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Stratigraphy, Sedimentology, and Ichnology of the Upper Cretaceous Frontier Formation in the Alkali Anticline Region, Bighorn County, Wyoming

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STRATIGRAPHY, SEDIMENTOLOGY, AND ICHNOLOGY OF THE UPPER CRETACEOUS FRONTIER FORMATION IN THE ALKALI ANTICLINE REGION, BIGHORN COUNTY, WYOMING.

by

C. Kittinger Clark

A THESIS

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The Upper Cretaceous Frontier Formation was studied along two strike-parallel cliff-lines in the Alkali Anticline region of the northeastern Bighorn Basin, Bighorn County, Wyoming. The unit comprises up to 145 m of mudrock, sandstone, conglomerate, and volcanic fallout sediments deposited along the western margin of the Cretaceous Western Interior Seaway (KWIS) in the mid- to late-Cenomanian. Eighteen facies, comprising six facies associations are identified from physical and biogenic sedimentary features. Sediments were deposited in open marine offshore to shoreface and subaqueous deltaic to delta platform environments. The observed trace fossil suites record departures from the archetypal ichnofacies. Such departures record environmental stresses associated with nearshore deltaic settings. Resolving the ichnological signature of these stressed nearshore settings was crucial to reconstructing the depositional environment. The Frontier Formation consists of multiple progradational and retrogradational sequences deposited during a low-frequency (high magnitude) lowstand characterized by lower-magnitude, higher- frequency fluctuations. This study reveals a complex succession of parasequences and deltaic coarsening upward successions deposited under low-accommodation conditions. Parasequence boundaries were the most useful for sub-regional correlation. Two sequence boundary candidates are identified in the Peay and Torchlight Members but they are not useful for correlating across the study area. This investigation provides new insights into the recognition and interpretation of the facies and stratigraphic architecture of nearshore sediments deposited in low accommodation settings, and provides a framework for future evaluations of similar deposits in the Western Interior Seaway.
ACKNOWLEDGEMENTS

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INTRODUCTION

Increasingly, sequence stratigraphic studies recognize accommodation as a significant depositional control in continental margin successions (Bhattacharya & Willis 2001; Fielding et al. 2008; Sadeque et al. 2007). Current stratigraphic models are largely biased toward successions where accommodation is not a limiting factor. Sequences formed under low accommodation regimes are generally thinner and less complete than their high accommodation counterparts (Van Wagoner et al. 1990; Mitchum & Wagoner 1991). The frequency and magnitude of changes in accommodation along continental margins strongly controls preservation potential and stratigraphic architecture of sediments deposited in nearshore environments (Porębski & Steel 2006). Facies relationships associated with limited accommodation directly influence reservoir character.

Accommodation as a Depositional Control

Sediment deposition in continental margin systems can be categorized as either supply- or accommodation limited (Porębski & Steel 2006). Shoreline trajectory and sediment dispersal patterns are directly impacted by the balance between accommodation and sediment supply (Steel et al. 2008; Porębski & Steel 2006). Shallow-marine sediments, deposited in accommodation limited settings, are commonly truncated by transgressive surfaces of erosion (TSE) and sequence boundaries. Ultimately, the extent of lateral progradation is a function of shelf slope, shelf width, accommodation, and sediment supply. In many cases, traditional key stratigraphic models are ill-suited for resolving the depositional history of continental margin deposits in low accommodation
settings. Consequently, the incorporation of new sedimentological data is indispensable in the evaluation of limited-accommodation sequence-stratigraphic successions.

Shoreline-Detached, Linear Sand Bodies in the Cretaceous Western Interior Seaway

Enigmatic, isolated, elongate sandstone bodies encased in shelf-mudstone facies are common to the Cretaceous Western Interior Seaway (KWIS) (Nielson & Johannessen 2008). The origins of these numerous, isolated elongate sandstone bodies have been vigorously debated. Despite decades of investigation, and being a well-known hydrocarbon play, the sequence-stratigraphic context of these numerous isolated sand bodies is still poorly resolved (Posamentier 2002).

Past investigations have proposed numerous mechanisms to explain the emplacement of sand bodies 20–40 m thick, 10s–100s km long, and kilometers from the paleoshoreline including: tidally influenced shelf ridges, reworked offshore bar complexes, mouth bars, storm-influenced sand-sheets, lowstand deltaic/shoreface deposits, and detached spit systems (e.g. Merewether et al. 1978; Tillman & Almon 1979; Boyles & Scott 1982; Winn et al. 1983; Palmer & Scott 1984; Tillman 1999; Bhattacharya & Willis 2001; Martinsen 2003b; Bhattacharya 2006; Nielsen & Johannessen 2008). Recent sequence stratigraphic investigations of the lower Frontier Formation in the Powder River Basin and correlative units conclude that many shelf sand bodies previously interpreted as distal offshore bars are better interpreted as top-truncated shoreface and deltaic deposits formed by forced regression during falling stage and lowstand of relative sea-level (Bhattacharya & Willis 2001; Bhattacharya et al. 2003; Bhattacharya 2006; Sadeque et al. 2007). Sadeque and others (2007) interpret coarsening upward successions, capped by coarse-grained lags in the Wall Creek
Member of the Frontier Formation in the southwestern Powder River Basin, to be prodeltaic, delta front deposits truncated by transgressive wave ravinement (Bhattacharya & Willis 2001; Sadeque et al. 2007). Most recently, Nielsen & Johannessen (2008) reinterpreted many of the isolated sandstone bodies in the KWIS as detached spit systems. Ultimately, the processes that resulted in the accumulation of these isolated sandstone bodies were influenced by relative changes in sediment supply, accommodation, and rate of relative sea-level change.

Geologic Setting

The Upper Cretaceous (Cenomanian and Turonian) Frontier Formation in north central Wyoming accumulated along the western margin of the KWIS by sediment shed eastward from the Sevier Orogenic Thrust Belt (Fig. 1 & 2) (Merewether & Cobban 1985; Bhattacharya & Willis 2001). Accumulation occurred during a low-frequency lowstand with superimposed higher frequency fluctuations in relative sea-level (Sadeque et al. 2007). Accommodation decreased eastward due to asymmetrical subsidence induced by foreland thrust loading (DeCelles & Mitra 1995). Consequently, thick successions of continental conglomerates and shallow marine siliciclastics in southwestern Wyoming and eastern Utah thin eastward (Hamlin 1996). East of the Sevier Thrust Belt in central Wyoming, the Frontier Formation is composed of shallow and deep-marine sediments deposited in a low accommodation setting along a shallow eastward-dipping slope (Fig. 3).

This study seeks to resolve the affects of accommodation and other depositional controls on the Frontier Formation in the Alkali Anticline region of north central Bighorn Basin, Wyoming through the use of sedimentology and sequence stratigraphy (Fig. 3).
Figure 2. Regional and local map of the study area around the Goose Egg and Alkali Anticline region in north central Wyoming. Twelve sections were measured along two strike-parallel exposures. Sections are numbered in the order they were measured.
A deeper understanding of the depositional controls on the Frontier Formation and similar successions deposited in low accommodation settings in the KWIS is fundamental to recalibrating current sequence stratigraphic models.

THE FRONTIER FORMATION IN WYOMING

Regional correlation

Past investigations of the Frontier Formation have focused on the Moxa Arch in southwestern Wyoming, and the southwestern margin of the Powder River Basin where the stratigraphy is constrained by subsurface and outcrop datasets (Merewether et al. 1984; M’gonigle et al. 1995; Kirschbaum & Roberts 2005). A generally west to east correlation and stratigraphic framework of the Frontier Formation and equivalent units across Wyoming was constructed from past investigations (Fig. 3). In this framework, the Frontier is correlated between the Moxa Arch, Lander, Alkali Anticline, and Tisdale Anticline in SW Powder River Basin where it is Cenomanian to earliest Coniacian in age (Figs. 2 & 3). Formation and member names vary between basins. Subsurface and outcrop stratigraphy is listed in ascending order unless otherwise stated.

Moxa Arch.— In SW Wyoming the Frontier Formation is preserved along the Moxa Arch in the Green River Basin (Fig. 2) (Kirschbaum & Roberts 2005). Locally, the Frontier is composed of interbedded marine and nonmarine facies (Fig. 3) (Hamlin 1995). In the subsurface the Frontier is divided into the Fourth Frontier, Third Frontier, Second Frontier, and First Frontier sandstones (Fig. 3) (Hamlin 1996). The Second Frontier sandstone is subdivided into five sandstone “benches” named in ascending order from the “Fifth” to the “First Bench Sandstone” (Hamlin 1996). In outcrop the Frontier is divided into the Chalk Creek Member, Coalville Member, Allen Hollow Shale, Oyster Ridge
Figure 3. Regional stratigraphic framework of the late Cretaceous Frontier Formation in Wyoming. Generalized depositional environments are shown. Correlations are based on biostratigraphic and radiogenic isotope ages. Wavy contacts indicate uncertainty of correlations. Biostratigraphic zonations and stage boundaries are after Cobban et al. (2006). Relevant sources are listed below each column.
Sandstone, and Dry Hollow Member (ascending order) (Cobban & Reeside 1952; Hamlin 1996).

**SW Powder River Basin.**—The Frontier Formation, between the Mowry and Cody Shales, is divided into 3 disconformity-bound members: Belle Fourche, Emigrant Gap, and the Wall Creek Members (ascending order) (Merewether et al. 1979). The Belle Fourche Member is further subdivided into the Harlan, Willow, Frewens, and Posey allomembers (Bhattacharya & Willis 2001). Allomembers are bound by flooding surfaces and interpreted as deltaic parasequences by Bhattacharya & Willis (2001). The informally named “Second Frontier”, in the upper Belle Fourche Member overlies the Posey Allomember. Where the conglomeratic Emigrant Gap Member is absent the Belle Fourche is overlain by the Wall Creek Member (Gani & Bhattacharya 2007; Vakarelov & Bhattacharya 2009).

**NE Bighorn Basin.**—Preserved deposits in the study area are interpreted to be equivalent to the Lower Frontier Belle Fourche Member in the southwestern Powder River Basin (Cobban 1990; Cobban 1994; Merewether & Gautier 2000). In the north eastern Bighorn Basin the Cenomanian Frontier Formation is composed of 75-145 m of coastal and shallow-marine siliciclastic strata, and volcanic ash (Fig. 4). The unit is divided into three sandstone members bound by disconformable contacts with finer-grained intervals, and is conformable between the Mowry Shale below and Cody Shale above (Figs. 3, 4, & 5). The Mowry-Frontier Formation contact in the Powder River basin is placed at the occurrence of the Clay Spur Bentonite (CSB) (Kirschbaum et al. 2009). In this study the base of the Frontier Formation is considered to be the first sandstone bed at the top of the Mowry Shale. Past sedimentological and paleontological
investigations of the Lower Cretaceous Mowry Shale depict the Mowry Sea as an oxygen-stratified basin with increasingly anoxic conditions basinward (Davis & Byers 1993). Named for exposures along Peay Hill and Torchlight Dome near the Greybull Oil Field, the lowermost and uppermost sandstone units of the Frontier are formally referred to as the Peay Sandstone and Torchlight Members, respectively (Hintze 1914). The middle sandstone body is unnamed. We propose that this previously unnamed mudrock and sandstone interval in the middle of the Frontier Formation be referred to as the Alkali Member for its exposure along the Alkali Anticline. We further divide the middle unit into the informal Sub-X Member, between the Peay Member and X-Bentonite (Fig. 4).

**Geochronologic Control for the Bighorn Basin**

**Biostratigraphic Control.---** Biostratigraphically, the age of the preserved sediments near Greybull, WY is constrained by the occurrence of *Acanthoceras amphibolum* and *Dunveganoceras pondi* in the upper Frontier Formation and *Baculites yokoyamai* in the basal Cody Formation (Fig. 3) (Hass 1949; Kirschbaum et al. 2009). Fossil data were taken from past investigations in the Greybull area (Hass 1949; Cobban & Reeside 1952; Kirschbaum et al. 2009). North of Sheep Mountain, the *Acanthoceras amphibolum* zone is interpreted to extend from the top of the Peay Member to the top of the Torchlight Member. The age of the Frontier Formation in the Bighorn Basin near Greybull, Wyoming is constrained by the Clay Spur Bentonite and *Dunveganoceras Pondi* zone (Fig. 3).

The out-of-context *Dunveganoceras pondi* and *Baculites yokoyamai* zones in the upper Frontier represent a loss of approximately 4 million years. Additional disconformities are inferred in the Peay and Alkali Members from transgressive lags and
Figure 4. Stratigraphy of the Frontier Formation in the Alkali Anticline Region with the proposed Sub-X and Alkali Members. Log is a composite section from Sections 1, 3, & 4. The Mowry/Frontier boundary is defined by the Clay Spur bentonite. The Cody Shale overlies the Torchlight Conglomerate (T3). Red Arrows indicate the position of the bentonite intervals.
Figure 5. South-facing panorama of a typical outcrop exposure of the Frontier Formation in the study area. The photograph was taken on the western limb of the Goose Egg Anticline at Section 1 where the unit is approximately 130 m thick. Picture shows the standard ridge-and-valley topography of the Frontier Formation. With the exception of the Mowry Shale, mudstone intervals form recessively weathered valleys. Exposure includes the Peay Member (P), Sub-X Member (SX), Alkali Member (A), Torchlight Member (T), and Cody Shale. The Mowry-Frontier contact is not shown in the panorama. The approximate boundary of each member is designated by a dotted line. The bentonite at the top of the Sub-X Member is usually removed by mining activity.
facies relationships, although the aforementioned is the only hiatus confirmed by geochronologic data (Fig. 4).

**Bentonites.** Bentonites provide useful data that record the geologically instantaneous deposition of volcanic ash. The Clay Spur, X, and Upper Bed bentonites are present in the study area (Fig. 4). The age of the Upper Bed bentonite is unknown. Thinner bentonites also occur but did not aid in correlating between sections. The informally named Upper Bed Bentonite below the Torchlight Member is an unreliable datum because it is commonly obscured by recessive weathering of the adjacent units. Bentonite presence and thicknesses vary laterally but individual beds occur consistently in the same stratigraphic position. Despite their regional variability, the three thickest bentonite beds are interpreted as primary bentonites. No known geochronologic data for these bentonite intervals exist. Based on the thickness and previous correlations, two of the bentonites are interpreted as being equivalent to beds in adjacent basins where there are ample geochronologic data.

**Clay Spur Bentonite.** In the north-western Powder River Basin the basal contact of the Frontier Formation with the Mowry is defined by the occurrence of the Clay Spur Bentonite (CSB) (Rubey 1931). An $^{40}\text{Ar}/^{39}\text{Ar}$ age of $97.17 \pm .69$ Ma was determined for the CSB (Obradovich 1993). Several weathered ash intervals within the study area are possible candidates for the CSB. We interpret the .5-1.5 meter-thick bentonite that occurs 20-35 meters below the Peay Member to be the Clay Spur Bentonite. The facies relationships and subsurface correlations developed by Kirschbaum and others (2009) in the Bighorn Basin support this conclusion. Around Sheep Mountain Anticline the Clay Spur Bentonite is commercially mined and referred to as the Beaver Bentonite (D. Close
2010, personal communication). Kirschbaum et al. (2009) did not interpret this bentonite bed to be the CSB, but we believe substantial evidence is present to justify such a conclusion.

**X Bentonite.**--- The X Bentonite is an extensive ash layer that occurs across much of the Western Interior Basin. This bentonite interval is alternatively known as the “Soap Creek”, “F bed”, “Marker”, or “Grey-red” bentonite (Tyagi et al. 2007). The X Bentonite occurs in the *Acanthoceras amphibolum* zone. In the Powder River Basin the X-Bentonite (there known as the Soap Creek or Soap Box Creek Bentonite) was determined via $^{40}\text{Ar}/^{39}\text{Ar}$ dating to be 94.93 ± 0.53 Ma (Obradovich 1993) and 94.96 ± 0.5 Ma (Cobban et al. 2006). No definitive ages for the X bentonite are available from the Bighorn Basin. We interpret the X Bentonite to be the 1.5-2.5 meter thick ash overlying the Peay Sandstone Member north of Sheep Mountain in the north-eastern Bighorn Basin. Bentonite mining companies refer to this thick bentonite as the Flat Bed or F-2 Bed (D. Close 2010, personal communication). The interpretations and subsequent correlation presented in this study are supported by the bed’s thickness and the occurrence of *Acanthoceras amphibolum* in the upper Frontier Formation near Greybull, WY (Fig. 3) (Hass 1949).

**INTRODUCTION TO ICHNOLOGY**

Sediments deposited in marine settings are influenced by the complex interplay of physical, chemical, and biogenic processes. Ichnology combined with sedimentological evidence provide an invaluable tool in resolving the relative influence of these processes. Whereas a detailed ichnological analysis aids in determining the relative influence of
physical and chemical processes that may implicate deposition in a specific environment, few physical sedimentary structures provide similar insight.

**Sedimentological and Ichnological Signatures of Brackish Water Settings**

Brackish water conditions can be identified by physical sedimentary structures and a distinctly stressed ichnological signature. Sand-filled spindle-shaped fissures are interpreted as subaqueously forming shrinkage (syneresis) cracks. Syneresis structures have been experimentally shown to form from varying clay flocculation in brackish water conditions (Plummer & Gostin 1981). Syneresis cracks do not require fully brackish conditions and can be formed by local changes in salinity (Coates & MacEachern 1999; MacEachern et al. 2007b). Prevalent syneresis development is consistent with river- and/or tide- influenced settings.

Well-oxygenated, silt- and sand-substrates with low turbidity, modest sedimentation rates, and normal salinity provide “utopian” environmental conditions for benthic fauna. The archetypal ichnofacies, in their basic form, are diagnostic of a finite range of environmental stress. Stressful, non utopian conditions result in the departure of a trace assemblage from the archetypal ichnofacies model (Martin 2004; MacEachern et al. 2007a). Such departures are well documented from deltaic and estuarine settings where environmental stresses limit the diversity and dimensions of trace communities (Savrda & Bottjer 1991; Raychaudhuri & Pemberton 1992; MacEachern et al. 2007a; Bann et al. 2008). Trace fossil assemblages are crucial in distinguishing the relative influence of wave, tide and river processes (MacEachern et al. 2007b). MacEachern et al. (2007a) and the articles therein, provides an excellent review of how to identify stressed trace fossil assemblages in continental margin systems (Coates et al. 2007;
Davison & MacEachern 2007; Gani et al. 2007). Seasonal and longer lived environmental variability result in environmental stress on the ichnofauna. The Bioturbation Intensity (Reinek 1963; Bann et al. 2004) and diversity of benthic organisms in an assemblage are a function of the frequency and magnitude of stress-inducing events (MacEachern et al. 2007a). Fluctuations in diversity and BI indicate dynamic environmental conditions. Thoroughly bioturbated intervals represent long lived fair weather conditions between sedimentation events. High wave energies adversely affect living conditions and severely limit the diversity of the resident trace assemblage. Alternatively, waves can also reduce environmental stress by buffering brackish or poorly oxygenated water (Gani et al. 2007). Storm- and river-dominated settings are prone to seasonal environmental changes. Consequently the environmental stress, recorded by the diversity and BI also fluctuates. Low diversity, high BI assemblages are also indicative of unfavorable conditions. Assemblages may record elevated bioturbation intensities with the variability of diversity depending on the duration and extent of environmental changes. Short-lived reductions in stress are typically recorded as high-intensity, low-diversity assemblages. Long-lived reductions in environmental stresses result in greater trace diversity and bioturbation intensity. Tide-dominated environments support very low diversity assemblages as a result of the associated environmental stresses (Gani et al. 2007; MacEachern et al. 2007b). Identifying stress in trace fossil assemblages is critical to accurately discerning between the relative influence of wave, storm, tide, and fluvial processes in nearshore environments. In this study, ichnology was crucial in determining the depositional environment of the Frontier Formation.
METHODS

Twelve outcrop sections of varying stratigraphic complexity, and completeness were measured along two parallel-to-strike transects in the Frontier Formation north of Sheep Mountain in the Alkali Anticline region, Bighorn County, WY. Sections were spaced 0.5-3.5 km apart. Distance between sections was reduced if 1) a section was uncharacteristically complete; 2) one or more members were exposed in high detail; 3) there was significant variability between sections; 4) exposure was obscured by bentonite mining operations. Details including lithology, thickness, geometry, physical and biogenic sedimentological structures, and paleocurrent data were carefully recorded at each section. Where exposure permitted, individual correlations were walked out between sections. The relative abundance of a trace fossil is evaluated as being very common (vc), common (c), moderate (m), rare (r), or very rare (vr) (after Sadeque et al. 2007). A value denoting bioturbation intensity from 0 to 6 was assigned to relevant intervals (after Bann et al. 2004). Beds of B= 0 are devoid of biogenic structures. BI=6 indicates complete homogenization of sediment by benthic organisms. Collected data are summarized in Tables 1-6, and Figures 3-8.

FACIES ANALYSIS

Eighteen lithofacies, divided into five facies associations, are defined on sedimentological, and ichnological criteria. Facies are classified according to their context within the Mowry Formation or Frontier Formation. The Mowry Formation (Mo), Peay (P), Sub-X (SX) Alkali (AF) and Torchlight (T) Members are divided into separate facies associations defined by the stratigraphic units because each interval was deposited under different environmental conditions, and in some cases intervals are separated by substantial hiatuses. Facies F1 and F2 however, occur in multiple members and
Figure 6. A) A sixty-five meter thick exposure of the Mowry Shale at section 3. A thirty-five meter Shale (Mo1) forms large, steeply-graded slopes. Eight meter-thick intervals of porcellanite and silicified sandstone (Facies Mo2 & Mo3) form steep cliffs in the Alkali Anticline area. Shale is interpreted as having been deposited in an offshore environment from pelagic fallout. Siliceous intervals were deposited by periodic bottom currents. Porcellanite formed due to a high abundance of radiolarians B) Interbedded, wavy, sandstone and bentonitic siltstone of facies Mo2 & Mo3. Rare trace fossils occur along bedding planes C) Interbedded siliceous sandstone with bentonitic siltstone (Mo3) (Section 2). Sandstone beds are 1-5 cm thick and siltstone beds are 3-8 cm thick. D) Multiple *Pterichnus* traces (Section 2) along bedding surfaces in facies Mo2. *Pterichnus* is very common to facies Mo2 and is one of only three traces comprising the *Nereites* ichnofacies E) *Zoophycos* (Zo) in facies Mo3 (Sections 2 & 3). Trace is not very common and was only observed at 2 sections.
constitute the Recurring Facies Association. The following facies analysis provides a succinct lithologic description for each facies and a detailed justification of our interpretations.

**Mowry (Mo) Facies Association**

North of Big Sheep Mountain Anticline, the Mowry Shale forms 100 m, high, steep-resistant slopes of laminated mudrock and porcellanite (Fig. 6A). The upper Mowry is divided into three lithofacies (Facies Mo1, Mo2, & Mo3) (Fig. 6A-6C; Table 1). The preserved facies in the upper Mowry in the Alkali Anticline Region are interpreted as having been deposited in an offshore environment by two predominant modes of emplacement: 1) bottom currents caused by seasonal storms or turbidity currents and 2) pelagic accumulation (Davis and Byers, 1993).

**Facies Mo1.---**

**Description** - Facies Mo1 consists of dark-grey shale (90-100%). The ratio of silt to clay-sized particles varies locally but typically increases up-section. Mo1 is occasionally punctuated by thin, moderately bioturbated, sandstone beds (0-10%) (Mo2 & Mo3) (Fig. 6A). Mo1 is sparsely bioturbated (BI=0-1), *Planolites* being the only trace observed.

**Interpretation** - The fine grain-size, mm scale lamination, and stressed trace assemblage indicate Mo1 was deposited in an offshore environment by pelagic accumulation under anoxic conditions. Sandstone beds were deposited by seasonal storm-induced flows or turbidity currents (Mo2 & Mo3). Sediment flows delivered more oxygenated surface waters allowing intermittent bioturbation. Oxygen stratification limited benthic colonization. The ichnofacies is indeterminate, but the trace assemblage is consistent with an exceedingly stressful environment, likely anoxic. Davis and Byers (1993)
estimated the frequency of bottom currents to be approximately 3 per 1000 years; bottom current activity was too infrequent to destratify the early Cretaceous Mowry Sea.

**Facies Mo2.---**

*Description* - Facies Mo2 consists of thinly bedded, very fine- to fine-grained sandstone (65%) and bentonitic siltstone (35%) (Fig. 6B). The sandstone exhibits flat to wavy bedding. Siltstone intervals are laminated and/or exhibit a “popcorn” weathering pattern, resulting from the episodic shrinking and swelling of bentonite. Less bentonitic siltstone intervals are also present in this facies. Sandstone and siltstone beds are 1-5 cm and 3-8 cm thick, respectively, and siltstone beds thin up-section. Bioturbation is largely absent within Mo2 (BI=0-2), but sandstone is more bioturbated than siltstone. Observed traces include ?*Pterichnus* (vc), *Planolites* (c) and *Thalassinoides* (vr) (Fig. 6D). ?*Pterichnus* occurs in the greatest abundance and is present in most sections.

*Interpretation* – Facies Mo2 was deposited in an offshore environment from current flows and pelagic accumulation. The facies has a more diverse trace assemblage and is coarser-grained than Mo1. Sandstone beds were deposited by storm and gravity flows. Sediment flows periodically delivered oxygenated surface waters to previously anoxic settings. Organisms were either transported along with the gravity flow or pursuing food resources at depth, taking advantage of uncharacteristically high oxygen levels. Colonization persisted until oxygen was depleted again and the pioneering assemblage died (ef. Föllmi & Grimm 1990). The *Nereites* ichnofacies is diagnostic of periods of slow sedimentation punctuated by gravity flows in marine settings (MacEachern et al. 2007b). More abundant gravity flows and overall better oxygenated conditions suggest Mo2 was deposited more proximal to the paleoshoreline than Mo1.
**Facies Mo3.---**

*Description* - Facies Mo3 consists of silicified, very fine- to fine-grained sandstone (75%) and siltstone (25%). Sandstone and siltstone bed thicknesses vary but are most commonly 1-5 cm and 1-3 cm respectively. Sandstone beds are platy, typically exhibit flat to wavy bedding, and locally contain carbonaceous plant debris and fish scales (Fig 6C). Sandstones also contain current ripple cross-lamination, gutter casts, and small-scale hummocky cross-stratification. Sandstone has a higher BI (BI=0-5) than siltstone beds (BI=0-1). Facies Mo3 has the highest diversity trace assemblage of the Mowry facies association with *Planolites* (c), *Zoophycos* (m), *Teichichnus* (m), *Lockeia* (r), and *Thalassinoides* (vr) (Fig. 6E). The assemblage is characteristic of the *Zoophycos* ichnofacies.

*Interpretation* - Graded bedding, gutter casts, and hummocky cross-stratification are indicative of offshore deposition by storm or turbidity flows. The inconsistent bioturbation intensities (BI=0-5) indicate an anaerobic environment characterized by intermittently high sedimentation rates. Despite a wide environmental range, the *Zoophycos* ichnofacies is generally associated with deposition in poorly oxygenated, organic rich, quiet-water settings below storm wave base (Pemberton et al. 1992a; MacEachern et al. 2007c). Genera of the *Zoophycos* ichnofacies, though resilient, are less tolerant of stressful conditions than constituents of the *Nereites* ichnofacies. Higher bioturbation intensities and a greater proportion of sandstone indicate Mo3 was deposited in a more proximal environment than facies Mo1 and Mo2. The physical and biogenic properties of the porcellanite beds are identical to Facies Mo2 and Mo3.
Figure 7. A) Thirty-five m cliff exposure of the Peay Member. The clinoforms shown in Figure 8 are present to the south. Thinly bedded sandstone and siltstone (Facies P1) coarsens into tabular sandstone beds with silt partings (Facies P2). At this locality (Section 4), Facies P1 is 7 m thick and Facies P2 is 15 m thick. Facies P1 and P2 are interpreted as lower and middle delta front deposits respectively. B) Trilite syneresis cracks exposed in positive relief along the base of sandstone beds which were deposited along a lower delta front (facies P1). Syneresis cracks formed due to freshwater input from a nearby river mouth. Image from Section 6. C) Facies 1 with small, deformed, syneresis cracks in carbonaceous shale. Syneresis structures are deformed from compaction beneath a centimeter-thick, ripple cross-laminated sandstone bed. Syneresis structures and absence of trace fossils indicate deposition in brackish-water conditions along a lower delta front due to freshwater input from a nearby river mouth. Photo from Section 2. D) Bedding plane view of a lower delta front sandstone (Facies P1) (Section 2). Syneresis cracks exhibit a sinusoidal geometry in contrast to those imaged in (B) & (E) (Fig. 7). The trace fossil *Nereites* is preserved in positive relief. E) Trilite syneresis cracks in Facies P1 (Section 4). Sand filled *Diplocraterion* burrows are also present. F) Close-up view of syneresis cracks in Facies P1 at section 6. These sand-filled spindle-shaped structures formed along a lower delta front.
Figure 8. A) Thirty-five meter thick cliff exposure near Section 4 represents a coarsening upward succession from interbedded sandstone and siltstone to tabular sandstone with silt partings. Deposits are interpreted as having been deposited along lower and middle delta fronts (Facies P1 & P2). Large-scale southerly dipping bed forms (clinoforms) downlap onto shelf-muds (Facies Mo 1). The downlapping geometry is illustrated in images B) and C). Downlap surface is interpreted as a sequence boundary candidate.
Figure 9. A) Coarsening upward succession from lower delta front (Facies P1) to middle delta front deposits (Facies P2) at section 4. Sandstone beds thicken towards the top of the succession due to an increase in the amount of wave/storm influence on sedimentation. Silt partings between the sandstone beds in P2 represent fair-weather conditions. A stressed Crustiana ichnofacies indicates deltaic processes influenced the benthic fauna. B) Middle delta front (Facies P2) overlain by an erosionally-based mouth bar (Facies P4). Photograph taken at Section 2. Mouth bar facies is resolved from sedimentary structures present in iron-rich nodules due to poor exposure quality. C) Diplodoraterion (Di) preserved along a bedding plane in facies P5 at Section 1. Trace-fossils are present along sandstone bedding planes and usually contains a low diversity expression of the Skolithos ichnofacies. D) Ophiomorpha (Op) burrow in upper delta front deposits (Facies P3). Bioturbation is very rare to absent. Photo taken at Section 4. E) Large Diplodoraterion (Di) burrow formed in a wave/storm dominated middle delta front (Facies P2). Photo taken at section 4. F) Plan view of a large, granule filled Thalassinoides (Th.) in middle delta front deposits (cliff exposure behind Section 3). Gravel clasts likely filled the burrow due to storm events. G) Upper delta front deposit (Facies P3) consisting of thinly bedded hummocky cross-stratified sandstone. Facies is often located above middle delta front (Facies P2) and below mouth bar deposits (Facies P4). HCS formed due to oscillatory flow during storm events along a wave/storm dominated upper delta front. Interval contains little to no trace fossils. Photo taken at Section 7. H) Intensely bioturbated (BI=4) tabular sandstone bedding-surface in middle delta front deposits (Facies P2). Only Taenidium is present in this photograph. Benthic fauna colonized sandstone bed surfaces during fair weather conditions following storm events. Diversity is limited because stressful conditions were not optimal for other benthic organisms. Photo taken at Section 3. I) 10-50 cm thick sandstone beds with wavy contacts and thin, 1-3 cm thick, silt partings (Facies P2). Sandstone beds were deposited by seasonal wave/storm action. Colonization by benthic fauna was deterred by an environmental stressor; likely rapid sedimentation or freshwater input from a nearby delta. Facies P2 was deposited along a middle delta front. Photo taken at Section 3. J) Climbing wave ripples in Facies P2 (middle delta front). Ripples formed as a result of high accommodation and high sediment supply during a seasonal storm. Photo taken at Section 2. K) Siderite nodules at top of Peay Member (P4) (Section 6). Nodules preserve sedimentary structures interpreted as formed in a mouth bar. The presence of siderite indicates reducing conditions and low sulphate activity. L) Interference ripples and symmetrical wave ripples preserved along sandstone bedding planes at the top of the Peay Member (Facies P5) at Section 1. Rippled bedding planes are locally bioturbated (BI=0-2). Facies P5 was deposited in shallow water during a relative rise in sea-level that drowned the underlying mouth bar (Facies P4).
The Peay Sandstone Member conformably overlies the Mowry Shale (Fig. 7A & 8A) and underlies the Sub-X and Alkali Members. The Peay Facies Association consists of a broadly coarsening-upward sequence of five facies that indicate deposition along a delta front and mouth bar (Table 2). The Peay Member contains thinly interbedded siltstone and sandstone (facies P1), medium bedded cross-stratified sandstones with silt partings (facies P2), thinly bedded-hummocky cross-stratified sandstone (Facies P3), a tabular cross-beded sandstone (facies P4), and a partial coarsening upward sequence from very fine- to fine-grained sandstone (facies P5). This facies association records the transition from a tidally and fluvially influenced delta front to a high energy upper shoreface/river mouth environment. Paleocurrent data indicate a dominantly south-southeast paleoflow direction (n=25). The Peay Member records stressed, low intensity, low diversity, assemblages of the *Cruziana* and archetypal *Skolithos* ichnofacies.

**Facies P1.---**

*Description* – P1 consists of a gradationally based, coarsening-upward succession of laminated siltstone (25%) interbedded with very fine-to fine-grained sandstone (75%) (Fig. 7C). Most sandstone intervals are 2-5 cm thick, thickening up-section (Fig. 7A). Laminated siltstone intervals are 1-5 cm thick, individual laminae are mm to several cm thick (Figs. 7C & 7F). Carbonaceous mudstone containing minor quantities of carbonaceous plant debris, locally occurs in lieu of the siltstone. Sharply-based sandstone beds exhibit limited physical sedimentary structures including flat to wavy bedding and wave-modified current ripples associated with millimeter-scale mud drapes. Sand-filled, semi-polygonal fissures are present in mudstone beds and along the basal contact of
sandstone beds (Figs. 7B,C, D, E, & F). Facies P1 is sparsely bioturbated (BI=0-2). Sandstone beds (BI=0-2) contain Planolites (c), Diplocraterion (m), Teichichnus (m), Thalassinoides (m), and Lockeia (r). Planolites (c) and Thalassinoides (m) are the only ichnogenera observed in the sparsely bioturbated (BI=0-1) siltstone and carbonaceous mudstone intervals (Fig. 7C).

**Interpretation** – The gradational base to P1 suggests that the facies is genetically related to Mo1 and likely marine. Interbedded sandstones, siltstones, and carbonaceous mud-drapes are the result of daily and seasonal energy fluctuations. Symmetrical and wave-modified current-ripple cross-lamination indicates multiple flow directions, although paleoflow data do not indicate bidirectional flow and preclude a macrotidal influence. Sandstone and shale were deposited during lower frequency storms or turbidity flows. Spindle-shaped, trilete cracks along the basal contacts of sandstones superficially resemble polygonal desiccation cracks, but are interpreted as syneresis structures (Figs. 7B & E). The subaqueous formation of these spindle-forms has been demonstrated experimentally to result from the mixing of brackish and normal marine waters (Plummer & Gostin 1981).

Brackish water conditions reduced the diversity and bioturbation intensity (BI=0-2) of the trace suite characteristic of the observed stressed, non-archetypal Cruziana ichnofacies (MacEachern et al. 2007a). Sediments deposited in the transition zone or upper offshore would be thoroughly homogenized by benthic fauna and not contain evidence of atypical salinities. Physical and biogenic structures indicate deposition in brackish environment characterized by high- and low-frequency energy level fluctuations. Facies P1 is interpreted as having been deposited during along a lower-delta front.
**Facies P2.**

*Description* - Facies P2 consists of well-sorted, fine- to medium-grained sandstone beds (90%) with siltstone partings (10%) (Figs. 9 A, B, & I). Sandstone beds are commonly ten cm thick, but vary up to 30 cm thick. Laminated siltstone beds are 1-3 cm thick and many contain carbonaceous plant debris. Sandstone beds exhibit flat- to low-angle stratification, rare small-scale cross-stratification, syneresis cracks, sole marks, interference ripples, ripple cross-lamination, climbing ripple cross-lamination, and rare hummocky cross-stratification (Figs. 9 A, I, & J). Normal grading is common but not ubiquitous in sandstone intervals. Erosional, internal reactivation surfaces are also present in sandstone beds and commonly bioturbated (BI=0-2). Well rounded granule- to pebble-sized chert clasts and rare shell fragments are present in sandstone beds. Large – scale dipping surfaces (clinoforms), accentuated by siderite precipitation along bedding planes, and inclined towards the south-southeast are present along one cliff exposure (Figs. 8A-C). Siltstone partings are minimally bioturbated (BI=0-3) by *Planolites*(c) and *Lockeia* (m). In contrast, sandstone beds have BI=0-4, with highest BI along bedding surfaces (Fig. 9H). The recorded trace assemblage in the sandstone intervals includes *Planolites*(c), *Lockeia* (r), *Thalassinoides* (c), *Taenidium* (c), *Gyrochorte* (r), *Cylindrichnus* (r), *Diplocraterion* (m), and *Ophiomorpha* (m) (Figs. 9E & H); traces are locally filled with chert granules (Fig. 9F). The most bioturbated intervals contain low-diversity trace-assemblages of primarily horizontal genera. Beds with predominantly vertical burrows (BI=1-2) are more common at the top of the facies.

*Interpretation* – An abundance of marine trace fossils, presence of wave-formed ripples, and lack of evidence of subaerial exposure indicates deposition of facies P2 in a marine
environment. Sandstone intervals are significantly thicker than siltstone layers indicating more proximal, higher energy environment than facies P1. Graded sandstone beds, climbing ripple cross-lamination, small scale cross-bedding, interference ripples, wavy bedding, and hummocky cross-stratification (HCS) indicate high energy deposition. HCS forms from strong, oscillatory-dominant combined flow (Dumas et al. 2005). Interference ripples were formed by multi-directional wave motion. Climbing ripple cross-lamination were likely deposited during major coastal storms (Bhattacharya & Giosan 2003; Bhattacharya 2006). Randomly distributed chert granules and burrows filled with gravel clasts were also transported by storms (Fig. 9F) (Bhattacharya & Walker 1991a). A trace assemblage comprising elements of the *Cruziana* and *Skolithos* ichnofacies occurs in this facies. Fair-weather conditions between major storm events are recorded by high intensity bioturbation along bedding planes by a proximal expression of the *Cruziana* ichnofacies. This ichnofacies is characteristic of a subtidal, poorly-sorted and unconsolidated substrate in moderate to low-energy conditions below fair weather wave base but above storm wave base (Pemberton et al. 1992b). The *Skolithos* ichnofacies is more characteristic of high-energy environments and rates of sedimentation. A combination of rapid sedimentation and brackish–water applied stress on benthic fauna, restricting BI values. Sandstone deposition occurred rapidly enough to deter extensive bioturbation. The thin siltstone layers record fair-weather conditions following the deposition of sandstone beds. P2 contains elements of different ichnofacies because of fluctuating stress associated with the environment of deposition. The observed physical and biogenic structures present in facies P2 indicate deposition along a south- to southeast prograding wave- and storm-influenced middle-delta front.
This facies is genetically related to facies P1 but represents deposition in a more storm-dominated environment.

**Facies P3.---**

*Description* - Facies P2 grades into Facies P3. Facies P3 consists of light grey, gradationally based, thinly-bedded fine- to medium-grained sandstone. The facies is 2-7 m thick, although individual beds are 3-5 cm thick (Fig. 9G). Sandstone beds contain flat to low-angle stratification, wavy bedding, small scale trough cross-bedding, and hummocky cross-stratification (Fig. 9 G). Flat to low-angle stratification is more common in the lower half of this facies. Small scale trough cross-bedding (15-30 cm thick sets) is more common up-section and eventually transitions to large-scale hummocky cross-stratification. Bioturbation is sparse to absent (BI=0-2), only *Ophiomorpha* (r) was observed in this facies (Fig. 9D).

*Interpretation* - The gradational contact between facies P2 and P3 suggests the two intervals are genetically related. Planar, low-angle, and hummocky cross-stratification indicates facies P3 was deposited in a more proximal, higher energy environment than facies P2. The increasing prevalence of HCS up-section suggests dominant oscillatory-flow, which is potentially indicative of deposition in a storm-dominated environment (Dumas et al. 2005). The limited variation in sandstone bed thicknesses is interpreted as being the result of wave processes. A storm-dominated environment would have varied bed-thickness depending on the intensity of storm events. High energy levels and sedimentation events limited the diversity and relative abundance of trace fauna. The ichnofacies is indeterminable due to insufficient data. Facies P3 is interpreted as having
been deposited along an upper delta front with exposure to regular wave reworking and modification.

**Facies P4.---**

*Description* - The Upper Peay Member, Facies P4, consists of tabular, medium-bedded, fine- to medium-grained sandstone (Fig. 9B). Rocks in this facies are dark red to orange and contain large (1-2 m) siderite nodules (Fig. 9K) (Khandaker 1991). They weather recessively and are in many places poorly exposed. Locally, nodules are the only remaining record of the facies. Sandstone beds exhibit planar to low-angle stratification, large-scale trough cross-bedding, hummocky cross-stratification, asymmetrical ripples, and interference ripples. Paleoflow measurements from ripple cross-lamination and trough cross-bedding indicate a south- to south-eastwardly paleocurrent direction. Bioturbation is moderate to absent (BI=0-2) and most concentrated along rippled bedding surfaces. The trace fossil assemblage consists of *Diplocraterion* (r) & *Planolites* (r).

*Interpretation* – P4 is interpreted as a mouth bar or river mouth deposit. Cross-bedding indicates dune migration to the south- southeast, parallel to the regional paleoshoreline. Interference ripples and symmetrical wave ripples suggest shallow water depths. Cross-beds indicate deposition in a near shore environment. The trace assemblage consists of a stressed indeterminate ichnofacies. High-energy and rapid sedimentation associated with the nearshore environment reduced BI. Bioturbating organisms colonized bed tops during fair-weather conditions. Nodules composed of diagenetic siderite indicate reducing conditions and low sulphate activity (Coleman & Prior 1982). Siderite frequently occurs as a secondary cement in association with sequence boundaries (Stonecipher 1999), but also forms in nearshore and intertidal environments (Coleman
1985). Overall, facies P4 is interpreted as the culmination of the underlying coarsening upward succession and was likely deposited along a mouth bar or in proximity to a river mouth. This facies is considered to be the most landward deposit in the Peay Sandstone.

**Facies P5.---**

*bDescription*—Facies P5 consists of a minor coarsening upward sequence from very fine- to fine-grained sandstone. This facies is typically 1-3 m thick, but is absent in southernmost section. The base of facies P5 weathers recessively but individual sandstone beds (.4-1 m thick) are well-exposed at the top of the facies. The topmost bed of the facies is variably covered with a thin layer of chert granules. Granule layer is commonly not preserved *in situ*. Facies P5 contains flat- to low-angle stratification, wavy- bedding, and surface ripple forms. Symmetrical, asymmetrical, and interference ripples are preserved along bedding surfaces (Fig. 9L). Orange sandstone bed tops are coated with a white, opalescent coating, and sparsely bioturbated (BI=0-2) by *Diplocraterion* (c), *Planolites* (c), *Lockeia* (m), *Ophiomorpha* (r), and *Conichnus* (?) (vr) (Fig. 9C).

*bInterpretation*—The general coarsening-upward sequence from very fine- to fine-grained sandstone and increased occurrence of marine trace-fossils indicates facies P5 was deposited in a more basinward environment than the underlying facies P4. The low-diversity, low-abundance (BI=0-2) trace-fossil assemblage records a stressed expression of the archetypal *Skolithos* ichnofacies. Sandstone beds are increasingly tabular at the top of facies P5 and likely record isolated instances of elevated current velocity, presumably during storm events. Sedimentation rates and energy levels are too great in storm-dominated settings for benthic organisms to colonize the substrate. Facies P5 and the
trace-fossil assemblage therein, could alternatively be interpreted as recording brackish water conditions in proximity to a delta. Facies P5 is interpreted as the record of a sediment pulse during transgression that preceded the formation of the lag at the top of the Peay Member. The rate of transgression increased and formed the thin lag interval. The slight rise of relative sea-level was sufficient to result in the abandonment of the mouth bar of facies P4. Facies P5 is not present in the southernmost sections because it was either eroded away during transgression or not deposited. The low erosional relief on the top of the Peay Member, and increasing thickness of the lag to the south, indicates that facies P5 was deposited and then removed during a subsequent transgression.

Frontier- Sub-X (SX) Facies Association

The Sub-X facies association consists of dark grey shale that coarsens upward into interbedded shale and sandstone (Table 3). This unit is present between the Peay and X-Bentonite. Thin gravel lags at the top and bottom of the facies association denote hialtal surfaces. These disconformities genetically separate the Sub-X Member from adjacent units. Although, the unit is not a formal member of the Frontier, the Sub-X Member is distinguished from the other facies associations because it is genetically and chronologically unrelated. The Sub-X is interpreted as having been deposited along a distal delta front.

Facies SX1.—

Description- Facies consists of a coarsening upward succession of silt-dominated heterolithic deposits that grade vertically into upward-thickening sandstone beds of very fine- to fine-grained sandstone separated by laminated siltstone (Fig. 10 A-C). Thin layers of black chert-granules are present at bottom- and upper-most contacts of the SX1.
The basal silt-dominated heterolithic deposits contain interbedded shale and very fine sandstone (2-3 cm). Sandstone beds are 5-15 cm thick at the top of the facies (Fig. 10B). Sandstone intervals are generally sharp-based but sharp internal bed contacts occur locally. (Fig.10B). Sandstone beds exhibit flat- to low-angle stratification, hummocky cross-stratification, and wavy bedding. A thin layer of chert granules occurs along the uppermost bedding surface, immediately below the X-Bentonite. Siltstone is minimally bioturbated (BI 0-2) and only contains Planolites(r). The most diverse and intense trace assemblages of the entire section are present in the sandstone beds at the top of the Sub-X Member. Bioturbation intensity is highly variable for individual sand bodies (BI=1-3). The trace suite includes Planolites (c), Rosselia (r), Cylindrichnus (r), Phycosiphon (r), Teichichnus (m), Navichnia (?) (vr), Fugichnua (vr), claw marks (?), and Lockeia (vr) (Fig. 10B).

**Interpretation** - The chert-granule layers at the top and bottom of this unit represent depositional hiatuses formed by sediment-winnowing by waves during relative rises in sea-level. The transgressive lags in conjunction with the abrupt shift in lithology from sandstone to finely laminated mudstone (shale) at the upper and lower boundaries of the Sub-X Member indicate relative rise in sea-level; however, the overlying shale in the Alkali Member (facies A1) is thicker and less sand-prone than the Sub-X member suggesting that the Alkali Member formed during a relatively larger transgression. Sandstone beds record elevated energy levels, likely from seasonal storms, where current velocities were sufficient to transport sand-sized sediments basinward. Siltstone records the fair-weather conditions between the deposition of sandstone beds. A low diversity trace-fossil assemblage, of an indeterminate ichnofacies, is present in the lower Sub-X
Figure 10. A-C) Sub-X facies association Photographs taken at Section 1. A) 10 m thick coarsening upward succession from shale to interbedded sandstone and siltstone. Sandstone beds are variably bioturbated by an archetypal expression of the Cruziana ichnofacies (B). Unit is located between the Peay Member and X-bentonite which is 2 m thick in this photograph. B) Thalassinoides and Planolites traces in sandstone bed at the top of the Sub-X facies association. Burrows are filled with a light-grey medium-grained sandstone. C) Interbedded sandstone and siltstone beds in the Sub X Mbr. Sandstone beds are thicker at the top of the succession but varies between 2-10 cm. The coarsening upward succession was deposited along a distal delta front. D-E) Multiple coarsening upward successions in the Alkali Member at Sections 1(E) and 7(D). Successions coarsen upward from siltstone to sandstone. Parasequences consist of Facies A2 and A3 and are interpreted as having been deposited along a delta front. Coarsening upward successions form parasequences bound by flooding surfaces. Two to four parasequences are present at localities across the study area. The top-most parasequences are capped by transgressive lags (F & G). Lag deposits, interpreted as transgressive surfaces of erosion (TSEs) are very useful in correlating facies across the study area. The parasequences that cannot be correlated across the study area was likely formed by autocyclic controls like delta-lobe switching. Staff is 1.5 m. F-G) Transgressive lag consists of chert, granule/pebble-conglomerate. Gravel overlies coarse-very coarse sandstone lag. Change in grain size and lag thickness reflects local variations in topography and wave energy during transgression. Lags are interpreted as transgressive surfaces of erosion (TSEs) that form during relative rises in sea-level. Lags are easy to correlate across the study area and were likely formed by allocyclic forcing. H) Facies A3, interbedded rippled sandstone and bioturbated siltstone deposited in a proximal delta front. Sandstone is sparsely bioturbated. Bioturbated siltstone intervals contain (Pl.) Planolites, (Th.) Thalassinoides, and (As.) Asterosoma. Photo taken at Section 1. I) Thalassinoides and Diplacrotorion along sandstone bedding surface in facies A3. An opalescent coating enhances the bioturbation in this facies. Photo from locality 4. J) Gradational contact between the upper Alkali Member and Torchlight Member at Section 9. The Upper Bed Bentonite (UBB) is indicated on the photograph. The UBB is not present at every section in the study area.
Member but passes upward to a distal expression of the archetypal *Cruziana* ichnofacies. Higher bioturbation intensities in sandstone are the result of elevated oxygen levels from storm input and increasingly proximal conditions (Föllmi & Grimm 1990; MacEachern et al. 2007a). The increase in the proportion of sandstone and BI up-section records the basinward progradation of shoreward facies. Facies SX1 is interpreted as having been deposited along a delta front during a normal regression following a relative rise in sea-level.

*Frontier- Alkali (A) Facies Association*

Stratigraphically, the previously unnamed Alkali Member is situated between the X-bentonite and the base of the Torchlight Member (Fig. 4). In the study area this 60-80 m thick interval of shale, heterolithic sandstone and siltstone, conglomerate, and bentonitic sediments is divided into five facies (Figs. 10 D-I; Table 4). Four of these facies are only present in the Alkali Facies Association. Additionally, the middle of the Alkali Member is characterized by high frequency, coarsening upward parasequences (Fig. 10s D &E). Parasequences are bound by flooding surfaces and locally capped by conglomeratic facies (Fig. 10 D). Facies are interpreted as prodelta (A1), delta front (A2 & A3), lag (A4), and post-eruption deposits (F2).

**Facies A1.**

*Description*—This facies consists of 20-30 m of dark grey laminated mudstone or siltstone (70-90%) sparsely interbedded with very-fine sandstone (10-30%). Sandstone beds, with poorly developed ripple cross-lamination, are more common at the top of the unit. Siltstone and sandstone beds are 3-4 cm thick, although individual siltstone laminae are 3-5 mm. Facies A1 is commonly expressed as recessively-weathered valleys or lowlands (Fig. 5). Bioturbation in facies A1 is rare to absent (BI 0-2) and limited to *Planolites*(c).
Facies A1 is slightly bentonitic above facies A2 and A3 where the facies has badlands topography.

*Interpretation*- The transgressive chert lag at the top of Sub-X Member (facies SX1), indicates the deposition of facies A1 following a relative sea-level rise. The shale’s primary physical structures are preserved due to infrequent biogenic alteration. The uncharacteristically low-diversity, low-intensity, trace assemblage may denote environmental stress (MacEachern et al. 2007b). Standard offshore-marine sediments are colonized by members of the *Cruziana*, *Zoophycos*, or *Nerieities* ichnofacies (MacEachern et al. 2007c). Each of these ichnofacies is indicative of different ambient conditions. The ichnofacies present in facies A1 is indeterminable from only one trace genus. A coarsening-upward trend indicated by the increasing proportion of sandstone beds higher in the facies suggests an increasingly proximal sediment source. A1 is interpreted as having been deposited in a distal prodeltaic environment. The proportion of sandstone increases up-section in response to the progradation of the delta front and greater exposure to storm currents. Fine-grained sediments were likely transported away from the delta front by longshore currents, perhaps in a mud plume. The settling-out of fine-grained sediment and perhaps the input of brackish water from the delta negatively impacted the trace fauna. Facies A1 record the deposition of a prodeltaic mud wedge during a normal regression following a relative rise in sea-level.

**Facies A2.**

*Description*- Facies A2 consists of intermittently bioturbated- to unbioturbated-heterolithic sediments, very fine-grained sandstone, and dark-grey siltstone. This facies forms multiple coarsening-upward successions that grade into well-cemented fine-
grained sandstone beds (facies A3). Separated by abrupt changes in lithology, a minimum of three such successions are present in facies A2. Heterolithic sediments consist of fine-grained sandstone beds (2-4 cm) and thin dark-grey carbonaceous shale (0-2 cm) beds (Fig. 10H). Siltstone beds are either finely-laminated or mixed with thin sandstone beds depending on the degree of bioturbation (BI=0-4). Sandstone beds exhibit flat- to low-angle stratification (c), slightly asymmetrical cross-lamination (c), wavy bedding (m), and syneresis cracks (r). Bioturbation is more prevalent in the siltstone beds (BI=0-4) than in the sandstone beds (BI=0-1). Homogenized siltstone intervals contain Planolites (m), Thalassinoides (m), Zoophycos (m), Asterosoma (r), and Schaubcylindrichnus (vr) (Fig. 10H). Only Planolites and Thalassinoides burrows are present in low abundance in the ripple cross-laminated sandstone beds.

Interpretation- Facies A2 conformably overlies the underlying facies (A1). Sandstone beds are thicker and more abundant higher up in the section in response to the increasing proximity of the sediment source. The unbioturbated beds of rippled and planar-stratified sandstone indicate periods of rapid deposition. The thin-bedded sandstones and siltstones were deposited between major sedimentation events. The sandstone beds record increased flow strengths likely due to storm events or slope failures. Sedimentary structure is preserved where sedimentation events were too frequent for organisms to colonize the substrate (MacEachern 2007b). In contrast, homogenized intervals represent hiatuses between sandstone deposition. The trace assemblage is interpreted as a stressed expression of the Cruziana ichnofacies. Periodic sand deposition deterred burrowing organisms resulting in the high-intensity, low-diversity trace-assemblage recorded in facies A2. Physical and biogenic structures indicate facies A2 was deposited along a
prograding delta front. The delta front is inferred to represent more proximal deposition than the genetically related prodeltaic facies (Facies A1).

**Facies A3.**

*Description*- Facies A3 consists of thinly bedded, very fine- to fine-grained sandstone. This facies is present at the culmination of each of the previously mentioned coarsening-upward sequences (facies A2) (Fig. 10D), but also occurs as sharply-based, isolated beds higher in the section. Sandstone beds are .2-1 meter thick and are locally interbedded with 2-5 cm thick siltstone or bentonite beds. Primary structures are highly variable but commonly include flat- to low-angle stratification, planar-stratification, and small-scale cross-bedding. Large-scale hummocky cross-stratification, gutter casts, and interference ripples are also present, but lower in abundance. In the upper Alkali Member facies A3 can be obscured by weathering of adjacent bentonite-rich intervals (A1). Facies A3 is variably bioturbated (BI=0-4) by one or two of the following genera: *Ophiomorpha* (c), *Diplocraterion* (c), *Planolites* (m), *Thalassinoides* (m), *Gyrochorte* (m), *Cylindrichnus* (m), and *Taenidium* (m) (Fig. 10I). In most sandstone beds vertical burrows are more abundant than horizontal traces, but surface-traces have greater BI where vertical burrows are less common.

*Interpretation*- Facies A3 is the most sand-prone portion of the coarsening-upward succession that contains facies A2. The greater proportion of sandstone in facies A3 suggests a more proximal environment relative to facies A2. Flat- to low-angle stratification, planar-stratification, small-scale cross-bedding, interference ripples, and hummocky cross-stratification form from high-energy, laminar to oscillatory flow. Sandstone beds record rapid deposition during periods of high energy. Where the facies
is sharply-based the sandstones are interpreted as storm deposits that accumulated along an increasingly proximal delta-front. The gradationally based sandstone beds are also interpreted as delta-front deposits. Such sandstone beds were initially colonized by vertically-oriented burrows during deposition and subsequently burrowed by horizontal traces during fair-weather conditions. The trace fossil assemblage is interpreted to record a stressed expression of the archetypal *Skolithos* ichnofacies. The trace suite is consistent with periodically rapid sedimentation or increased current energy (MacEachern 2007b).

**Facies A4.---**

*Description*- A4 consists of sharply based coarse- to very-coarse-grained sandstone and/or locally conglomeratic intervals of well-rounded granule- to pebble-sized black-chert clasts (Figs. 10F & G). This facies has alternating beds of clast-supported pebble-conglomerate and grain-supported granule-conglomerate (Fig. 10G). Intervals are .2-.7 m thick and some occur as two separate intervals divided by coarse-grained sandstone. Conglomeratic intervals and gravel-sized clasts are less abundant higher in the facies but still occur along bedding planes or in thin, .2 m wide, lenses. Conglomeratic intervals have sharp contacts with coarse-grained sandstone beds (Fig. 10 F). Facies A4 commonly lacks sedimentary structure but locally preserve flat- to low-angle stratification, wavy bedding, or interference ripples. Low-angle stratification is more abundant in the sandstone intervals. Although individual conglomerate intervals transition laterally into sandstone, facies A4 is correlatable across the study area. No bioturbation was observed in this facies.

*Interpretation*- The absence of sedimentary structures and overall planar geometry of facies A4 precludes a fluvial origin. Facies A4 is interpreted as a transgressive lag
formed by wave-ravinement and winnowing of fine-grained sediments during a relative rise in sea-level (Hart & Plint 1995; Hwang & Heller 2002; Hart & Plint 2003). Locally, variations of the topography and wave energies may account for lateral and vertical variations in facies thickness and presence of conglomeratic intervals (Hwang & Heller 2002). The crude fining-upward sequence from gravel to coarse-sandstone may indicate a prolonged, multi-tiered transgression (Hwang & Heller 2002). Presumably, the conglomeratic intervals are more abundant at the base of this facies because the effect of wave-winnowing was more pronounced during the initial stages of relative sea-level rise.

**Frontier-Torchlight (T) Facies Association**

The Torchlight Facies Association consists of tabular- to cross-bedded sandstone and conglomerate (Fig. 10 J; Table 5). The Torchlight Member is 5-10 m thick, but measured thicknesses are only partially complete due to weathering. The facies association consists of upper shoreface sediments incised by fluvial channels that are capped by a thick, transgressive lag.

**Facies T1.---**

*Description*- Facies T1 consists of unbioturbated (BI=0) tabular, flat-stratified very fine- to fine-grained sandstone. This interval is 2-5 m thick, and individual sandstone bedsets are 2-5 cm, locally up to 1 m thick. The unit exhibits ubiquitous flat- to low-angle stratification as well as interference ripples and hummocky cross-stratification in lower abundance. Facies T1 has gradational and sharp lower and upper contacts, respectively (Figs. 11 A, B, D, E, & G). The sharp contact between facies T1 and the overlying facies T2 is indicated by a shift from planar- to cross-stratified strata and angular, 1-3 cm,
Figure 11. A) Panorama of the Torchlight Member at Section 7. Sharply based trough cross-bedded channel deposits (Facies T2) incising into underlying upper shoreface (Facies T1). B) Sharp contact between TXB T2 and flat-stratified T1. The erosional contact is identified as a sequence boundary candidate (white line) (Section 7). C) Sharply-based Torchlight Conglomerate (T3) with crossbedded strata (T2). (South of Section 1) D) Multidirectional cross-bedding in the upper Torchlight Member (Section 1). E) White arrows indicate an erosional contact between T2 and T1 marked by angular siltstone clasts and quartz pebbles & cobbles. Contact between these two facies is considered a sequence boundary candidate. Black Arrows: Fine sandstone incising into medium grained sandstone. Interpreted as channel incision. (Section 8) F) Chert and porphyritic andesite pebbles and cobbles found in the Torchlight Conglomerate (Section 11). G) Sharp contact between TXB T2 and flat stratified T1. Again, erosional contact between these two facies is interpreted as a sequence boundary candidate. H) Bidirectional TXB in the Torchlight Member (T2) (Section 8).
mudclasts (Fig. 11 E). Rounded quartz and chert pebbles are locally present along this contact.

Interpretation- The gradationally-based facies T2 is the genetic extension, or more proximal, coarser-grained equivalent, of the underlying facies A3. HCS and flat- to low-angle stratification suggest deposition in a high energy environment affected by storm currents in a marine setting. A lack of bioturbation suggests benthic colonization was deterred by an ambient stress or stressors. Sandstone beds up to a meter thick at the top of the facies exhibit uniform sedimentary structure. Each sandstone bed was deposited, in full, by a single depositional event, presumably the result of increased flow-velocities during seasonal storms. Fair-weather deposits were likely reworked during the deposition of the thicker sandstone beds. Facies T1 records sediment deposition and reworking in a storm-dominated upper shoreface.

Facies T2.---

Description- Facies T2 consists of 3-7 m of flat- to low-angle and/or cross-stratified fine- to medium-grained sandstone (Figs. 11B, D, G, & H). Bed sets are 1-3 cm thick. Well-rounded, chert granules and pebbles are present along bedding planes (Fig. 11E). The facies has sharp upper and lower contacts (Figs. 11B, 11C, & 11G). The lower contact is marked by angular mudclasts and rare rounded quartz pebbles (Fig. 11E). Facies T2 locally contains semi-arcuate, sharp internal scour surfaces marked by an abrupt shift in grain-size from medium- to fine-grained sandstone (Fig. 11 E). Mudclasts are only present at the lower boundary between facies T1 and T2. Paleocurrent measurements indicate a dominantly south- to southeasterly paleoflow direction (n=104).
**Interpretation**- Mudclasts, quartz pebbles, and the abrupt changes in grain size both within and along the lower contact of facies T2 indicates erosional incision. Sediments of facies T2 show no biogenic (BI=0) or physical sedimentary structures consistent with deposition in a marine environment. Paleoflow measurements of individual TXB in facies T2 indicate unidirectional subaqueous dune migration to the south-southeast (Fig. 12). Facies T2 is interpreted as the deposits of fluvial channels that incised into underlying sediments (Facies T1). The erosional base of this facies is a candidate for a sequence boundary. Additional record of subaerial exposure could have been removed by fluvial incision.

**Facies T3.---**

**Description**- Facies T3 consists of a 40 cm thick clast-supported conglomerate locally known as the Torchlight Conglomerate. It consists of well-rounded, granule- to cobble-sized black chert, andesite, granodiorite, diorite, as well as rare carbonate and quartzite clasts (Figs. 11C & F). Facies T3 is clearly erosional into the underlying T2 (Fig. 11C). The conglomeratic interval is only present *in situ* in a few localities and is typically represented by a modern deflation surface of gravel-sized clasts. Facies T3 contains low-angle cross-stratification at one locality, but is generally devoid of physical sedimentary structure. The base of the Cody Shale is represented by 20-45 m of intensely weathered sandstone (?) above the Torchlight Conglomerate; the top of this interval culminates in a sub-regionally correlatable ridge of large calcareous septarian nodules.

**Interpretation**- Facies T3 is interpreted as a transgressive lag. It represents significant erosion and sediment reworking (Hwang & Heller 2002). Gravel was likely reworked from overlying fluvial and proximal coastal plain environment during transgression and
associated wave ravinement. It is likely associated with deposition of the overlying Cody Shale. Although the Frontier Formation is interpreted to be primarily Cenomanian in age it is reasonable to assume that this facies formed during the earliest Turonian during the transgression of the Cody Sea.

**Frontier-Recurring (F) Facies Association**

Two facies reoccur throughout the section. Facies are not genetically related to surrounding facies and cannot be classified as one of the other facies associations. Facies are somewhat variable but represent deposition under similar environmental conditions (Table 6). Recurring Facies include pebble lags and weathered ash intervals.

**Facies F1.---**

*Description*- F1 consists of a thin (1-2 cm), sub-rounded to rounded, granule-pebble, black-chert conglomerate. Petrified wood and bone fragments are a minor component in some localities. Facies F1 occurs as a single layer of gravel-sized clasts. It is present in the Peay and Alkali Members but differences in thickness, primary structure, and clast composition distinguish facies F1 from other coarse-grained conglomeratic intervals in the study area.

*Interpretation*- The genetic discordance between facies F1 and underlying facies is represented by the abrupt juxtaposition of clast size and composition between the two facies. Facies F1 is interpreted as transgressive lags concentrated by wave winnowing along flooding surfaces during relative rises in sea-level (Hwang & Heller 2002). Surfaces are not well developed indicating that the extent of sea level change, topography, wave or tides, and duration were not sufficient to deposit a thick lag.

**Facies F2.---**
Description- F2 is .1-2.5 meter thick bentonite intervals. A minimum of four bentonite beds are present in the study area. As discussed earlier in this discourse, bentonite beds are useful because they readily identifiable in the field due to their white color and distinct “popcorn weathering” pattern and record geologically instantaneous events.

Interpretation- Bentonite beds are interpreted to be primary volcanic ash. Bentonite beds were deposited by ash fallout following volcanic eruptions. The Clay Spur and X-Bentonites are the thickest and most reliable bentonites for sub-regional correlation.

Depositional Systems Overview

The Upper Cretaceous Mowry, Peay, Sub-X, Alkali (previously unnamed), and Torchlight Facies Associations were formed in nearshore deltaic and non-deltaic systems along the western margin of the Cretaceous Western Interior Seaway (KWIS). The Peay, Sub-X, and Alkali Members of the Frontier Formation in Bighorn County Wyoming record subaqueous delta deposition with the exception of the upper Peay Member which accumulated in mouthbars. The identification of stressed and archetypal expressions of the Skolithos and Cruziana ichnofacies in the Peay and Alkali Members facilitated analysis of the depositional environment. The identified ichnological response to the relative stress induced by wave, river, and tidal processes are evident in these deltaic facies. Paleoflow measurements from trough cross-stratification in the Peay and Torchlight Members, and large –scale dipping surfaces (clinoforms) in the Peay Member (P2) indicate the predominantly southerly sediment dispersal direction. Similar investigations of sedimentary deposits along the western margin of the KWIS report south- to southeast directed paleoflow (Tillman & Martinsen 1984; Hart & Plint 1989; Bhattacharya & Walker 1991a; Bhattacharya & Walker 1991a; Winn et al 1991;
Sedimentation in the KWIS was influenced by a strong counterclockwise gyre driven by Coriolis forcing, seasonal storms, and thermohaline-induced circulation (Slingerland & Keen, 1999). A combination of these processes controlled sediment dispersal and the stratal-stacking patterns observed in the study area.

**STRATIGRAPHY**

Sub-regionally correlatable key stratigraphic surfaces are identified in the Peay, Sub-X, Alkali, and Torchlight Members of the Frontier Formation in the Alkali Anticline region (Fig. 12). Typically, sequence boundaries are the most distinctive surfaces in a stratigraphic succession and aid in regional correlation. In outcrop, sequence boundaries can be recognized by an abrupt juxtaposition of proximal shallow-water facies over more basinward-facies. In low-accommodation settings proximal facies and their associated sequence boundaries are commonly removed by transgressive erosion. As such, standard sequence stratigraphic nomenclature is less applicable to the Frontier Formation and similar low-accommodation deposits in the KWIS. Transgressive surfaces of erosion (TSE), parasequences sets, flooding surfaces (FS), regressive surfaces of marine erosion (RSME), and sequence boundaries (SB) are the most useful surfaces for sub-regional correlation in low accommodation settings. Recognition of these key-surfaces facilitates the division of the Frontier Formation into recognizable units that can be correlated across the 12 km long study area. Sequence stratigraphic interpretations are summarized in Figure 12.

*Key Surfaces*
Transgressive Surfaces of Erosion (TSE).--- Coarse grained lags associated with surfaces of erosion form regionally correlatable surfaces. Lags consist of coarse sand, gravel, bone, and wood fragments that were concentrated by wave and/or tide winnowing of sediment during a relative rise in sea-level. The clast size distribution and thickness of a transgressive lag depend on the thickness of eroded sediments, types of facies being eroded, and pre-existing topography (Hwang & Heller 2002). Not all transgressions result in lags. Transgressive surfaces of erosion, and associated lags, commonly represent the reworking of 6-15 m of sediment (Martinsen 2003a). Lags do not represent a basinward shift in facies and therefore do not fulfill the requirements of a sequence boundary (Van Wagoner et al. 1990). Erosion can remove evidence of subaerial exposure and sequence boundaries. In the study area TSEs are recorded by 1-50 cm thick lags of very-coarse sandstone to cobble-sized gravel. Lags are common at the top of parasequences, particularly in low accommodation settings, and are invaluable for sub-regional correlations. Past studies in the KWIS rely on similar erosional surfaces to correlate between allomembers (Bhattacharya & Walker 1991b; Embry 1993; Bhattacharya & Willis 2001). At the current level of resolution, allomembers cannot be identified in the study area. If the regional variability of the TSEs is established in outcrop and subsurface data, designating allomembers may aid future correlations in the northeastern Bighorn Basin.

Parasequences and Flooding Surfaces (FS).--- Parasequences consist of relatively conformable successions of genetically related beds separated by marine-flooding surfaces (Van Wagoner et al. 1990; Mitchum & Van Wagoner 1991). Flooding surfaces (FS) are marked by a distinct juxtaposition between facies that can indicate a
relative increase in water-depth or decrease in sediment supply (Van Wagoner et al. 1990). Flooding surface formation is influenced by the balance of allocyclic and autocyclic controls. In the study area, parasequences occur as genetically-coupled successions of shallow-marine sediments. Parasequences, or stacked parasequence sets, are bounded by flooding surfaces or sequence boundaries. At least four parasequences, interpreted as having prodeltaic origins, occur in the upper Alkali Member (A2 & A3). Each parasequence consists of a broadly coarsening-upward succession from laminated mudrock to a sand-prone facies. The formation of lag-capped parasequences is likely connected to allocyclic processes (e.g. eustatic & tectonic cycles). Within deltaic systems, the subtle, locally restricted parasequences are likely the product of autocyclic factors such as lobe switching and abandonment (Catuneanu et al. 2009). In the study area, the parasequences that can be correlated across multiple localities are likely allocyclically controlled. Despite their lateral discontinuity, parasequences and parasequence sets can serve as reliable markers for correlating regional stratigraphy in either subsurface or outcrop exposures where standard key-stratigraphic surfaces are unavailable (Bhattacharya & Walker 1991a; Bhattacharya & Walker 1991b; Bhattacharya and Willis 2001; Sadeque et al. 2007).

Regressive Surfaces of Marine Erosion (RSME).--- The regressive surface of marine erosion (RSME) is a subaqueous scour surface formed by wave- or tidal-erosion in wave-dominated lower shoreface settings (Plint 1988; Plint & Nummedal 2000; Catuneanu et al. 2009). These surfaces are characteristically represented by sharply-based shoreface deposits overlying genetically discordant offshore-facies (Plint 1988). Sharp-based shoreface/delta front deposits indicate missing transitional facies. Such a
sharp erosional contact is classified as a regressive surface of marine erosion (RSME) (Plint 1988; Posamentier & Morris 2000). RSMEs record forced regressions, or actively falling relative sea-level during the falling stage systems tract (FSST) (Plint & Nummedal 2000). The stratal architecture of forced regressive successions, and the associated RSME, is variably influenced by seafloor gradient, net sediment influx and variability relative to base-level fall, and the rate of relative sea-level fall. (Posamentier & Morris 2000). High-order sequences are not necessary to remove marine facies and produce an RSME (Plint & Nummedal 2000). Wave-dominated shorelines can generate RSME in lower-shoreface and shelf deposits during small-scale fluctuations in relative sea-level (Hampson et al. 2007). In the study area the base of the Peay Member sharply overlies the Mowry Facies Association and superficially resembles an RSME. The thickness of the shale below the Peay Member is relatively constant within the study area which is inconsistent with the falling stage systems tract (FSST). At the current level of resolution, the observed stratal architecture of the lower Frontier Formation in the Alkali Anticline region is not consistent with formations in other areas of the KWIS that are interpreted to represent the FSST.

**Sequence Boundaries (SB).**--- Sequence boundaries can be identified on the basis of an abrupt basinward shift in facies. Evidence of subaerial exposure can be indicative of such a shift. Two sequence boundary candidates (SB) are identified in the study area. The proposed SBs are at the base of Peay Member, and below the fluvial channel facies in the middle of the Torchlight Member (facies T2). In this discussion the SB candidates in the Peay and Torchlight Members are designated SB1 and SB2,
respectively. SB1 and SB2 cannot be definitively identified as sequence boundaries because their regional extent and stratigraphic context are as yet unknown.

The first sequence boundary candidate (SB1) is placed at the base of the Peay Member where clinoforms in facies P2 downlap onto the overlying shale. The downlap surface represents the most abrupt basinward shift of facies from shelf mudstones to middle delta front and is interpreted as a sequence boundary candidate. The presence of a sequence boundary cannot be confirmed unless future analyses to determine the surface’s regional extent.

The second sequence boundary candidate (SB2) is placed in the Torchlight Member of the upper Frontier Formation between facies T1 and T2. SB2 is tentatively placed at the base of facies T2, where cross-stratified sandstone incises into flat-bedded sandstone. This contact is interpreted as fluvial incision by facies T2 into the upper shoreface (Facies T1). Incision does not automatically qualify SB2 as a sequence boundary. Although T2 incises into T1, fluvial incision can occur between two genetically related facies and not be related to a basinward shift of facies. SB2 cannot be definitively classified as a sequence boundary unless future investigations determine it to be a regionally correlatable sequence-stratigraphic surface.

Discussion of the Stratigraphy

The results of this investigation provide new insight on the affect limited accommodation has on the stratigraphic architecture and preservation potential of shallow marine sediments deposited along the continental margin. Parasequences as well as the associated flooding surfaces (FS) and transgressive surfaces of erosion (TSE) proved more useful for sug-regional correlation than traditional key surfaces like sequence
boundaries (SB), and subaerially exposed sediments. Frequent relative rises in sea level likely resulting from tectonic forcing associated with the migration of the forebulge across the KWIS precluded the preservation of paralic coastal plain sediments. Transgressive ravinement in accommodation-limited environments removed any paralic facies and sequence boundaries that may have ever been present. The results of this study have serious implications for current sequence stratigraphic models and their inapplicability in accommodation limited settings in the Cretaceous Western Interior Seaway and beyond.

CONCLUSIONS

1. This study analyzed the sedimentology, ichnology, and sequence stratigraphy, of the Frontier Formation in the Alkali Anticline region north of Sheep Mountain Anticline in the northeastern Bighorn Basin, Bighorn County, Wyoming.

2. The Frontier Formation is divided into the genetically distinct Peay, Sub-X, Alkali (previously unnamed), and Torchlight Members.

3. The Frontier Formation accumulated along the western margin of the Cretaceous Western Interior Seaway (KWIS), eastward of the Sevier Orogenic Belt. In the Alkali Anticline region the Upper Cretaceous Frontier Formation consists of 75-145 m of nearshore and shallow marine siliciclastics and volcanoclastic sediments. The unit was deposited in a low-accommodation setting during an overall low-frequency lowstand with intervals of relative rises in sea-level. Sediment deposition and stacking geometries in the study area were strongly controlled by fluctuations in accommodation.

4. The Frontier Formation in the Alkali Anticline region, Bighorn County, WY, was deposited during the Cenomanian between the Clay Spur Bentonite (97.17 ± .69 Ma) and
*Dunveganoceras pondi* zone (94.71 ± 0.5 Ma) (Cobban et al. 2006). Frontier deposits in the study area are interpreted to be equivalent to the Belle Fourche Member in the southwestern Powder River Basin. This correlation presumes the bentonites in the lower Frontier Formation are equivalent to the Clay Spur and X-Bentonites in the Powder River Basin. The X-Bentonite indicates the Peay and Sub-X Members were deposited in the mid- to late-Cenomanian, between 97.17 ± .69 Ma (Clay Spur Bentonite) and 94.96 ± .5 Ma (X-Bentonite).

5. A detailed facies analysis identified eighteen lithofacies, comprising six facies associations. Lithofacies were distinguished based on observed physical and biogenic structures. Because many of the facies are unique to a single stratigraphic position and do not recur elsewhere in the section, the Frontier Formation does not lend itself to a standard lithofacies analysis.

6. The Mowry Facies Association consists of dark-grey shale and slightly bioturbated sandstone. This facies association accumulated in an offshore environment by bottom currents and pelagic fallout. Sediments are bioturbated by constituents of the *Nereites (?)* and *Zoophycos* ichnofacies.

7. The thick, gradual coarsening upward succession comprising the Peay Member of the Frontier Formation consists of discrete intervals of deltaic and near shore siliciclastics. The succession in the Peay Member is composed of lower to upper delta front and mouth bar deposits. The uppermost interval of the Frontier Formation records a low-magnitude transgression that is succeeded by a greater-magnitude increase in relative sea-level. The Peay Facies Association is varyingly bioturbated (BI=0-4) by trace assemblages constituting non-archetypal variants of the *Cruziana* and *Skolithos* ichnofacies.
8. The Sub-X Facies Association consists of a coarsening upward succession from shale to interbedded siltstone and sandstone beds deposited along a distal delta front.

9. The Alkali Facies Association records deposition in a prodeltaic and delta front setting. Transgressive surfaces of erosion (TSE), indicated by gravel lags and erosional contacts, are also present. A minimum of four parasequences are present in the Alkali Member. The Alkali Facies Association contains trace genera related to the *Cruziana* and *Skolithos* ichnofacies. These sub-regionally and locally-occurring coarsening upward successions were deposited ahead of individual delta lobes that prograded to the south/south east. High-frequency parasequences in the Alkali Anticline region accumulated in a low-accommodation setting affected by allocyclic and autocyclic controls. Parasequences were erosionally truncated by transgressive wave ravinement.

10. The Torchlight Facies Association consists of flat to trough cross-stratified sandstone and is capped by a .4 m granule to cobble lag. Sediment, in the lower Torchlight Member was deposited in the upper shoreface. The upper Torchlight Member, records fluvial incision of the underlying sediments.

11. The observed trace-fossil assemblages contain atypically low diversities and abundances for sediments deposited in a shallow marine setting. Such trace-fossil suites record departures from the archetypal ichnofacies in sub-utopian conditions. Resolving the ichnological signature of deltaic and similarly stressful environments was invaluable in reconstructing the depositional environment.

12. The absence of subaerially exposed facies indicates significant transgressive marine ravinement of nearshore deposits. Erosional contacts, and associated flooding surfaces were reliable intervals for sub-regional correlation in the study area.
13. In near-shore, low accommodation settings top-truncated parasequences are more helpful in reconstructing the stratigraphy, than the standard key-sequence stratigraphic surfaces such as sequence boundaries.

14. Two sequence boundary candidates are identified in the study area based on evidence of subaerial exposure and stratal architecture; one at the base of the Peay Member where clinoforms downlap onto the Mowry Shale, and another in the Torchlight Member where trough cross-stratified sediments incise into flat-stratified, upper shoreface deposits. Neither of these sequence boundary candidates can be definitively recognized without additional investigations of their regional extent.

15. Paleoflow measurements in the Peay and Torchlight Members indicate a predominantly southerly paleocurrent direction. A southerly directed long shore current transported sediment parallel to the paleoshoreline. These findings are consistent with past investigations of Cretaceous sandstone bodies in the KWIS.

16. Clear economic and academic interests require a better understanding of the depositional driving-forces responsible for forming isolated sand bodies in thick transgressive shelf-muds. Despite uncertainties, autocyclic- and/or allocyclic- induced changes in accommodation strongly controlled the deposition of these enigmatic sand bodies. Nevertheless, more regional lithostratigraphic studies are required to better resolve the sequence-stratigraphic context of the Frontier Formation, and similar isolated sandstone bodies in the Western Interior.
<table>
<thead>
<tr>
<th>Facies</th>
<th>Lithology</th>
<th>Sedimentary Structure</th>
<th>Accessories</th>
<th>Ichnological Data</th>
</tr>
</thead>
</table>
| **Mo1** Offshore | *dark-grey shale (90%)*  
*Mo2 intervals (10%)*  
* slst and claystone | *lamination (c)* | * (BI=0-1)*  
*Pl. (c) -* |
| **Mo2** Bottom currents and Pelagic Fallout | *thinly bedded siliceous VF sst & bentonitic slst*  
*sst (65%), slst (35%)*  
*sst (1-5 cm), slst (3-8 cm)*  
*slst beds thin up-section* | *flat to wavy bedding (vc)* | *Slst: (BI=0)*  
*Sst (BI=0-2)*  
*Highest BI on bedding planes*  
*Pt(vc), Pl. (c), Th. (vr)*  
*Nereites (?) ichnofacies* |
| **Mo3** Offshore | *Silicified VF-F sst & slst*  
*sst (75%), slst (25%)*  
*sst (1-5 cm), slst (1-3 cm)* | *laminated*  
*sharp to gradational contacts with Mo1*  
*slst partings (c)*  
*flat to wavy lamination (c)*  
*asymmetry. ripples (c)*  
*gutter casts (vr)*  
*HCS (vr)* | *fish scales (r)*  
*plant debris (vr)* | *Slst: absent-low (BI 0-1)*  
*Sst: moderate-high (BI 0-5), average (BI 0-3)*  
*Pl. (c), Z. (m), Te. (m), Lo. (r), Th. (vr)*  
*Zoophycos ichnofacies* |

### Peay Facies Association

<table>
<thead>
<tr>
<th>Facies</th>
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<th>Sedimentary Structure</th>
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</tr>
</thead>
<tbody>
<tr>
<td><strong>P1</strong> Lower Delta Front</td>
<td>*interbedded VF-F sst &amp; sltst sst (2-5 cm), sltst (1-5 cm) *sst (75%), sltst (25%)</td>
<td>*carbonaceous mudstone partings (c) *flat- to wavy-bedding (vc) *wave-modified current ripple cross-lamination (m)</td>
<td>*syneresis cracks (c) *mud drapes (m) *plant debris (vr)</td>
<td>*(BI=0-2) *diminutive traces w/ exception of surface traces. *Pl. (c), Di. (c), Th. (m), Te. (m), Lo. (r), &amp; Ne. (r). stressed proximal Cruziana ichnofacies</td>
</tr>
<tr>
<td><strong>P2</strong> Middle Delta Front</td>
<td>*tabular F-M sst w/ sltst partings *sst (10-50 cm), sltst (1-3 cm) *sst (90%), sltst (10%)</td>
<td>*flat to low-angle stratification (c) *interference ripples (c) *climbing wave ripples (m) *gutter casts (r) *small TXB (r) *HCS (c)</td>
<td>*syneresis cracks (c) *plant debris (m) *chert granules (r) *shell hash (vr)</td>
<td>*(BI=0-4) *Th. (c), Ta. (c), Pl. (c), Op. (m), Di. (m), Cy. (r), Gy. (r), Lo (r), Co. (?)(r), &amp; claw marks (r) Cruziana and Skolithos ichnofacies</td>
</tr>
<tr>
<td><strong>P3</strong> Upper Delta Front</td>
<td>*HCS F-M sst (100%) *beds 3-5 cm thick</td>
<td>*wavy bedding (c) *flat to low-angle stratification (vc) *HCS (vc)</td>
<td>*(BI=0-2), largely absent *Op. (r), Di (r) -</td>
<td></td>
</tr>
<tr>
<td><strong>P4</strong> River Mouth/Mouth bar</td>
<td>*flat-stratified F-M sst. *beds 15-20 cm thick</td>
<td>*TXB (c) *HCS (m) *interference ripples (m)</td>
<td>*siderite nodules (vc) *chert granules are present in sst beds</td>
<td>*(BI=0-2) *Di. (c), Op. (c), Pl. (c), Lo (m), Co. (?) (vr) Skolithos ichnofacies</td>
</tr>
<tr>
<td><strong>P5</strong> Delta Abandonment</td>
<td>*1.5 m coarsening up sequence *tabular 10-30 cm thick sst beds</td>
<td>*asymmetrical ripples (c) *interference ripples (c) *syneresis cracks (r)</td>
<td>*chert lag on top bedding surface</td>
<td>*(BI=0-3) *most traces on rippled surfaces *Di (m) &amp; Pl. (m) Skolithos (?) ichnofacies</td>
</tr>
</tbody>
</table>

**Table 2.** Physical and biogenic sedimentary structures of the Peay Facies Association. Co.-* Conichnus, Cy.-* Cylindrichnus, Di.-* Diplocraterion, Gy.-* Gyrochorte, Lo.-* Lockeia, Ne.- Nereites, Op.-* Ophiomorpha, Pl.-* Planolites, Ta.-* Taenidium, Te.-* Teichichnus, & Th.-* Thalassinoides.

### Sub-X Facies Association

<table>
<thead>
<tr>
<th>Facies</th>
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</tr>
</thead>
<tbody>
<tr>
<td><strong>SX1</strong> Distal delta front</td>
<td>*slst coarsening upward to interbedded F-M sst and sltst beds. * sst (2-3 cm, up to 5-10 cm) *sltst (5-10 cm) *sst (25%), sltst (75%)</td>
<td>*laminated slst *wavy bedding (c) in sst *HCS (r) *Interference ripples (vr)</td>
<td>*syneresis cracks (vr) *plant debris (r) *chert-granule lag on top surface</td>
<td>*(slst; (BI=0-2) * Pl. (c) &amp; Di. (r) *Sst: (BI 1-3) *Pl. (c), Te. (m), Cy. (r), Ro. (r), Ph. (r), Fu. (vr), Lo. (vr), Na. (vr), surface traces (vr) Archetypal Cruziana ichnofacies</td>
</tr>
</tbody>
</table>

**Table 3.** Physical and biogenic sedimentary structures of the Sub-X Facies Association. Cy.-* Cylindrichnus, Fu.- Fugichnia, Lo.-* Lockeia, Na.-* Navichnina, Ph.-* Phycosiphon, Pl.-* Planolites, Ro.-* Rosselia, & Te.-* Teichichnus.
### Alkali Facies Association

<table>
<thead>
<tr>
<th>Facies</th>
<th>Lithology</th>
<th>Sedimentary Structure</th>
<th>Accessories</th>
<th>Ichnological Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1 Distal Prodelta</td>
<td>*Dark grey shale interbedded with VF sst</td>
<td>*finely laminated siltstone (vc)</td>
<td>*(BI=0-2)</td>
<td>*(Pl. (c))</td>
</tr>
<tr>
<td></td>
<td>*sst more common at unit top. *shale (3-4 cm), sst (3-4 cm) *shale (60-90%), sst (10-40%)</td>
<td>*unconsolidated sand intervals</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>*shale (60-90%), sst (10-40%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>*finely laminated siltstone (vc)</td>
<td>*wave ripples</td>
<td>*(Pl. (c))</td>
<td></td>
</tr>
<tr>
<td>A2 Distal Delta front</td>
<td>*Thinly interbedded silt st. and VF sst. coarsening upward to VF-F sst</td>
<td>*variable proportion of sst- &amp; sltst</td>
<td>*(BI=0-4)</td>
<td>*(Pl. (m), Th. (m), Sch. (vr), Z. (m), Rh.? (vr), As. (r))</td>
</tr>
<tr>
<td></td>
<td>*sst (2-4 cm), sltst (3-5 cm) *sst (50%), sltst (50%)</td>
<td>*flat to low-angle stratification</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>*variable proportion of sst- &amp; sltst</td>
<td>*wave ripples</td>
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<tr>
<td></td>
<td></td>
<td>*sulphur staining</td>
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<td></td>
<td></td>
<td>*syneresis cracks</td>
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<tr>
<td></td>
<td></td>
<td>*coarsens up to Mi4</td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td>*Carbonaceous shale beds</td>
<td></td>
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</tr>
<tr>
<td>A3 Proximal Delta front</td>
<td>*well cemented VF-M sst. *10-50 cm thick *sst (95%), outsized clasts (5%)</td>
<td>*TXB (m) *flat to low-angle stratification (c) *HCS (r) *sole marks (r) *interference ripples (r)</td>
<td>*chert granules-pebbles distributed throughout</td>
<td>*(BI=0-4)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>*variable structure and thickness</td>
<td>*(Pl. (c), Di. (c), Th. (m), Pl. (m), Gv. (m), Cm. (m), Ta. (m))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>*most bioturbation on bedding surface</td>
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<td></td>
<td></td>
<td></td>
<td><strong>Skolithos ichnofacies</strong></td>
</tr>
<tr>
<td>A4 transgressive lag</td>
<td>*C-VC sst &amp;/or well-rounded chert to pebble clasts. *May be matrix or grain supported *20-70 cm thick</td>
<td>*flat to low-angle stratification (c) *interference ripples (c) *wavy bedding</td>
<td>*Multiple coarse-grained intervals</td>
<td>*(BI=0)</td>
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</tbody>
</table>


### Torchlight Facies Association

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>T1 Upper Shoreface</td>
<td>*F sst (100%) *beds commonly 2-5 cm, up to 1 m *weathers recessively *facies 2-5 m thick</td>
<td>*flat to low-angle stratification (c) *HCS (r)</td>
<td>*mudchips *rare quartz pebbles along upper contact</td>
<td>*(BI=0)</td>
</tr>
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<tr>
<td>T2 Fluvial Channel</td>
<td>*F-M sst *3-7 meters thick *incomplete thickness</td>
<td>*flat to low-angle stratification (c) *TXB (c) *interference ripples (m)</td>
<td>*local chert granules</td>
<td>*(BI=0)</td>
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<tr>
<td>T3 Transgressive Lag</td>
<td>*chert and andesite clast-supported conglomerate. *granule to cobble *well-rounded *40 cm thick</td>
<td>*erosional lower contact *low-angle crossbeds (vr)</td>
<td>*rarely in situ</td>
<td>*(BI=0)</td>
</tr>
</tbody>
</table>

**Table 5.** Physical and biogenic sedimentary structures of the Torchlight Facies Association.
Recurring Facies Association

<table>
<thead>
<tr>
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<th>Ichnological Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>* chert granule- pebble conglomerate</td>
<td>* interference ripples (r)</td>
<td>-</td>
<td>(BI=0)</td>
</tr>
<tr>
<td>Upper Shoreface</td>
<td>* petrified wood fragments (r)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>* well-rounded clasts</td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>*2-3 cm thick</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F2</td>
<td>* bentonite interval</td>
<td>* popcorn weathering</td>
<td>-</td>
<td>(BI=0)</td>
</tr>
<tr>
<td>Bentonite Bed</td>
<td>*1-2 m thick</td>
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<td></td>
<td>* up to 15% fine siliciclastics</td>
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</tbody>
</table>

Table 6. Physical and biogenic sedimentary structures of the Recurring Facies Association.
The regional extent of these candidates needs to be verified prior to classifying them as sequence boundaries. Between two and four parasequences, represented by coarsening upward successions (Kirschbaum et al. 2009). Sections are hung from the Clay Spur Bentonite (CSB) located in the porcellanite interval of the Mowry Shale. Quality of exposure varies between localities and is...
REFERENCES


