflected south, eastern sources deflected north) generating the alongshore currents responsible for the counterclockwise gyre circulation (Slingerland et al., 1996). Deflected asymmetric deltaic depositional model after Fielding (2010).
Southward sediment dispersal patterns and delta progradation is attributed to deposition in a high energy, shallow water, deflected asymmetric deltaic environment (cf. Fielding, 2010). As rivers transported sediment from the Sevier highlands into the KWIS, the interaction between buoyant fresh water and saline sea water generated offshore-dipping, water surface slopes (Snedden & Nummedal, 1990; Slingerland et al., 1996). Geostrophic alongshore currents were generated with the interaction between the Coriolis Effect and water flow down the dipping water surface slopes (Slingerland et al., 1996).

**Figure 15b:** The modern Po River Delta along the western margin of the Adriatic Sea (Cattaneo et al., 2003) is invoked as a modern-day analog to Frontier Formation deposition within the KWIS.

Alongshore currents parallel to the western KWIS paleoshoreline drew in northern Boreal Ocean waters and southern Tethyan Ocean waters, initiating a counterclockwise flow gyre within the KWIS (Fig. 15a) (Slingerland et al., 1996).
River discharge rates cannot compete with strong southward alongshore currents (Bhattacharya & Giosan, 2003). Thus, sands are swept down current, and resulted in the deposition of north-south elongate, east-west laterally-restricted sandstone bodies. Additionally, such bodies are potentially separated 10’s to 100’s of kilometers from equivalent shoreline and terrestrial facies resulting from deposition during relative sea level lowstand conditions (Fig. 15a).

Cross-section B-B’ (Appendix 2B) best illustrates multiple deltaic progradation events that are recorded in the entire Frontier Formation stratigraphic succession (Stucco, Peay, Potato Ridge, Alkali, Torchlight, Spence Members) in the eastern Bighorn Basin. Multiple episodes of compensational stacking occur throughout, similar to those defined by Brown (1979). These stacking patterns develop where thick accumulations of the stratigraphically younger interval overlie thin accumulations of the underlying unit (e.g., thinning and thickening relationships between Peay and Potato Ridge and Potato Ridge and Torchlight, Appendix 2B). As the Peay sandstone thins southward (down depositional dip) into a facies assemblage likely representing distal deltaic and offshore deposition, thickening in the overlying Potato Ridge sandstone is observed. Up-dip thinning of the Potato Ridge Member coincides with the thickest intervals of the Torchlight Member sandstone. A comparative analysis of interval isopach maps (Fig. 13) indicates possible multiple regional fluvial input locations that generated the observed compensational stacking patterns throughout the depositional history of the Frontier Formation. While the Alkali and Spence Members do not contain extensive sandstone body intervals within
the study area, it is likely that their associated accumulations represent the offshore equivalent of more distant delta progradation events.

SEQUENCE STRATIGRAPHY

Past analyses of Frontier Formation depositional environments in the Bighorn Basin lack a sequence stratigraphic context (Cobban & Reeside, 1952; Hunter, 1952; Griggs, 1970; Khandakar, 1991; Keefer et al., 1998; Merewether et al., 1998, among others). Such attempts to interpret the sequence stratigraphy of the Frontier Formation have occurred in other basins throughout Wyoming (i.e. Powder River Basin: Mieras, 1992; Bhattacharya & Willis, 2001; Vakarelov et al., 2006; Gani & Bhattacharya, 2007; Lee et al., 2007; Vakarelov & Bhattacharya, 2009); however, with much difficulty. The preserved nature of the isolated, mudstone-encased sandstone bodies in the Upper Cretaceous stratigraphic record does not allow for the direct application of sequence stratigraphic principles. Often, top-truncated sandstones are missing terrestrial-equivalent facies (fluvial), which increases the challenge in interpreting sequence boundaries. This study will attempt to define the Frontier Formation sequence stratigraphically in terms of parasequences, sequences, key stratigraphic surfaces, and systems tracts. Such an analysis will further refine a depositional environmental interpretation for the Frontier Formation and enhance the stratigraphic framework established in Clark (2010).
Parasequences

Van Wagoner et al. (1990), Kamola & Van Wagoner (1995), and Catuneanu (2006) define a parasequence as ‘a relatively conformable succession of genetically-related beds or bedsets bounded by marine flooding surfaces or their correlative surfaces’. In outcrop, parasequences typically display a shoaling and coarsening up character, from basal offshore marine shales, to interbedded and burrowed HCS and planar laminated sandstones, to trough and tabular cross-bedded sandstones that are overlain by upper shoreface/foreshore sediments (Van Wagoner et al., 1990). Wireline logs generally display an abruptly-topped upward-decreasing gamma ray pattern indicative of shallowing upward parasequences (Fig. 14; Cant, 1992). Parasequence tops are often defined by the presence of a pebble lag separating shallow water marine sandstones from overlying offshore marine shales (Van Wagoner et al., 1990; Catuneanu, 2006). Juxtaposition of deep water facies directly above shallow marine sediments indicates an abrupt rise in relative sea level, accounting for the occurrence of a pebble lag (Van Wagoner et al., 1990; Catuneanu, 2006). As such, these surfaces are candidates for transgressive surfaces of erosion and/or maximum flooding surfaces (Van Wagoner et al., 1990; Catuneanu, 2006).

Transgressive surfaces of erosion form as wave and tidal action scour underlying strata during regional marine flooding events (Van Wagoner et al., 1990; Cantuneanu, 2006). Significant removal of underlying nearshore and terrestrial facies often results in the deposition of a transgressive pebble lag as high-energy winnows away fine-grained deposits (Van Wagoner et al., 1990; Catuneanu, 2006). As most
Siliciclastic parasequences contain poorly preserved transgressive facies, the transgressive surface of erosion may be coincident with the maximum flooding surface (Kamola & Van Wagoner, 1995; Catuneanu, 2006). Maximum flooding surfaces are used to define the maximum landward extent of the shoreline and are characterized by the separation of overlying progradational strata from a combination of either underlying retrogradational (when present) or progradational strata (Catuneanu, 2006).

A sequence stratigraphic analysis of measured outcrop sections reveals a multitude of shallowing-and coarsening-up parasequences and associated sequence stratigraphic surfaces within the Frontier Formation (Appendix 1A, B; Appendix 2A-E; Figs. 4, 11, 16). Such surfaces are correlated based upon direct physical observation. Surfaces were not extended into subsurface correlations as a lack of direct facies control (outcrop, core) generates a high degree of uncertainty in well-log cross-sections 10’s of kilometers away from measured outcrop sections.

Shallowing up from basal offshore shales to proximal shallow marine sandstones recording tidally and fluvially-influenced, wave-dominated deltaic progradation, the Peay Member forms a major parasequence within the region. This parasequence is capped by a regionally extensive, low relief pebble lag that can be regarded as the transgressive surface of erosion overlain by a maximum flooding surface (Fig. 16). The pebble lag surface likely represents a significant reworking and winnowing of nearshore and coastal marine sediments during relative sea-level transgression. Confident placement of a sequence boundary within the Peay Member
is challenging without preserved terrestrial and coastal plain facies. Additionally, correlation with up depositional-dip terrestrial facies cannot be performed directly as sandstone bodies are completely encased in offshore marine sediments, isolated 10’s to 100’s of kilometers from contemporaneous shorelines.

Even though sandstone body thicknesses are minimal within the measured outcrop sections, the shales above the top-bounding surface of the Potato Ridge Member are another candidate for a maximum flooding surface (Fig. 15). As with the Peay, a laterally traceable, distinct pebble lag occurring at the top of a shallowing and coarsening upward progradation succession is interpreted as a transgressive surface of erosion (Fig. 15). The outcrop expression of Potato Ridge deposits likely represents distal or off-flank deposition associated with deltaic progradation.

As many as six shallowing and coarsening up cycles are observed within the Alkali Member (Appendix 1A, B). While these cycles may indeed occur regionally, the majority of them were not laterally traceable throughout the region. As such, only two pebble lag bearing surfaces are interpreted as transgressive surfaces of erosion occurring above shallowing and coarsening upward sediment packages as they are correlatable between adjacent measured outcrops localities (Appendix 1A, B). The outcrop expression of the Alkali Member likely is the distal equivalent of distinct deltaic progradation events.

Representing an abrupt and significant shallowing of relative sea level, the juxtaposition of coastal fluvial sandstone and floodplain siltstone above nearshore and distal marine sediments likely implies a sequence boundary within the Torchlight
Member (Fig. 16). This surface is identified by basal scours fill with chert pebble accumulations, above which fluvial trough cross-stratified sandstone occur (Figs. 4, 16). Sequence boundaries are commonly positioned at the base of fluvial deposits that overlie marine strata, as the surface represents the maximum basinward shift of the shoreline (Catuneanu, 2006). Therefore, the Torchlight Member contains evidence for the most basinward shoreline shift throughout the depositional history of the Frontier Formation. A regionally significant conglomerate is preserved at the top of the Torchlight Member and is a prime candidate for a transgressive lag (Fig. 16). The chert/andesitic pebble and cobble bearing Torchlight conglomerate likely represents a regionally significant, prolonged high-energy transgressive event, possibly coinciding with the ~ 4 m.y. hiatus observed within the fossil record (Figs. 2, 16).

**Systems Tracts**

Thin, dip-elongate, laterally restricted, lobate (Peay, Potato Ridge, Torchlight) morphologies observed within the Frontier Formation are suggestive of lowstand systems tract deposition. Regionally, such deposits are isolated and completely encased in offshore marine mudstones, distally positioned 10’s of kilometers from associated contemporaneous shorelines (Fig. 15 a, b). Transportation of sediments to such distal localities likely occurred during a significant relative sea-level drawdown. Outcrop and subsurface data display gradual coarsening/shoaling upward trends within distal locations suggesting lowstand deltaic progradation (Catuneanu, 2006). Placement of the shallow marine sandstone bodies within the falling stage systems
**Figure 16:** Paleobathymetric reconstruction of the Frontier Formation Composite Section. Two sequence boundaries (SB, red line) interpreted. Sequence Boundary 1 is placed at the base of the Peay Member. The Peay SB is questionable as there is no direct evidence for a genetic relationship to subaerial exposures in the vertical succession; however, such a surface is interpreted as the sandstone bodies represent deposition during lowstand sea-level conditions. Sequence Boundary 2 is placed within the Torchlight Member. The Torchlight SB corresponds to a regionally extensive erosional surface above which fluvial channel and floodplain deposits lie. Transgressive Surfaces of Erosion (TSE) are abundant throughout. They are represented in outcrop by the presence of pebble lags that are overlain by offshore marine sediments. Such surfaces are interpreted as the remnants of extensive sediment winnowing during a regional transgression.
tract is not warranted as prograding clinoform sets do not downcut into underlying
distal deltaic facies (Appendix 1A, B). Gently dipping clinoforms within the thin
proximal deltaic sandstone of the Peay Member suggest low accommodation
conditions during deposition (Fig. 10). Therefore, the various sandstone bodies within
the Frontier Formation are said to represent accommodation-driven or
accommodation-limited deposition (cf. Porebski & Steel, 2006).

During sea level lowstand, shorelines are positioned distally, representing a
basinward shift in facies belts. Accommodation capacity is rapidly achieved near the
shoreline and surplus sediments are shed into distal portions of the basin (Catuneanu,
2006). This generates thin, low relief, and dip-elongate deposits as gently-dipping,
prograding clinoform sets fill the available accommodation (Fig. 10). Under such
conditions, the interplay between accommodation and energy flux are crucial to the
accumulation or erosion of sediments. Vertical successions through Frontier
Formation parasequences indicate alterations in the accommodation vs. energy flux
ratio (Catuneanu, 2006). An up section increase of wave-influence evidence (HCS)
(Fig. 9f) indicates a decrease in the ratio as higher energy conditions ultimately
prevail. As the energy flux dominates, a significant portion of upper
shoreface/nearshore sediments in low relief settings are removed during transgressive
wave ravinement events, resulting in isolated deltaic sandstone bodies as observed
within the Frontier Formation.
ACCOMMODATION CONTROLS

Climate, tectonics, and eustacy are the main allogenic controls responsible for cyclic depositional patterns appearing throughout the stratigraphic record. Autogenic controls (delta lobe switching) are also important, but given the presence of aerially extensive pebble lags, regional transgressions were likely generated by allogenic forces. When observing vertical stacking trends sequence stratigraphically, shoaling up parasequences bounded by flooding surfaces are likely driven by climate and eustatic changes in sea level and sediment flux (Van den Berg van Sarpoea & Potsma, 2008). Such climatically-driven eustatic sea level changes may have been forced by Milankovitch Cycles (Miller et al., 2003; Catuneanu, 2006). Miller et al. (2003) interpret large (10’s of meters) and rapid (< 1 m.y.) eustatic changes in Mesozoic coastal successions of New Jersey. Such changes are attributed to glacioeustatic events through the correlation of large $^{18}$O increases with sequence boundaries (Miller et al., 2003). Even as the Late Cretaceous is synonymous with greenhouse climates, Miller et al. (2003) calculate that a possibility existed for small inland ice sheets to occur in Antarctica under such climatic conditions. Milankovitch cycle fluctuations could have generated waxing and waning of the ice sheets, possibly influencing sea levels by ~ 25 meters (Miller et al., 2003). A similar hypothesis is used for similar KWIS high-frequency stratigraphic cycles observed in the Book Cliffs (Hampson, 2010). As deposition of the Frontier Formation occurred in the back-bulge portions of the Sevier Orogenic Foreland Basin, even small eustatic fluctuations could have dramatically changed the accommodation balance.
In addition to eustatic sea level fluctuations, climate controls the amount of sediment supplied to basins. Seasonal storms along the tectonically-active Sevier Orogenic Belt likely generated ample sediment supply. Such storm events initiated high discharge events, which would be responsible for transporting large sediment volumes into the basin. Periods of climatic calm, as well as tectonic uplift stasis can negatively affect sediment accumulation within shallow water environments, allowing for periods of non-deposition and abandonment of progradational deltaic parasequences. This does not imply that Frontier Formation deposits are strictly supply-dependent. As previously discussed, sedimentation in distal, shallow portions of the Sevier Orogenic Foreland Basin is extremely sensitive to fluctuation in accommodation.

Tectonic influences on transgressive-regressive cycles were also significant during Sevier Foreland Basin deposition. Periodic thrusting of the Sevier Orogenic Belt and the associated migration of the forebulge were ongoing throughout much of the Late Cretaceous. Van den Berg van Saparoea & Potsma (2008) interpret tectonic influences as controls on low resolution sequence stratigraphic cycles (stratigraphic sequences). The associated sequence boundary and flooding surface within the Torchlight Member may be associated with tectonic rejuvenation of the Sevier Orogenic highlands and foreland bulge migration. Catuneanu (2006) highlights recent studies that emphasize that such pulses can occur over short-term (< 1 m.y.) or long-term (> 1 m.y.) periods. Therefore, foreland basins are extremely sensitive to pulses of tectonic uplift and subsequent stasis. Uplift generates a readily available sediment
supply, while also controlling accommodation throughout the basin. Tectonic pulses may be responsible for the cyclic progradational behavior observed throughout the Frontier Formation, coinciding with a lack of sediment accumulation and several unconformities during the Cenomanian-Turonian (Fig. 2).

Given the paleogeographic locations and depositional environment (Fig. 1), it is unlikely that only one allogenic control is responsible for every transgression-regression cycle within the Frontier Formation. Increases and decreases in sediment supply (climate & tectonics), subsidence (tectonics), and sea level (climate & eustacy) exhibit a process/response relationship in accommodation modulated by environmental energy flux (Catuneanu, 2006). Therefore, an interpretation is invoked that allows for multiple allogenic controls to influence the deposition and preservation of the various top-truncated, isolated, offshore marine mudstone-encased sandstone bodies of the Frontier Formation.

**HYDROCARBON IMPLICATIONS**

As with recent analyses on the Frontier Formation in the Powder River Basin (Vakarelov & Bhattacharya, 2009; Bhattacharya & Willis, 2001; among others), this study aims to improve upon depositional environmental interpretations using current sequence stratigraphic methods so as to fully understand the hydrocarbon exploration potential within the Bighorn Basin. Regional sandstone body geometries reveal depositional dip-elongate, strike-restricted lensoid shapes with internal heterogeneities. Such internal heterogeneities include interbedded sandstones and
siltstones that contain thickness and length variations along strike and dip. A probability exists for the occurrence of numerous stratigraphic pinchout traps on both member and intramember scale. Member scale subsurface correlations reveal depositional strike and dip pinch out trends coinciding with multiple laterally discontinuous sandstone bodies, while surface cross-sections display complex heterogeneities internally within member sandstone bodies. The ability to improve upon and understand both large and small scale lateral and vertical facies variations will aid reservoir modelers who are concerned with interwell heterogeneities that may negatively influence hydrocarbon production (Enge & Howell, 2010; Deveugle et al., 2011). Such efforts will further develop hydrocarbon exploration models and potential within the region.

CONCLUSIONS

A detailed facies analysis of a ~ 30 kilometer outcrop belt of the Cenomanian-Turonian Frontier Formation in the northeast Bighorn Basin facilitates regional surface and subsurface correlations that invoke sequence stratigraphic and depositional environment interpretations. Correlation of regionally significant stratigraphic horizons on top of these cycles (transgressive surfaces of erosion, sequence boundaries) reveals dip-elongate, strike-restricted, shoestring lensoid geometries for analyzed sandstone bodies (Peay, Torchlight). Observed in both outcrop and subsurface, sandstone accumulations cap regionally occurring coarsening-up cycles. As such, these elongate, lensoid geometries represent the
southward progradation of tidally- and wave-influenced, fluvially-dominated shallow marine deltaic systems during relative sea-level lowstand.

Periods of relative sea-level lowstand punctuating an overall Late Cretaceous sea level rise facilitated the transportation of sediments by fluvial processes into low accommodation regions of the Sevier Foreland Basin. Similar to the proposed model of the Ferron Sandstone in south-central Utah (Fielding, 2010), sediments were deflected south-southeastward upon entering the KWIS, resulting from the combination of the Coriolis Effect and pressure gradients, which produce shore-parallel geostrophic flows. Pebble-cobble lags capping lowstand deltaic sandstones are inferred as transgressive ravinement surfaces, recording shoreline transgression during sea-level rise. Sequence boundaries, as observed within the Peay and Torchlight members, represent maximum shoreline regression during sea level fall. Such fluctuations of sea level enhance the importance of accommodation controlled by allogenic forces (climate, eustacy, tectonics) in shallow marine settings.

An area of thinning over an apparent arch within the Peay Sandstone appears along the depositional-dip outcrop cross-section (S 4-8, Fig. 5). Such an anomalous thinning-thickening trend down depositional dip is interpreted to represent a transect through off-flank portions of a digitate lobe. These areas may be prevalent in regions not studied in this analysis and may be crucial for hydrocarbon exploration. Additional significant opportunities occur for the stratigraphic entrapment of hydrocarbon reserves within potential reservoirs on both the member and intramember scale. The detailed facies analysis of measured outcrop sections will
allow reservoir modelers to better predict interwell heterogeneities. As such, this sedimentologic and stratigraphic analysis of the Frontier Formation within the eastern Bighorn Basin will contribute to understanding the depositional history of similar units regionally and throughout the stratigraphic record.
Works Cited


Wright, L.D. (1977) Sediment transport and deposition at river mouths: A synthesis
Appendix 1B: Depositional Strike Cross-Section
Appendix 2A: Subsurface Cross-Section A-A'
Appendix 2B: Subsurface Cross-Section B-B'
Appendix 2D: Subsurface Cross-Section D-D’

D

D’

Spence
Torchlight
Alkali
Potato Ridge
Paay
Stucco
Mowry

16.3 km
3.4 km
6.5 km
5.8 km
4.3 km

49-043-20422
49-043-20533
49-043-20510
49-043-20650
49-043-20652
49-043-20721
## Appendix 3: Facies Table

<table>
<thead>
<tr>
<th>Facies</th>
<th>Physical Structures</th>
<th>Biogenic Structures</th>
<th>Lateral &amp; Vertical Variations</th>
<th>Depositional Environment</th>
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<tbody>
<tr>
<td>A</td>
<td>Dark grey laminated shale with bentonitic intervals, bentonite exhibits popcorn weathering, plant debris in mudstones</td>
<td>BI = 0 - 1</td>
<td>Laterally continuous (5-10 m thick), vertically, thin (cm’s) sandstone stringers appear up-section, thick bentonite beds more laterally continuous.</td>
<td>Offshore Marine</td>
</tr>
<tr>
<td>B</td>
<td>Dark grey laminated, fissile mudstone (80 – 90 %) with interbedded very fine grained, thin lithic sandstone intervals (10 – 20 %), sandstones increases up-section, symmetric and asymmetric/interference ripples, flat-low angle cross-bedding, plant debris and yellow sulfurous patches</td>
<td>BI = 0 – 2 (sst); <em>Planolites</em>, <em>Diplocraterion</em>, sediment swimming traces</td>
<td>Entire unit is laterally continuous (10 – 15 m thick), thin sandstone stringers show lateral impersistence variability. Sandstone stringers increase in abundance and thickness up-section.</td>
<td>Prodelta</td>
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<td>C</td>
<td>Thinly interbedded dark grey, fissile siltstone (25 – 75 %) and very fine grained lithic sandstone (25 - 75 %), flat-low angle cross-stratification, wave-modified current ripple cross-lamination, HCS, interference &amp; symmetrical ripples, synaeresis cracks, plant debris and yellow sulfurous patches</td>
<td>BI = 0 – 2 (slst), 1 – 4 (sst), Proximal <em>Cruziana</em> Ichnofacies; <em>Planolites</em>, <em>Thalassinoides</em>, <em>Diplocraterion</em>, <em>Gyrochortes</em>, <em>Rhizocorallium</em>, <em>Ophiomorpha</em>, <em>Asterosoma</em>, <em>Lockeia</em>, <em>Cylindrichnus</em></td>
<td>Entire unit is laterally continuous (7 – 10 m thick), individual sandstone bodies show lateral variability as thinner units pinch out over short distances (lensoid geometries). Vertically, sandstone beds thicken while siltstone partings decrease in abundance and thickness.</td>
<td>Distal Delta Front</td>
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<td>Tabular, sharp-based, thick fine-medium grained lithic sandstone (95 %) with thin siltstone partings (5 %), flat-low angle cross-stratification, aggrading wave ripples, HCS, massive-flaggy bedding, small-scale TXB,</td>
<td>BI = 0 – 4, <em>Cruziana/Skolithos</em> Ichnofacies; <em>Planolites</em>, <em>Diplocraterion</em>, <em>Thalassinoides</em>,</td>
<td>Entire unit is laterally continuous (10 – 15 m thick) along depositional strike, laterally, individual sandstone beds form gently-dipping clinoforms. Variations in facies thickness observed up and down depositional dip. Vertically, thin siltstone partings disappear, while</td>
<td>Middle Delta Front</td>
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<td>Description</td>
<td>BI/Other Ichnofacies</td>
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<td>E</td>
<td>Amalgamated, sharp-based, fine-medium grained lithic sandstone with flat-low angle cross-stratification, HCS, small scale TXB, massive-flaggy bedding, symmetrical, asymmetrical, and interference ripples, chert granules</td>
<td>BI = 0 – 2, Skolithos Ichnofacies; Planolites, Diplocraterion, Thalassinoides</td>
<td>Proximal Delta Front/River Mouth</td>
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<td>F</td>
<td>Very fine-fine grained lithic sandstone, HCS, flat-low angle cross-stratification, dispersed black chert pebbles</td>
<td>BI = 0</td>
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<td>G</td>
<td>Brown, fissile, laminated siltstone, abundant plant debris,</td>
<td>BI = 0</td>
<td>Coastal/Alluvial Flood Plain</td>
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<td>H</td>
<td>Fine-medium grained lithic sandstone with flat-low angle cross-stratification, bipolar trough cross-stratification, interference and wave ripples, dispersed chert granules, bivalves</td>
<td>BI = 0</td>
<td>Coastal Fluvial Channel</td>
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<td>I</td>
<td>Coarse-very coarse sandstone &amp; clast-supported pebble-cobble chert and andesite conglomerate, +/- interference ripples, dispersed fish vertebrae, crocodile teeth, petrified wood</td>
<td>BI = 0</td>
<td>Transgressive Lag</td>
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Appendix 4a: Paleocurrent Data (Peay Member-Ripples & Cross-Bedding)

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- TCA = Tin Can Alley; C. Gully = Carcass Gully
- All data are in degrees
### Appendix 4b: Paleocurrent Data (Torchlight Member Cross-Bedding)

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