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Fluvial and Sequence Stratigraphy Analysis of the Hell Creek and Fort Union Formations to Test Models for Sedimentation Across the Cretaceous-Paleogene Boundary in Makoshika State Park, Glendive, Montana

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by

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ABSTRACT

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Under the Supervision of John L. Isbell

The Cretaceous-Paleogene Boundary outcrops extensively throughout Makoshika State Park in Glendive, Montana. A distinct change in sedimentation style occurs across the Cretaceous- Paleogene in the Williston Basin deposits found in eastern Montana and western North Dakota. The well documented Hell Creek Formation of the Upper Cretaceous period consists of fresh and brackish water influenced deposits on the western low-lying coast of the Western Interior Seaway. The overlying Fort Union Formation consists of coals and fluvial sandstone deposits. Geologic explanations for the depositional shift include tectonic forces of the Sevier/Laramide Orogeny to the west, The Cretaceous-Paleogene Extinction Event, and the advancement and retreat of the Cannonball Sea to the east. At several locations throughout Makoshika State Park in Glendive, Montana, the Hell Creek and Fort Union Formations are characterized by the incision of large paleovalleys. The appearance of the incised valleys and their channel fill suggests the change in sedimentation style is due to a change in base level associated with regression and transgression of the Western Interior Seaway. This study uses

sequence stratigraphy to test the fundamental forces leading to a shift in the depositional environments of the Cretaceous- Paleogene and to add to a more complete record of the Williston Basin deposits of Eastern Montana and Western North Dakota.

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My kind and patient advisor and mentor John Isbell

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And my wonderful Mom and my Dad who never got a chance to read this.

1. INTRODUCTION

Makoshika State Park located in Glendive, Montana (see Figure 1) is known for excellent preservation of Late Cretaceous vertebrate fossils contained in the Hell Creek Formation as well as extensive outcroppings of the Cretaceous-Paleogene (K-Pg) boundary. The K-Pg boundary records the mass extinction that famously wiped out the dinosaurs among many other types of faunas and floras. The overlying Fort Union Formation caps the uplands and highest buttes in the park and provides a window into the environments of the Paleocene epoch of the early Paleogene Period of the Cenozoic Era (see Figure 2).

The Hell Creek Formation in the Williston Basin of eastern Montana and western North Dakota, including strata in Makoshika State Park, consists primarily of fluvial channel and well-drained floodplain deposits of sandstone, siltstone, and shale with occasional marine and brackish marine intercalations (Fastovsky, 1987; Murphy et al., 2002). A distinct change in sedimentation style occurs across the K-Pg Boundary where overlying strata of the Fort Union Formation is comprised primarily of variegated fine grained deposits (alternating shale and siltstone with some fine-grained sandstone beds), coal beds, sandstones, and siltstones (Fastovsky, 1987; Murphy et al., 2002). These units were deposited in mixed lacustrine, poorly-drained fluvial floodplains including mires, and fluvial channel environments with occasional interbedded deposits of brackish and marine influence (Fastovsky 1987; Fastovsky and McSweeney, 1987). At several locations throughout Makoshika State Park, strata of the lower Fort Union Formation are cut by a local, erosionally-based, thick sandstone unit that forms a major cliff forming unit in the park. Additionally, locations within the Hell Creek Formation may also display an erosionally-based sandstone that cuts into strata below.

Three main hypotheses have been proposed to explain the changes in depositional style across the K-Pg Boundary. The first suggests that fluctuations in relative sea level of the Cannonball Sea, located just to the east resulted in an elevated water table, which lead to lacustrine development of the Fort Union floodplains (Fastovsky and McSweeney, 1987; Fastovsky and Sheehan, 1994; Johnson et al.,2002). The second hypothesis suggests that Laramide tectonism and lithospheric loading to the west resulted in changes in the position of the shoreline and changes to the position of the water table (Catuneanu et al., 2000), and a third hypothesis suggests that the loss of land plants across the boundary resulted in increased erosion, which lead to aggradation within fluvial channels, increased overbank flooding, and ponding of waters on the floodplains (Sheehan et al., 2004; Fastovsky et al., 2008).

The intended goals of this thesis are to: 1) document the changes in environments that influenced sedimentation across the Cretaceous-Paleogene boundary, 2) identify the nature of the thick local sandstone units in the park, and 3) to test hypotheses on the cause(s) of the change in sedimentation across the K-Pg boundary.

1.1 Background

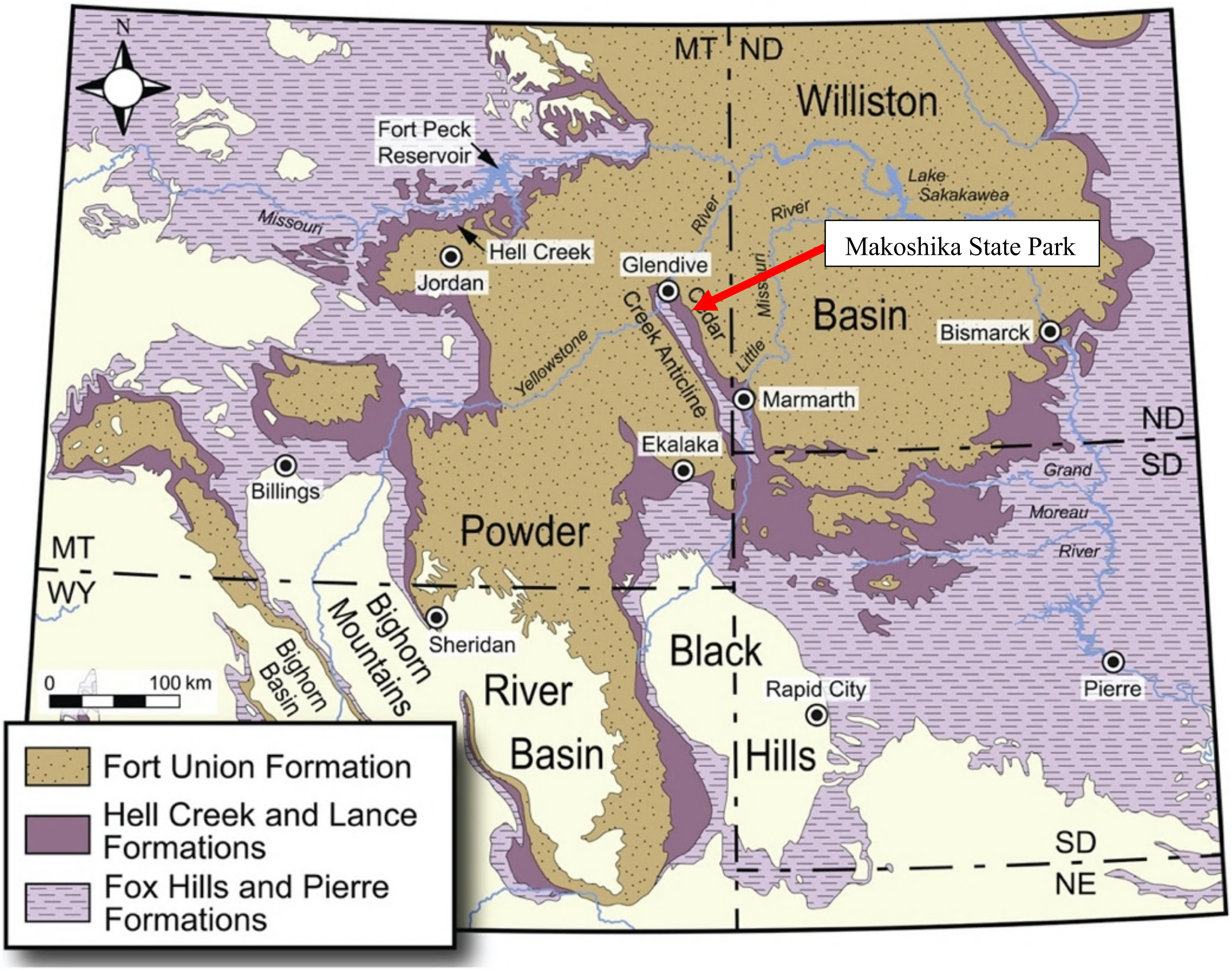

Figure 1 Geologic map of the Williston and Powder River basins including Hell Creek Formation and Fort Union Formation deposits. Makoshika State Park (see red arrow) is located on the Cedar Creek Anticline on the western margin of the Williston Basin. (Fastovsky, 2015, Redrawn from Hartman, 2002).

This study continues the extensive work done by past studies conducted throughout the Williston Basin. Previous work includes descriptions of the Cretaceous-Paleogene boundaries dating back to 1856. The earliest identification of the Fort Union member as Tertiary deposits comes from Meek and Hayden's description of Williston Basin deposits (Hayden, 1856; Meek, 1862). Later Barnum Brown first described the Hell Creek Formation and separated it from the overlying Fort Union Formation (Brown, 1907). Additional studies, including more recent work describe the lithologic (Fastovsky 1986; Murphy et al., 2002), stratigraphic (Hicks et al., 2002; Nichols and Johnson, 2002), and paleontological records of these strata (Sheehan et al, 2000).

The Williston Basin of Montana and North Dakota contain clastic deposits eroded off uplifted blocks of the Laramide Orogeny to the west (Hartmann and Kirkland, 2002). Clastics from these uplands prograded eastward across a low-gradient coastal plain (Fastovsky 1987; Fastovsky and McSweeney, 1987) before interfingering with transgressive and regressive marine deposits of the Western Interior Seaway. This seaway extended north to south from the Gulf of Mexico to the Arctic Ocean and stretched from central North Dakota into Iowa and Minnesota during the Late Cretaceous and Early Paleocene (see Figure 2; Fastovsky and McSweeney, 1987; Fastovsky and Sheehan, 1994; Peterson 1986). Much of this history is recorded by Cretaceous-Paleogene strata in Makoshika State Park, located in Glendive, Montana (see Figure 1) exposed due to the park in relation to the Cedar Creek Anticline.

The sedimentology and paleoenvironments have been described in the past by the numerous studies investigating the abundant fossil record of the dinosaurs in this region. The Cretaceous-Paleogene boundary marks a mass extinction event that among other species, wiped out the non-avian dinosaurs. Across this boundary, the depositional environment also shifts abruptly from well-drained fluvial floodplains to a flooded landscape dominated by lacustrine deposits (Fastovsky, 1987).

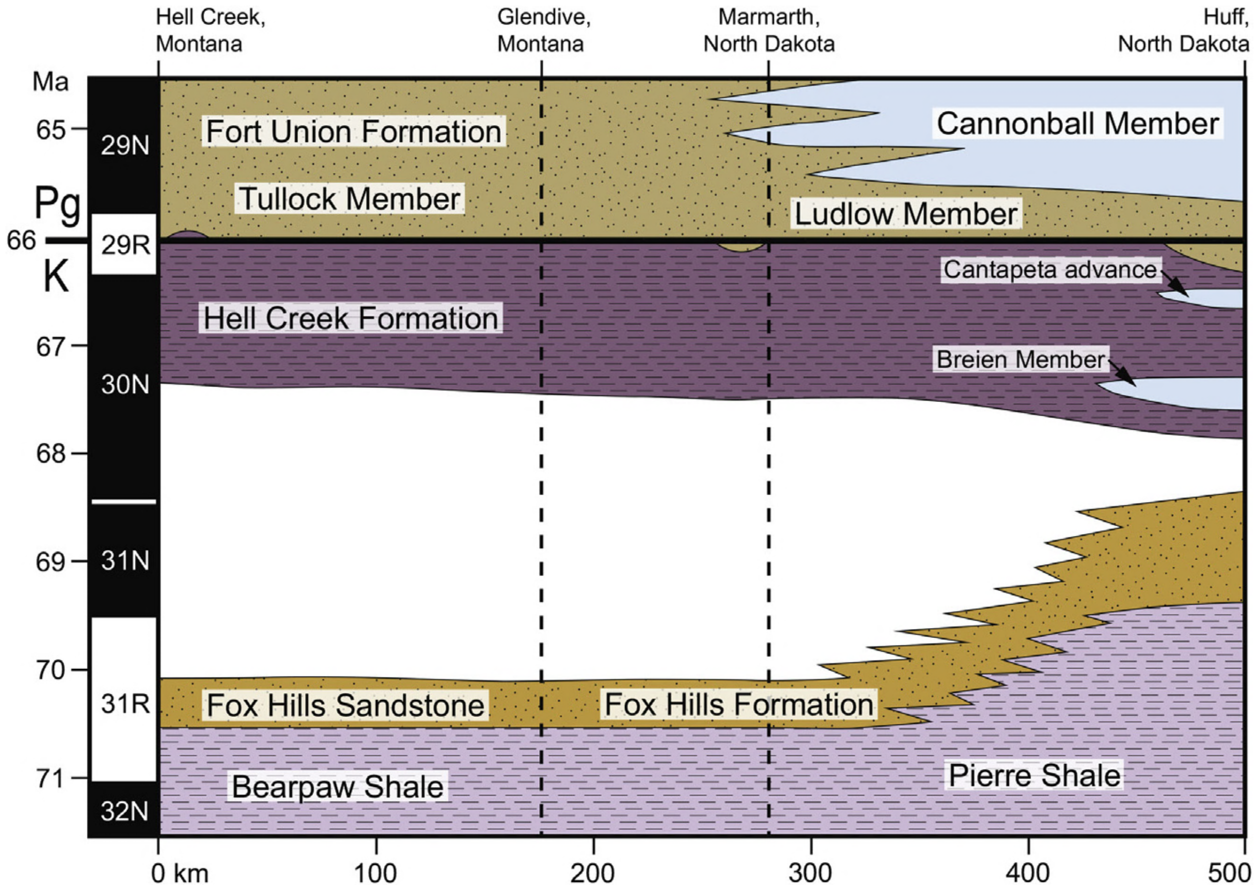

Figure 2 Time space diagram showing interfingering of the marine influenced Western Interior Seaway deposits of the east and the clastic Laramide Orogenic deposits to the west. The white section separating the Fox Hills Sandstone and the Hell Creek Formation represents a hiatus (Fastovsky, 2015, Redrawn from Johnson et al., 2002).

Throughout Makoshika State Park and adjacent areas, the Upper Cretaceous deposits of the Fox Hills Formation are dominated by marine deposits transitioning to coastal fluvial deposits at the top of the Fox Hills and overlying Hell Creek formations. Deposits of the Fox Hills Formation approximately date to 71.5 Ma to 67.5 Ma (Macauley, 1964), and range in thickness from 30 to 152 m. Lithologically, this unit contains white to grayish fine- to medium-grained argillaceous sandstone (Meek and Hayden, 1861). Fox Hill Formational deposits can be found in eastern most Montana and North and South Dakota (see Figure 1). The deposits of the of the Fox Hill are interpreted as being marine deposits of the Western Interior Seaway (Anna, 1986; Jenkin, 1990) at the base and transitions into non-marine strata at the Colgate Member (see Figure 2), found near Makoshika State Park, at the top. The Colgate Member has been

interpreted as shallow tidal influenced marine and non-marine fluvial deposits, (Murphy et al., 2002, referencing Waage, 1968). The Upper Cretaceous deposits of the Hell Creek Formation dates from 67.5 Ma to 65.5 Ma (Macauley, 1964) and preserve the sediments deposited by fluvial systems draining the young Rocky Mountains uplifting in the west during the Laramide phase of orogenesis (Peterson, 1986). Lithologically, Hell Creek Formation deposits contains fine- to very fine-grained white sandstones interbedded with drab gray and purple hued mudstones containing bentonite clays that have weathered to a popcorn-like texture. Weakly developed paleosols can be observed associated with the mudstones (Fastovsky, 1986, 1987; Murphy et al., 2002). In the region of Makoshika State Park, the Hell Creek Formation has been interpreted as aggradational, high sinuosity fluvial systems draining the Rocky Mountains to the west during the Laramide Orogeny (Peterson, 1986).

By contrast, the overlying Lower Paleogene strata of the Fort Union Formation lithologically consists of abundant multi-colored laminated siltstones that have been described as variegated beds (Archibald, 1982). The variegated beds were deposited through the suspension settling of fine-grain particles in quiet waters such as lacustrine and peat-forming environments (Fastovsky, 1987). Widespread but discontinuous coal and lignite beds can also be found within the Fort Union Formation. The formation of the variegated beds highlights a change in deposition style from the well-drained landscape deposits of the Hell Creek Formation to the poorly-drained landscape represented in the Fort Union Formation deposits (Fastovsky and Dott, 1986; Fastovsky, 1987). Isolated fluvial deposits cutting through the variegated beds have been described in the literature, but their origin is not well understood (Fastovsky and Dott, 1986; Bercovici et al., 2009). This study also documents fluvial deposits resting on an incision surface that cuts downward through the lower most Fort Union Formation and the sandstone and shale

beds of the upper Hell Creek Formation (see Figure 3). Photographs show similar incision surfaces also exist in the Hell Creek Formation.

Figure 3 Picture of paleovalley consisting of Hell Creek Formation deposits overlaying the variegated bedding and incising shales and sandstones of the Fort Union Formation deposits.

This study examines the changes that occurred across the Hell Creek – Fort Union contact and uses sequence stratigraphy to test the scenarios that caused the abrupt shift in sedimentation style across that boundary. As mentioned previously, three main scenarios are hypothesized to have driven the change in depositional style across the boundary. These are: 1) transgression of the Cannonball Sea, 2) tectonic loading during the Laramide Orogeny, and/or 3) the K/Pg extinction event.

The first scenario suggests that a rise in sea level associated with a marine transgression of the Cannonball Sea resulted in a rise in the water table leading to a gradually flooded landscape covered by widespread shallow lakes and ultimately marine units (Fastovsky and Sheehan, 1994; Johnson, 2002; Johnson et al., 2002). This change would have recorded a gradual change in accommodation space, a change in fluvial style, and an increase in fine-grained lacustrine facies through time as accommodation gradually changed due to the rising base level (transgressive Cannonball Sea). Changing paleosols (dry soils going to wet soils), and an increase in coal abundance and seam thickness through time would also be expected. Additionally, if associated with the base level fluctuations of the Cannonball Sea, a cyclical

pattern of transgressive and regressive deposits may occur with development of multiple incised valley fills associated with drops in base level (falling eustatic sea levels).

The second scenario suggests that the rise of the Rocky Mountains during the Laramide Orogeny resulted in tectonic loading to the west and an increase in accommodation in the foreland basin (Catunaenu et al., 2000). In this scenario, the change in accommodation space would be gradual at a near constant rate over a long timescale (Catuneanu et al., 1997), and the associated deposits would be similar to the transgression scenario, however, the highest accommodation in the basin would be to the west with decreasing subsidence/accommodation to the east, with possible stream incision across an upwarping forebulge associated with flexural loading by the orogenic belt. Stream paleoflow direction might be observed as shifting westward depending on the location of the foreland basin or a shallowing trend and coarsening grain-size across the boundary depending on the location of the forebulge. Incision of streams into a rising forebulge would be expected with a reversal of stream flow with drainage off of the rising forebulge back to the west toward the developing foredeep (Flemings and Jordan, 1990).

More recently, both Sheehan and Fastovsky (Sheehan et al. 2004; Fastovsky et al., 2008) suggested a scenario in which the bolide impact of the Cretaceous-Paleogene mass extinction event (Alvarez et al. 1980) led to a loss of vegetation throughout western North America resulting in an increase in erosion across the landscape (Sheehan, 2004; Fastovsky, 2008). This theory states that the thermal blast associated with the bolide impact would have ignited forest fires across western North America (Robertson et al., 2004). Additionally, the following nuclear winter caused by debris from the bolide in the atmosphere would severely damage vegetation globally. The loss of vegetation would increase runoff and erosion of clastics choking streams with sediment. Widespread flooding would occur due to the choked streams overflowing their

banks. The resulting sediments would represent a relatively instantaneous change in the depositional environment and would likely show no signs of the gradual change that may be seen with the geologically slower transgression and tectonic loading theories. The impact induced flooding hypothesis would also have been a single event and long term cyclicity would not occur in this scenario.

This study will use the collected observations and data and their associated interpretations to test the three stated hypothesis and attempt to suggest the likelihood of one hypothesis being the main driving factor to the change in depositional style across the K-Pg Boundary. The results of this study will increase our understanding, especially in the terrestrial realm, of a much studied and important time in our planet's history. In the attempt to add to our understanding of the history and deposition of the late Cretaceous and early Paleogene Williston Basin, the following questions will be asked:

1. What sedimentary facies existed within the Hell Creek Formation deposits of Makoshika State Park? Once the facies are identified, they will be used to interpret the depositional environments of the Late Cretaceous as they relate to testing of the three hypotheses.
2. What sedimentary facies existed within the Fort Union Formation deposits of Makoshika State Park? Once the facies are identified, they will be used to interpret the depositional environment of the Early Paleogene as they relate to testing of the three hypotheses.
3. How do the facies change across the Cretaceous-Paleogene boundary within Makoshika State Park? Once, a change is identified, the principles of fluvial and sequence stratigraphy will be applied to the observed evidence to test the three

main hypothesis and identify the main driver causing a change of sedimentation across the boundary.

By addressing the above questions this study will test the three hypotheses to gain a more fully resolved understanding of the landscape evolution associated with the K-Pg Boundary along the western margin of the Williston Basin.

2. Methods

In July of 2008 a study was conducted by a three-person team consisting of Quintin Bendixen, John Isbell, and Lori Voelker at Makoshika State Park in Glendive, Montana. The team collected data both physical and observational over a seven-day period. The study primarily focuses on the uppermost portions of the Hell Creek Formation and the overlying Fort Union Formation studied at five separate locations within the park. The field work consisted of the collection of rock samples, photographing outcrops, sketching outcrops, collection of sedimentological data, and measuring outcrops with a 1.5 meter Jacob Staff with an Abney Level for the construction of a total of 8 stratigraphic columns. The sedimentological data collected consisted of lithology, grain size using hand lens according to Nichols (1999), sedimentary structures and paleocurrent direction using a Brunton Compass and plotted on stereonets using https://geographyfieldwork.com/RoseDiagramCreator.html and Rick Allmendinger's Stereonet 11 www.geo.cornell.edu/geology/faculty/RWA/programs/stereonet.html. Sandstone bodies deposited within river channels were classified as single or multistory sandstone bodies according to Gibling (2006) (Figure 4). A story is defined as an erosional based package of sediment. Multistoried bodies are characterized by multiple erosional based packages cutting into underlying packages all stacked at different levels within a composite sedimentary body. Such

multistoried sediment packages typically occur where channel sandstone bodies are filling former depressions or incised valleys and the deposits are stacked vertically (Gibling, 2006; Gibling et al., 2011). Changing channel deposit stacking patterns, the occurrence of incised valleys, and the deposition of thick floodplain deposits are used in this thesis to indicate changing rates of accommodation within depositional basins (Jervey, 1988; Shanley and McCabe, 1994; Gibling et al., 2011). Accommodation represents the space available to

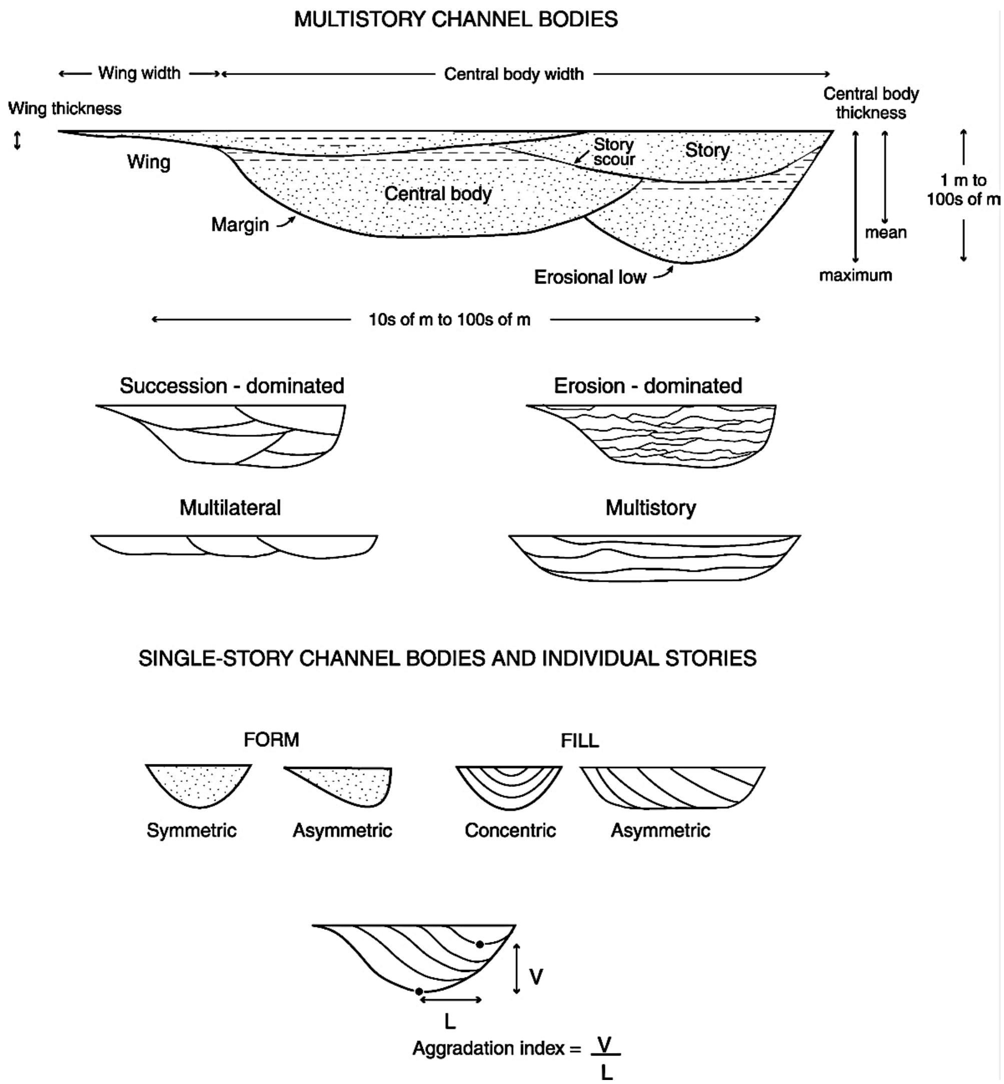

Figure 4 Terminology for describing the cross-sectional geometry of channel bodies from Gibling (2006)

deposit sediment and is the sum of the space created/destroyed by basin subsidence/uplift and base level (sea level) rise and fall (Emery and Myers, 1996; Catuneanu, 2006). Accommodation

space can be either positive represented by depositional settings or negative represented by net erosional settings (Jervey, 1988). Photographs were taken at each site along with descriptions of the “big picture”. Samples were collected for further analysis. Measurements, observations, and collections were taken from five sites located throughout Makoshika State Park (see Figure 5). The study sites are the informally named Valley (Site 1) located at 47°03.956'N 104°41.486'W, the informally named Valley Amphitheater (Site 2) located at 47°03.833'N 104°41.411'W, the Amphitheater (Site 3) located at 47°03.899'N 104°40.469'W, Eyeful Vista (Site 4) located at 47°03.791'N 104°40.053'W, Sand Creek Overlook (Site 5) located at 47°01.211'N 104°38.118'W, Valley View (Site 6) 47°02.881'N 104°41.417'W and the informally named ELP (Site 7) located at 47°04.969'N, 104°42.263’W. The majority of data collected comes from Site 1 with a total of seven stratigraphic columns titled VA-VF constructed along the Site 1 location (see Figure 3). Additional observations were made throughout the Site 1 area describing and documenting the nature of strata there as to better understand the nature and causes of a thick lenticular sandstone that extended for several hundred m across the area at this site. The data were used to first reconstruct the depositional environments of the Hell Creek Formation. Second, the data from the overlying layers were used to interpret the depositional environments of the Fort Union Formation. By comparing the environments of the two stated formations, the evidence was used to test the three hypotheses stated in the introduction in an attempt to better understand the cause(s) that resulted in the change of depositional style across the K-Pg boundary and its causes along the western margin of the Western Interior Seaway in what is now Makoshika State Park, Montana.

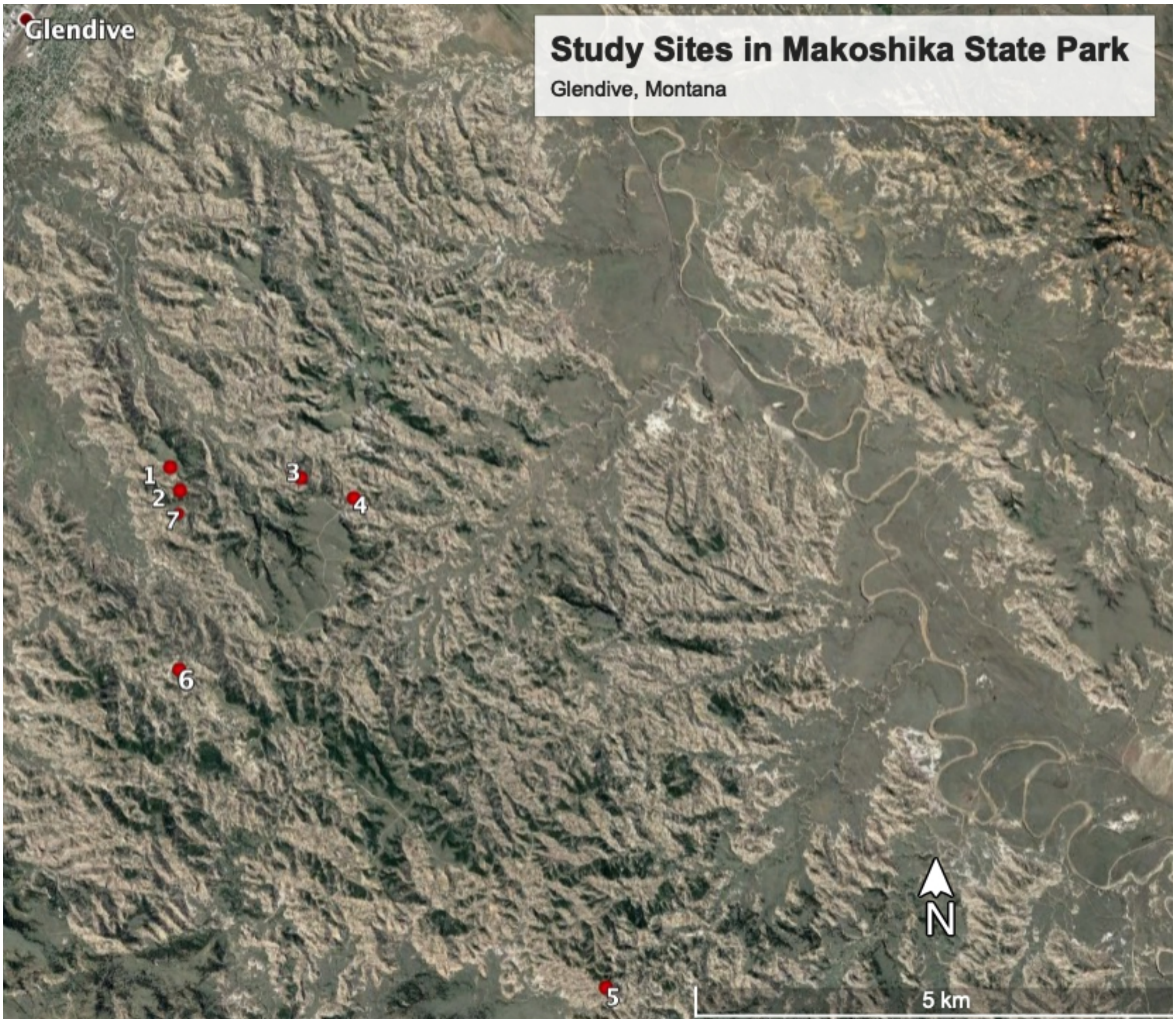

Figure 5 Location of Makoshika State Park. Main areas of study plotted in red.

3. Upper Hell Creek Formation

The Hell Creek Formation is exposed in Montana, North Dakota, and South Dakota (see Figure 1), with equivalent units known as the Lance Formation in Wyoming and the Frenchman and Scollard formations in Canada. Accurate thickness measurements across the basin have been difficult due to lateral discontinuity of beds, units being thicker than topographical relief, weathering of bentonitic surfaces, and the difficulty in identifying the upper contact (Johnson et al., 2002). Thickness estimates range from 170 m in Garfield County, Montana (Brown, 1907) down to 41 m in McCone County, Montana. From east to west, the Hell Creek Formation

extends nearly 700 km (Johnson et al., 2002). The easternmost deposits of the Hell Creek Formation interfinger with marine deposits related to the transgressive and regressive cycles of the Western Interior Seaway described as the Breien Member and the Cantapeta marine advances (Murphy et al., 2002) as seen in Figure 6, which may have influenced deposits within Makoshika State Park.

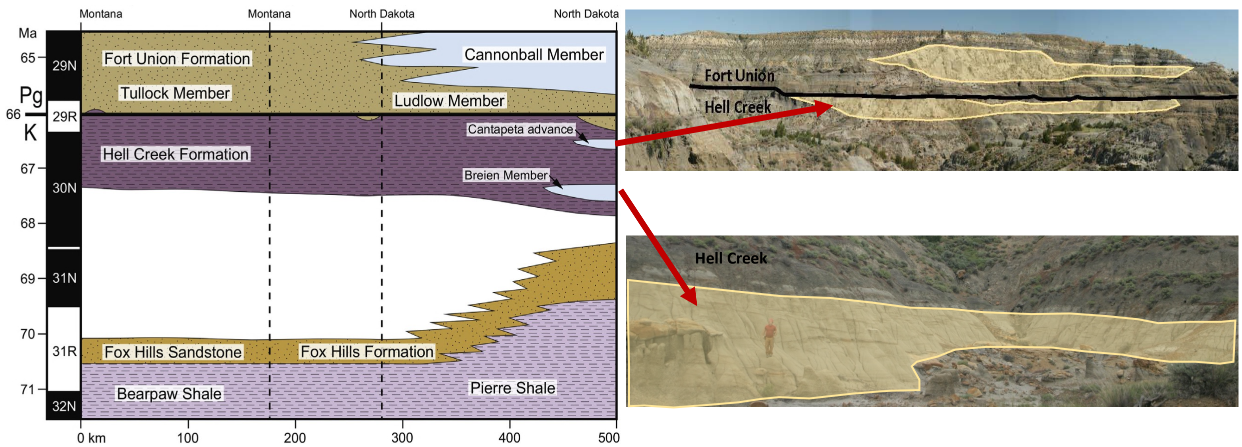

Figure 6 Photographs of incised valleys in the Hell Creek Formation as they relate to Figure 2's Stratigraphy of Maastrichtian formations, northern Great Plains, USA. (Fastovsky, 2015, Redrawn from Johnson et al., 2002).

The upper Hell Creek Formation of Makoshika State Park consists of three facies as shown in Table 1 and includes: 1) fine- to medium-grained cross stratified sandstones 2) very-fine- to fine-grained thin sheet to lenticular sandstones and 3) laminated fine-grained deposits of siltstones and mudstones. Although common throughout the park, the measured and described sections in this study include only the top ~1 – 12 m of the upper Hell Creek deposits. However, the formation was observed and photographed at multiple sites.

Facies Association	Lithologies	Sedimentary Structures	Interpreted Transportation Mechanisms	Depositional Environment
Cross Stratified Sandstone	Medium- to fine-grained sandstone	Single- and Multistoried channels with lateral accretion and cross bedding	Unidirectional flowing water	Meandering and valley confined streams
Thin sheet to lenticular sandstone	Very-fine- to fine-grained sandstone	Laminations and rare ripple cross-bedding	Lower flow regime	Crevasse splays
Laminated Fine-grained Sediment	Mudstone and siltstone	Vertical accretion with horizontal laminations	Settling from suspension	Floodplains/wetlands

Table 1 Hell Creek Formation Facies in Makoshika State Park

3.1 Cross-Stratified Sandstone

Figure 7 Photo example of cross-bedded sandstone (cross-bedding highlighted in yellow) at Site 6 within the Hell Creek Formation. Person for scale.

3.1.1 Description

Between 30% and 40% of the upper Hell Creek Formation consists of fine- to medium-grained sandstone deposits (Fastovsky, 1987). Although only a few meters of upper Hell Creek sandstone were measured for this study, reconnaissance work and photographs indicate that the sand bodies range from a few meters to over 30 m in thickness (Murphy et al., 2002) and can be

found at different stratigraphic levels (see Figures 9, 11, and 12) throughout the entirety of the Hell Creek Formation. The sandstone bodies rest on a low relief (1 m of relief) basal erosion surface that extends laterally for hundreds of meters across the outcrop (see Figure 8). However, due to modern weathering, erosion, and vegetation, the thicker sandstones cannot be traced for long distance within the park. The sandstones range from very-fine- to fine-to-medium-grained. Grain size fines upward in the sandstones and grading into the fine-grained laminated facies can be seen in the highest stratigraphic sand deposits (see Figure 9). Compositionally, the sandstones are lithic arenites derived from the decomposition of volcanic rocks eroded from source regions to the west (Fastovsky 1987).

Figure 8 Erosional surface marking the basal contact of the cross-bedded sandstone body of the Hell Creek Formation and the underlying fine-grained deposits (trowel for scale).

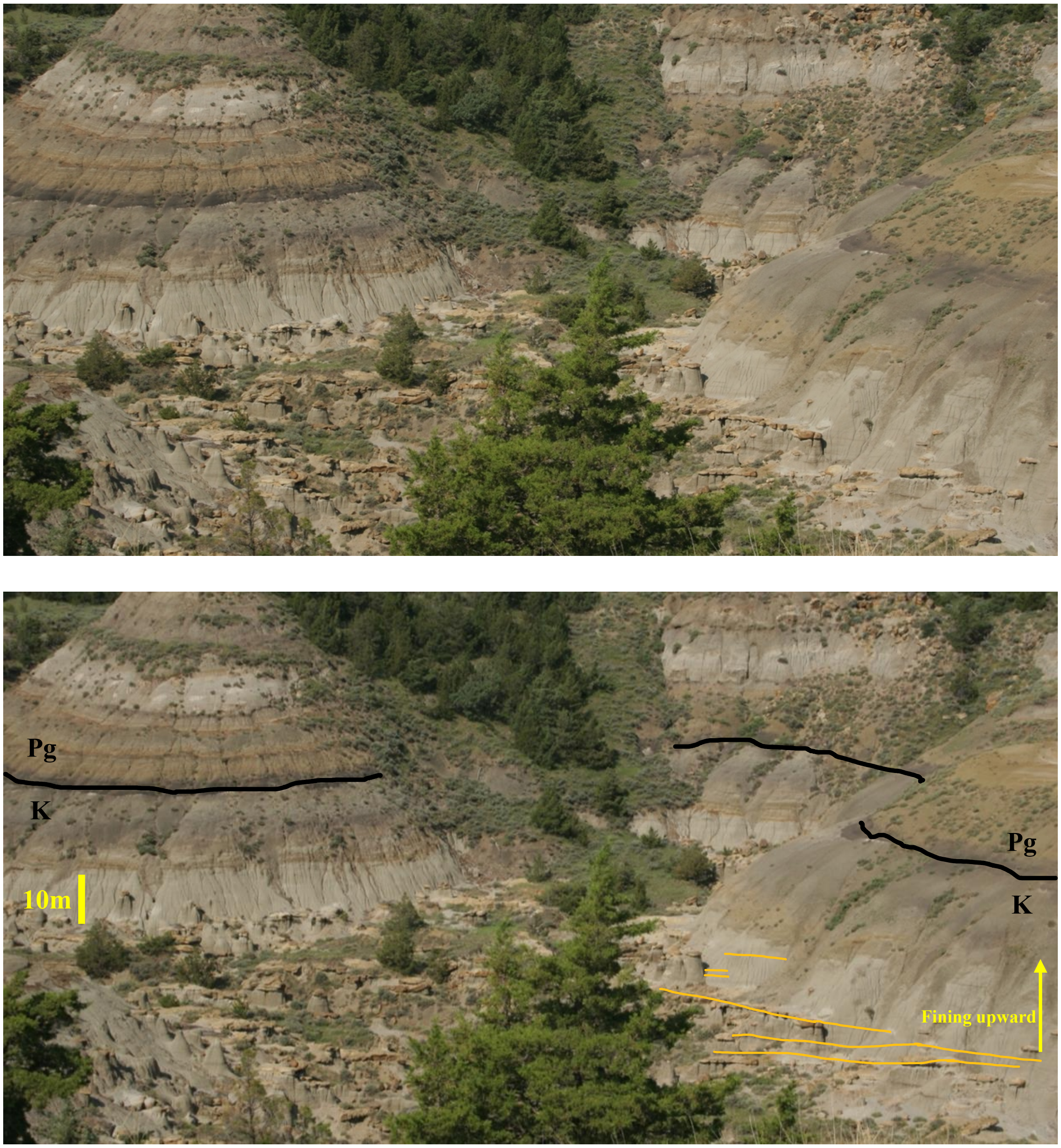

Figure 9 Photo of Hell Creek formation sandstone deposit at Site 6. Note the downlapping orange colored concretions preserved in the body (highlighted in yellow) marking possible lateral accretion surfaces. Note the fining upward at the tops of the sandstone bodies where the sandstone fines into the overlying shales. 10 m line for scale.

The cross-stratified deposits within Makoshika State Park range from 5-30 m in thickness and may appear massive due to intense weathering and/or covering by a smectitic "popcorn weathering" texture. These cross-stratified sandstones fine upward and are cross-bedded (see Figure 7). Sandstones within these deposits display lateral accretion surfaces that downlap onto basal erosion surfaces. In many places, these lateral accretion surfaces and basal erosion surfaces

define amalgamated, stacked, or multistoried (after Gibling, 2006) channel bodies (see Figure 11). The cross-stratification is typically highlighted by either concretions of secondary iron precipitation, as shown in Figure 11, or intraclastic clay-ball or plant debris (Fastovsky, 1987). Roots and root casts are abundant in this facies, as are microscopic pedogenic voids (Fastovsky and McSweeney, 1987). Paleoflow direction measurements of cross-bedding were taken at Site 7 (See Figure 12), with an average flow direction to the east-southeast at 116º. One erosional-based, thick-bodied, multistoried (at least 2 possibly 3 stories) sandstone body located 400 m north of Site 3, extends for over 500 m along an E-W trending ridge (Figure 10). This body cuts deeply into the underlying Hell Creek Formation, possibly as much as 30 m. The cliff face this body was located on was not accessible during the field study.

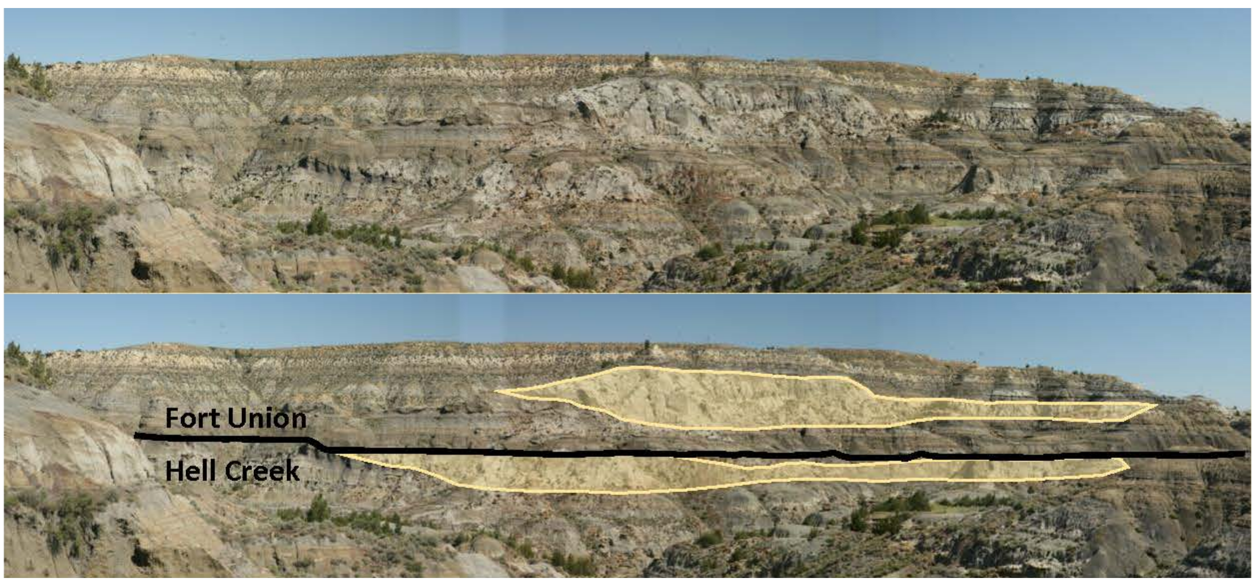

Figure 10 Incised valley in the upper part of the Hell Creek Formation north of Site 3 and in the overlying Fort Union Formation.

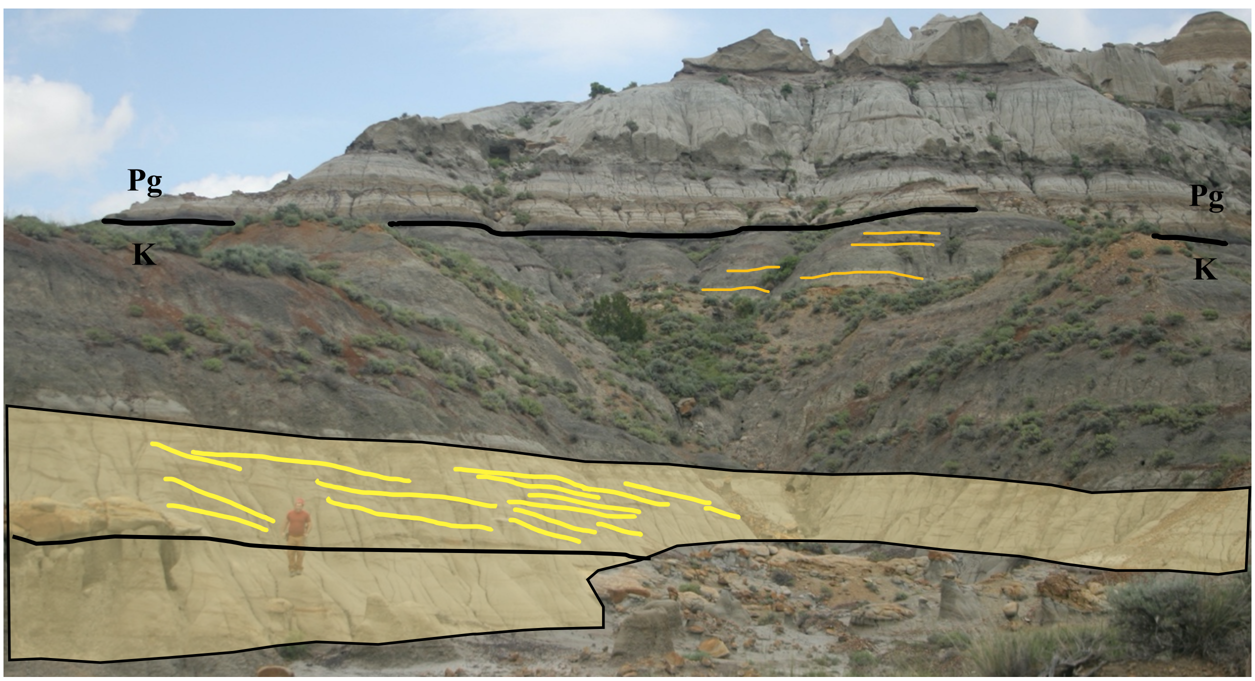

Figure 11 Photo of Hell Creek formation sandstone showing the lateral accretion (drawn in yellow) of at least two stacked channels (highlighted in yellow with black line representing contact between the two channels) and thin lenticular crevasse splay deposits (highlighted in orange). This Multistory sandstone body suggests a possible incised valley within the Hell Creek Formation. The accretionary surfaces are often highlighted by plant debris and darker mud size clasts. Person for scale.

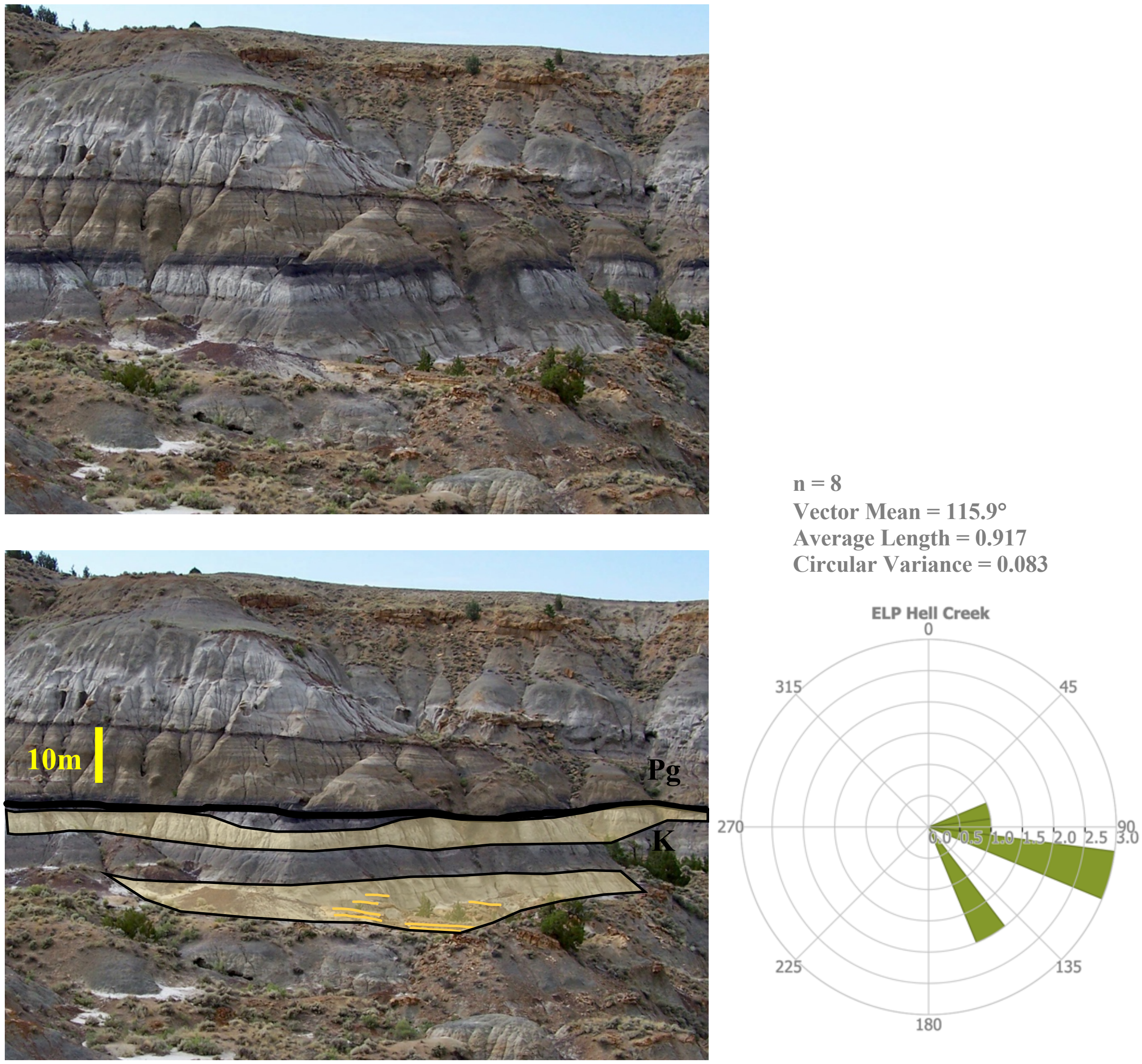

Figure 12 Photo of Hell Creek formation sandstone concretion (highlighted in yellow) paleocurrent flow direction measurements made at Site 7. Notice two sand bodies below the K/Pg boundary found at different stratigraphic levels (shaded in yellow). Paleoflow Rose Diagram average of 115.9º

3.1.2 Interpretation

Previous studies have interpreted the cross-stratified sandstones as of fluvial origin consistent with meandering river channels migrating across a floodplain (Fastovsky, 1987; Fastovsky and McSweeney, 1987; Johnson, 2002). Data collected in this study agrees with that interpretation. The thicker sandstone bodies resting on a laterally continuous erosion surfaces and containing cross-bedding are consistent with deposits of confined flow from within stream channels (Allen 1964, 1965, 1970). The occurrence of lateral accretion suggests deposition on an

inner point bar within a sinuous channel where deposition occurred on the sloping bar and a cutbank on the outer margin of the channel results in lateral migration of the channel as it migrates across its floodplain (Bridge 1975). The abundance of lateral accretion suggests deposition occurred from highly sinuous channels. Fining upward within the sandstones resulted from decreasing fluid velocity on the inside channel bend in a sinuous channel with the high velocity flow in the thalweg moving to the outside of the bend forming a cutbank on the opposite outerbank of the channel (Bridge, 2006). The geometry of the sand bodies, where stacked erosionally-based packages of lateral accretion occur, suggest channel migration back and forth across a floodplain within a confined setting and perhaps suggest that gradual filling of space within an incised valley system occurred (Gibling, 2006). Because only the upper most channel fines upward, this suggests that subsidence, or the creation of accommodation was relatively low during deposition of multistoried channel bodies in the Hell Creek Formation. The occurrence of root structures in the channels suggests that discharge fluctuations occurred over the course of deposition and that vegetation colonized the tops of some point bar deposits.

3.2 Thin Sheet to Laminated Sandstone

3.2.1 Description

Thin sheets to lenticular bodies of very-fine to fine-grained sandstone commonly occur and are typically less than 0.75 m thick, tens of meters in width, and fine laterally in the direction of paleoflow (Fastovsky, 1987). These sandstones tend to display overly sharp bases. Ripple cross-bedding occurs but is commonly obliterated by intense modern weathering (Fastovsky, 1987; Flight, 2004). The deposits typically interfinger with the surrounding laminated fine-grained facies (see Figure 11 and Section 3.3). Some of these sheets overlie channel bodies (see

thin sandstone layer at the top of the sandstone body in Figures 8 and 11). Organics and root structures were also observed within these deposits.

3.2.2 Interpretation

The thin very fine- to fine-grained sandstone deposits at the tops of channels and within fine-grained deposits that grade laterally into shale are interpreted as unconfined flows or crevasse splays as indicated by their sharp bases and gradational lateral contacts. The wedge-shape, sheet-like shape; lateral relationships with fine-grained material, and thinness of the bodies are all consistent with overbank deposition as crevasse splays (Coleman, 1969; Reineck and Singh, 1973; Elliott, 1974). Root structures in these sandstones indicates episodic sedimentation of crevasse splays and the colonization of these deposits by plants following overbank flooding (Fastovsky, 1987).

3.3 Laminated Fine-Grained Deposits

3.3.1 Description

Between 50% and 60% of the upper Hell Creek Formation is composed of siltstones (Fastovsky, 1987). Additionally, silty mudstones and mudstones occur and are described in previous works (Murphy et al., 2002; Flight, 2004). The layer's colors vary with gray mudstones predominate, but purple and green mudstones also occur (see Figure 13). The laminated fine-grained layers are typical of the Hell Creek Formation throughout Makoshika State Park. This facies is commonly weathered to a "popcorn texture" due to the dominate occurrence of clay minerals of smectite and illite within the mud sized fraction. A fresh surface reveals the planar lamination within these fine-grained layers. Occasional graded bedding was identified as well as being described in previous studies (Fastovsky, 1987). Root structures consisting of carbonized material that occurs oblique to perpendicular to bedding is common throughout the laminated

mudrocks. Throughout the upper Hell Creek Formation, the fine-grained laminated layers are also found lateral to cross-stratified sandstone facies and interfingering with thin very-fine- to fine-grained lenticular sandstones which have been documented within the park (see Figure 11) and elsewhere (Fastovsky, 1987; Flight, 2004). Laterally continuous sandstone sheets that rest on sharp to slightly erosional lower surfaces are dm- to m-scale in thickness and occur scattered throughout the mudrocks (see thin sheet sandstone facies).

Figure 13 Photo of Site 5. Notice the laminated fine-grained gray, green and purple layers towards the bottom. Hell Creek/Fort Union contact shown by the K/Pg contact to the right of the photo. 10 m line for scale.

3.3.2 Interpretation

The laminated fine-grained deposits of the upper Hell Creek Formation in the region of Makoshika State Park are interpreted as floodplain deposits, which are consistent with previous

studies (Fastovsky, 1987; Murphy et al, 2002). The laminations are a result of a very low energy regime on distal floodplains where fine-grained sediment settled from suspension as floodwaters that overtopped their channel banks receded. Slight graded-bedding ending with layers of silt are a result of the sheet-wash flooding from isolated channels (Bridge, 1984). Root structures represent colonization of these deposits by plants, where the preservation of laminations suggest that deposition occurred over intervals too short to allow for extensive development of soils. The presence of root structures and the darkened organic deposits demonstrate that pedogenic process began in the region before being buried by subsequent pulses of sheet-wash flooding. Clasts of older soils (pedorelicts) can be found contained within younger soils (Fastovsky, 1987). Fastovsky and McSweeney (1987) attribute the pedogenic features to a seasonally fluctuating water table and that seasonal flooding limited the time frame for soil development resulting in poorly formed soils (Fastovsky and McSweeney, 1987).

3.4 Depositional Environment for the upper Hell Creek Formation

Figure 14 Photo of Site 4. Notice the lenticular sand deposits interfingering the fine-grained deposits. Hell Creek/Fort Union contact shown by the K/Pg contact to the right of the photo. 20 m line for scale.

The facies of the upper Hell Creek Formation described in this study support previous interpretations of a depositional environment consistent with a broad vegetated floodplain dissected by meandering streams that often overflowed their banks (Fastovsky, 1987; Johnson, 1989). As noted by Fastovsky (1987) “Fine-grained sediments, erosive and asymmetrical channel bases, lateral accretionary deposits, and lenticular repetitive patterns of facies are all compatible with a meandering steam system (Leopold et al., 1964; Allen, 1964; 1965, 1970)”. Fastovsky (1987) described the upper Hell Creek as “a broad, low-relief, fine-grained, alluvial plain [that] was drained by southeast-directed meandering channels of moderate size. Channel migration was probably largely through avulsion, with sweeping migration being of slightly lesser significance. Fluvial sedimentation occurred in an unstable landscape with a high but fluctuating water table” (Fastovsky and McSweeney, 1987). The instability of the landscape was largely a function of channeling and periodic flooding, which scoured and redeposited flood-

plain material as rounded intraclasts in channel fills and diffuse silt and clay-sized material that settled out of suspension on flood plains. Soils that formed in flood-plain deposits typically are incipiently developed. Weak soil development, eroded horizons, and pedorelicts are all indicative of repeated erosion and deposition (Fastovsky, 1987). Fastovsky described the landscape as follows: “Despite the instability of the setting, the flood plain was richly vegetated (Johnson and Hickey, 1990; Wolfe and Upchurch, 1986) and bore localized accumulation of plant debris.” Multistoried channel sandstone bodies likely represent incised valley fills where the valley walls inhibited extensive migration of channel belts. Such features interspersed within thicker floodplain deposits indicate fluctuations in base level and the fluctuations in the rates of the creation of accommodation space (Shanley and McCabe, 1994).

4. Lower Fort Union Formation Facies

The Fort Union Formation preserves deposits from the earliest Paleogene (Paleocene). Deposits from this period are found within the Williston Basin of North Dakota, South Dakota, and Montana as well as the Powder River Basin of Montana and Wyoming, and in the Alberta Foreland Basin to the north (see Figure 1). Generally, the Fort Union is thicker to the west and thins to the east. The easternmost deposits of the Fort Union Formation interfinger with marine deposits related to the transgressive and regressive cycles of the Western Interior Seaway described as the Cannonball Member of the Fort Union Formation (Murphy et al., 2002) as seen in Figure 6. Strata of the lower Fort Union Formation, as described in this chapter are the stratigraphic equivalent to the Tullock Formation found elsewhere in Montana and the Ludlow Formation found in North Dakota (see Figure 6). In Makoshika State Park, the lower Fort Union consists of three facies as shown in Table 2 and includes: 1) Channel-filled sandstones, 2) Variegated Bedding, and 3) Organic Accumulations. The channel-filled sandstones are further

separated into Cross-stratified Sandstones, Amalgamated and Laminated Sandstones, and Deformed Sandstones. Measured sections range from 18 – 40 m thick.

Facies Association	**Lithologies**	**Sedimentary Structures/Subfacies**	**Interpreted Mechanisms**	**Depositional Environment**
Channel Sandstone	Medium- to fine-grained sand	Single- and Multistoried channels with lateral accretion and cross bedding	Unidirectional flowing water	Meandering and valley confined streams
		Amalgamated with Laminated Channel Fills	channel flow with tidal influence	Estuary deposits
		Soft-sediment Deformation	Gravity flow	Subaqueous gravitational failure
Wedge Shaped Sandstone	Fine- to very-fine-grained sand	Rippled Thins and fines laterally	Unconfined flow from overbank flooding	Crevasse splays
Variegated Bedding	Mudstone and Siltstone	Horizontal laminations	Settling from suspension in a lacustrine setting	Lacustrine
Organic Accumulations	Black Shale and Lignite	Horizontal laminations	Settling from suspension and plant growth Accumulation of organic matter in wetlands	Swamp or wetland

Table 2 Fort Union Formation Facies in Makoshika State Park

4.1 Channel Sandstone

Fine- to medium-grained sandstone commonly occurs above the variegated beds throughout Makoshika State Park and occurs in either single storied sandstone bodies associated with the variegated beds, or as an incised valley fill. Measured sections at Site 1 (A-F locations), Site 2 and Site 3 record multistoried sandstone deposits up to 25 m thick (Figures 15, 22, 34 and 35). These sandstones occur in a trough-shaped depression incised into underlying strata (incised valley fill). Other bodies such as at Site 4 are 2 to 5 m thick and represent single-story sandstones. The sandstone deposits contain the following structures: cross-stratification with cross-bedded concretions and amalgamated with laminated channel fill. Occasional shale drapes were observed on localized crossbedding and localized soft-sediment deformation and laminated sandstone clast also occur.

4.1.1 Description

Fine- to medium-grained sandstones with cross-stratification occur throughout Makoshika State Park in lower Fort Union Formation strata. Cross-stratified sandstones were observed and documented at the following locations for this study: Site 1, Site 2, Site 4, Site 5, and Site 7. Shale draping's of the cross-stratified sandstone were documented at the Site 3 location. The cross-stratified sandstones occur as both single-story and multistory sandstone deposits. Sandstones occur as single-story sandstone sheets within or overlying the mudrocks and siltstones of the variegated bed facies (see Figure 16). The upper parts of these sandstones fine upward from medium-grained to fine-grained to very- fine-grained sandstone to siltstone (see Figures 7, 15, and 22). The cross-stratified sandstones are 2 to 5 meters thick and can be traced laterally in some locations for over 100 m. Sandstones within these deposits contain lateral accretion surfaces that downlap onto basal erosion surfaces. In several places, lateral

accretion surfaces and basal erosion surfaces define stacked or multistoried channels creating wedge shaped bodies (see Figures 15 and 22). Multistoried/amalgamated bodies fill a large, incised valley that has an erosional basal contact that cuts downward through the K/Pg Boundary and into the underlying Hell Creek Formation as seen at the Site 1 location (Figures 17, 18, and 19). Stratigraphically, the lowermost sand bodies erode into the variegated beds below (see Figures 15 and 19). As shown in Figure 15, the cross-stratification is typically highlighted by either concretions of secondary iron precipitation with and without shale drapes or through downlapping sandstones. Paleocurrent measurements of the Fort Union cross-bedded sandstones show a south-east flow direction with an average orientation of 133° (see Figures 20 and 21).

Amalgamated channels are documented within the Site 2 location. They are part of the incised valley fill. These sandstones are constructed with multiple stacked concave-upward erosive surfaces that cut into each other (see Figure 23). Individual channels measure up to 5 m thick and extend laterally for at least 30 m before being cut out by overlying erosional surfaces. In the Site 1 location, the basal erosional surface cuts into the variegated bedded facies below. The channels are filled with siltstone to fine-grained sandstone containing ripple cross-stratification (see Figure 24) as well as horizontally-laminated channel-fill strata consisting of rhythmic sandstone-shale couplets which appear towards the top of the channels (see Figure 25). Contacts range from the erosional contacts of the cross stratified amalgamated channels to the sharp contacts of the laminated fill, which drape onto sandstones lower in the channels.

Figure 15 Site 2 wedge shaped sand bodies of the Fort Union Formation (highlighted in yellow) with lateral accretion shown by downlapping concretions and shale draping (yellow lines mark concretions and dashed black lines mark shale draping). Person for scale.

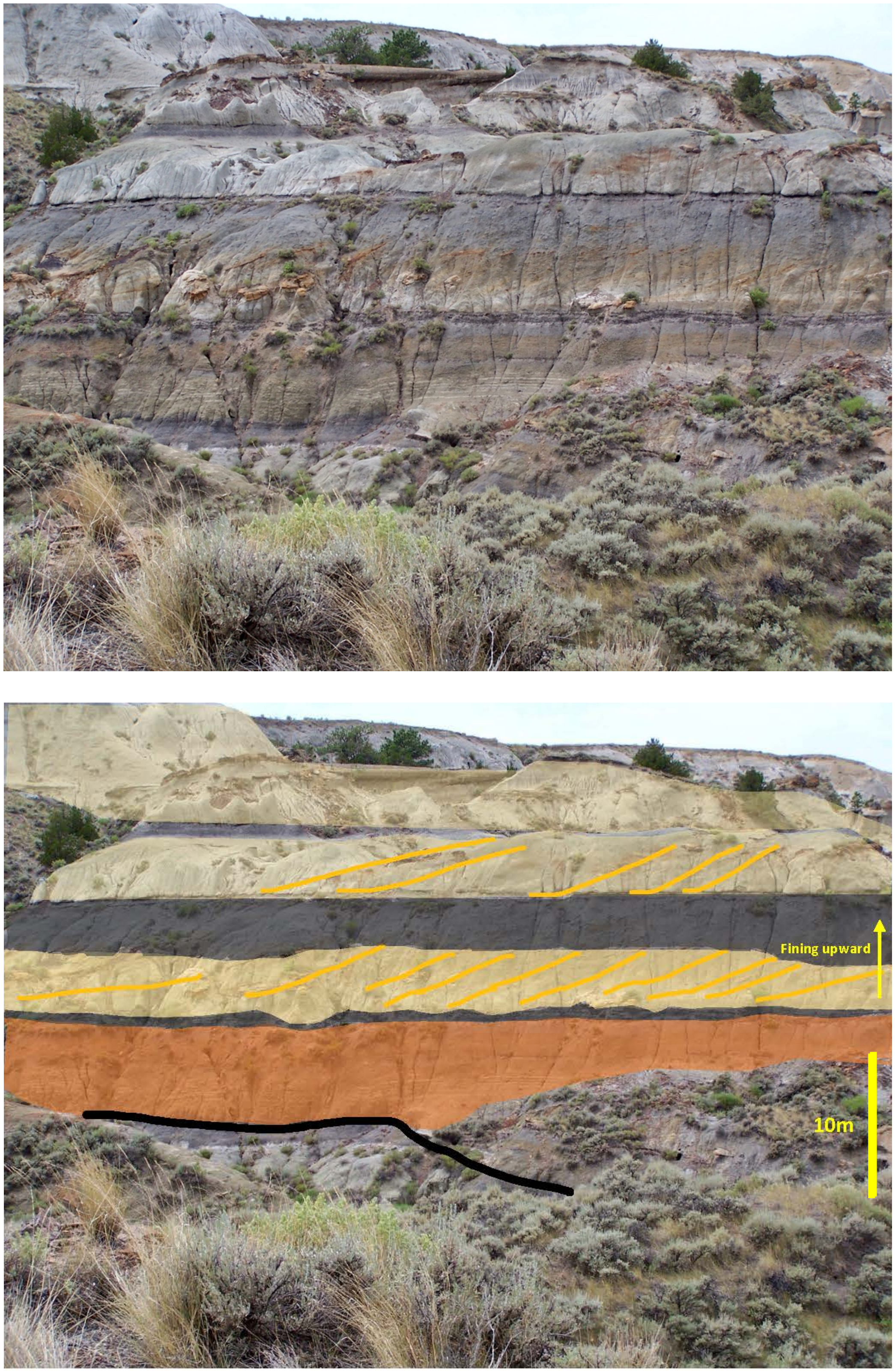

Figure 16 Photo of Site 4. Notice the two single-story sheet sandstones separated by shale with downlapping lateral accretion (highlighted in yellow). Both sandstone bodies overlay a thin layer of organic-rich shale (highlighted in grey). The lower sandstone fines upward into shale. Variegated bedding (highlighted in orange) overlays the lowermost laterally extensive coal, seen as lignite here (highlighted in black) marks Hell Creek/Fort Union contact. 10 m marked for scale.

Figure 17 Photograph of sandstone basal erosion contact with the lignite marking the K/Pg Boundary (see marking). Backpack for scale.

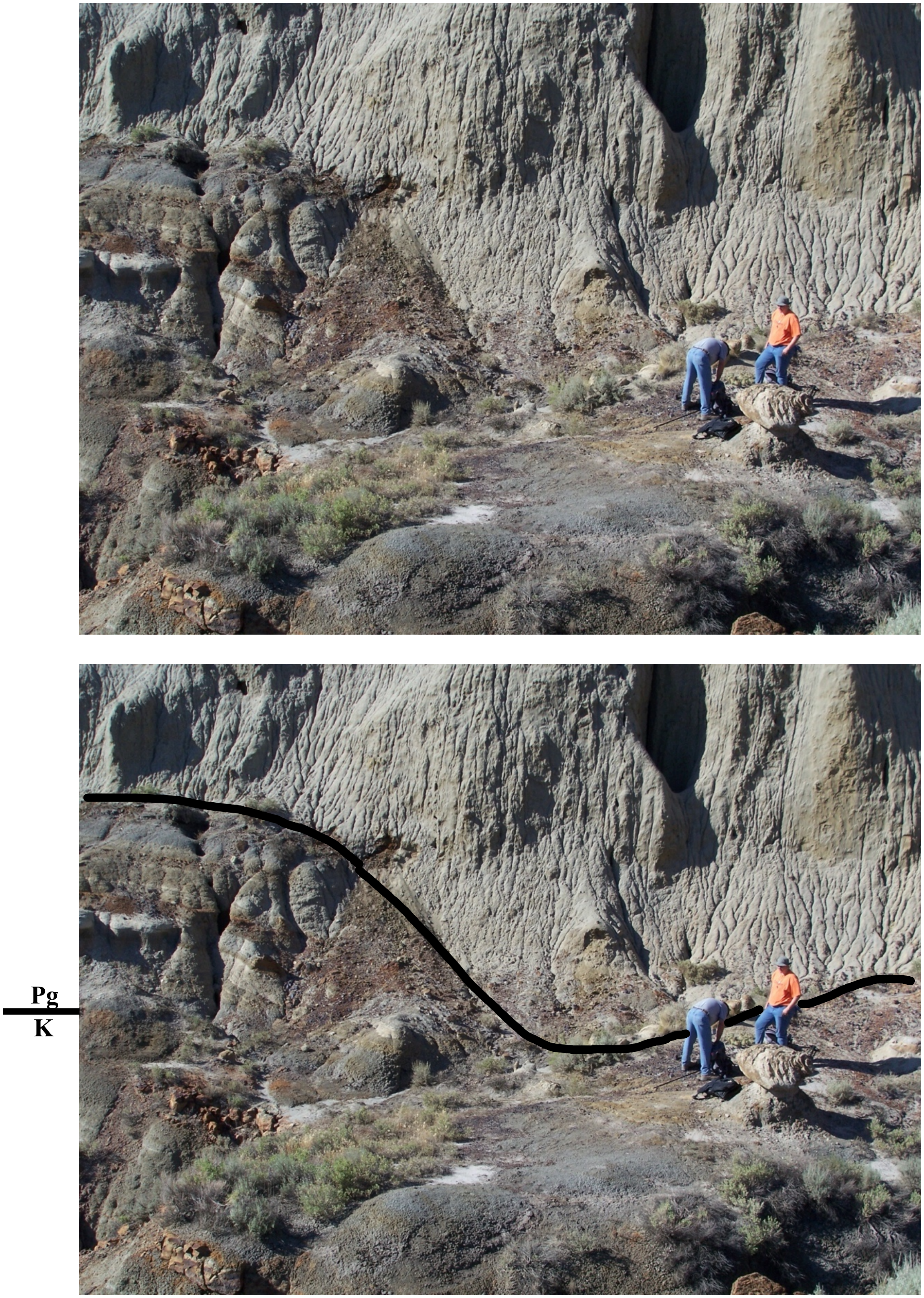

Figure 18 Photograph showing basal erosion of cross-stratified sandstone through the variegated bedding down through the K/Pg Boundary (marked on the left). People for scale.

Soft-sediment deformation was observed in association with the laminated fill (see Figures 23, 27, 28, and 29). Deformed layers of laminated deposits occur at the Site 2 location. The deformed clasts consist of the laminated fine-grained sandstones and shale described above. This soft-sediment deformation occurs as slump blocks (see Figures 27 and 28) and flame structures (see Figure 29). The slump blocks consist of angular clasts up to 1.75 m in diameter of alternating wavy bedded fine-grained sandstones and organic-rich mud rhythmites. The clasts are surrounded by medium-grained sandstone. One of the clasts contains folded sediment preserving an overturned fold nose (see Figure 28). The flame structures measure up to 25 cm in thickness. They consist of near-vertical alternating wavy bedding of fine sands and organic mud drapes (see Figure 29). The soft-sediment deformed layers are overlaid by stacked amalgamated channels.

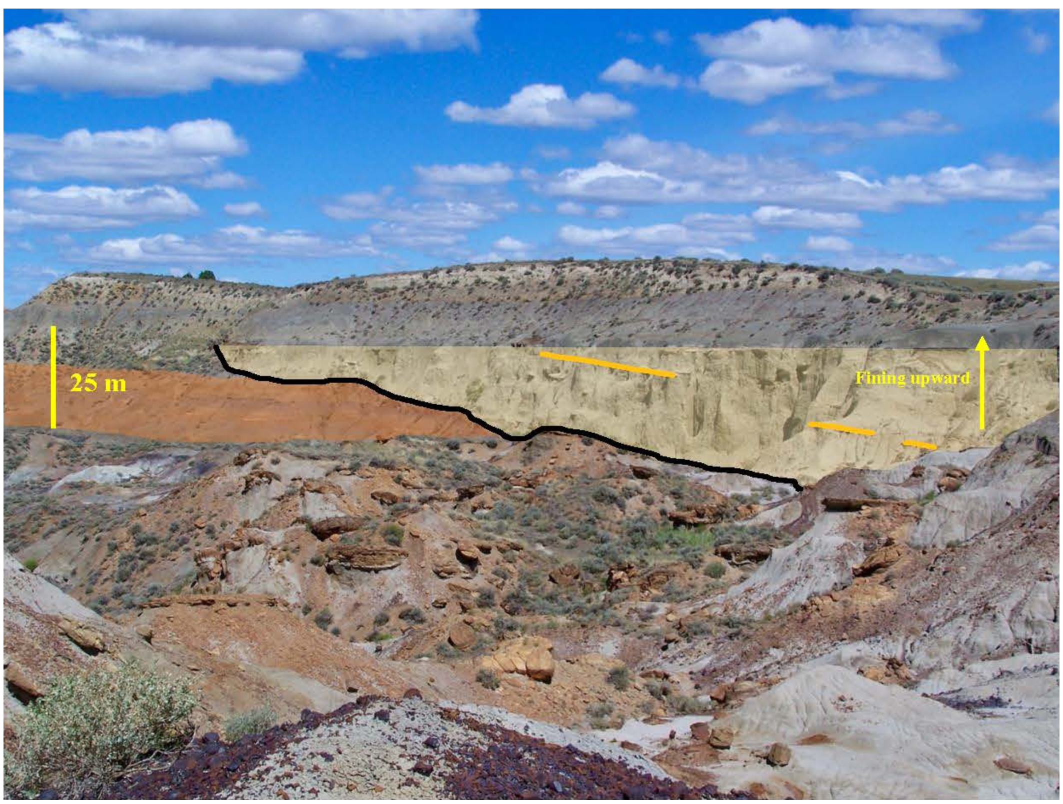

Figure 19 Photo of the Site 1 location showing cross-stratified sands (highlighted in yellow with lateral accretion in orange) eroding through the variegated bedding (highlighted in orange). Erosional surface marked in black. Scale marked on the left.

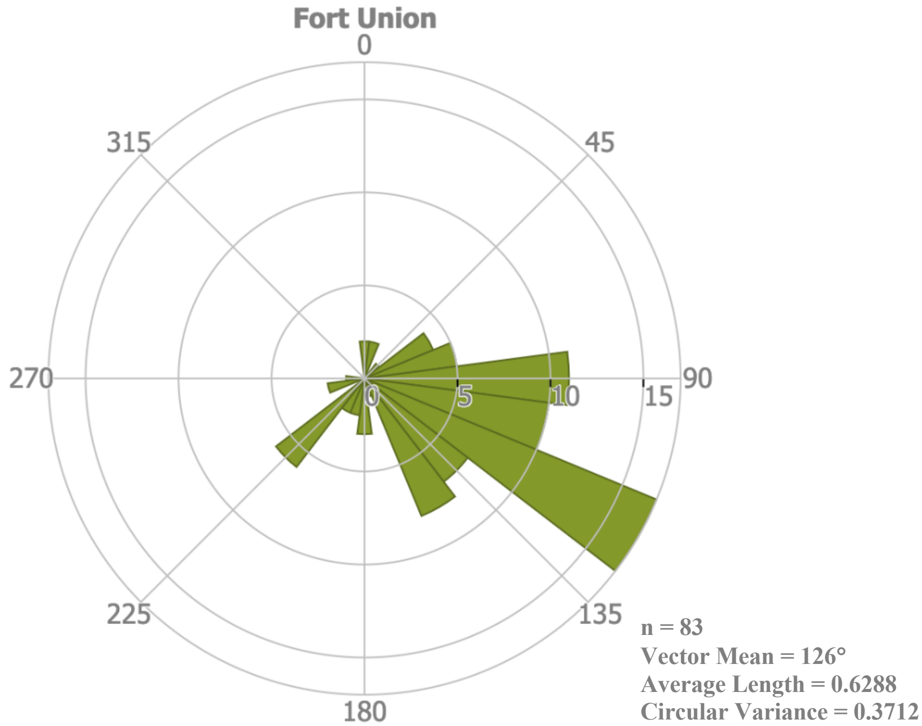

Figure 20 Rose diagram of the Fort Union measured paleoflow directions with an average of 126°.

Figure 21 Photo of cross-bedded sandstone at Site 3. Person measuring paleocurrent directions for scale. Average paleocurrent in this location were ~124 degrees. Paleocurrent measurements of the Fort Union cross-bedded sandstones throughout Makoshika State Park show a south-east flow direction with an average of 133°.

4.1.2 Interpretation

As with the upper Hell Creek cross-stratified sandstones, thick sandstone bodies resting on laterally continuous erosion surfaces and containing cross-bedding are consistent with deposits of confined unidirectional flow within fluvial channels (Allen 1964, 1965, 1970). The geometry of the sandstones are present in both single-story and multistory channels.

The single-storied channels represent the migration of sinuous meandering streams in a high accommodation setting across their floodplains resulting in the deposition of the inner point bar forming the observed lateral accretion deposits. During stream migration, a decrease in fluid velocity produced when the high energy of the streams cut bank is followed in sequence by the decreasing energy of the streams point bar side of the meander, which results in progressively finer material being deposited in an upward fining succession within the single-story sandstones (Allen 1964).

The multistoried sand bodies were observed as amalgamated channels and stacked packages of lateral accretion resting on basal erosion surfaces (Figures 22 and 23). The stacked packages of laterally accreting sandstones represent channels migrating back and forth, in a lower accommodation setting across a confined floodplain in an incised valley, resulting in a stacking of channel bodies (Shanley and McCabe, 1994).

The rhythmites, laminated rhythmic sandstone-shale couplets, that fill the channels in the upper portion of the sandstone channels contain laminations consisting of alternating sands and muds suggesting deposition from fluctuations in flow perhaps influenced by tidal activity (Nio and Yang, 1991). Further evidence of a tidal influence can be found in the alternating thickening and thinning pattern within packages of the couplets bounded by thicker sandstone layers, which are similar to rhythmites deposited under spring to neap tidal influence (Nio and Yang, 1991;

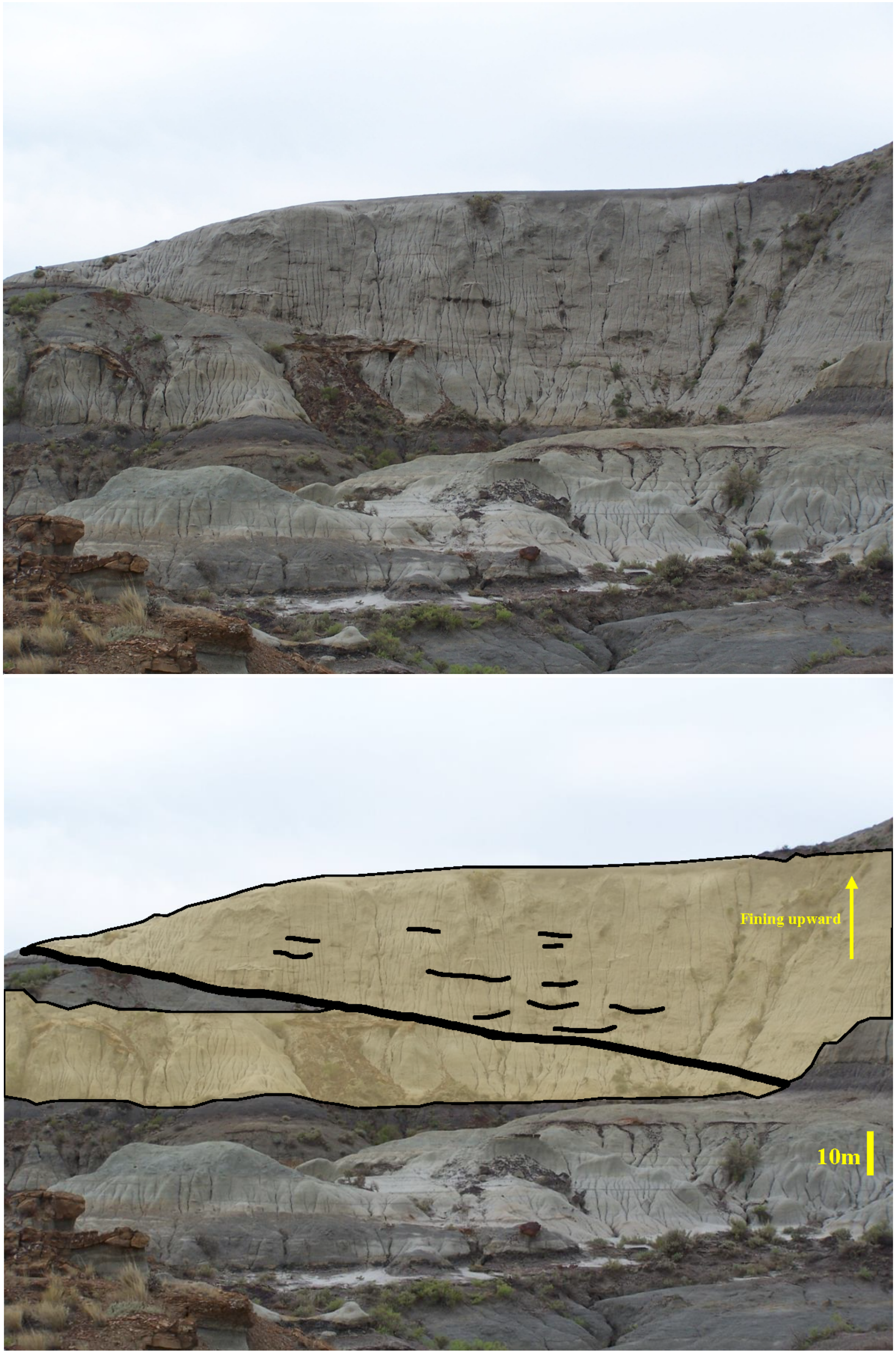

Figure 22 Photo of Site 4 demonstrating stacked channeling. The upper channel's incision is marked by the bold black line and scours are marked by mostly concave black lines. The amalgamation shown may be associated with the large incised valley described in the Site 1 and Site 3 locations. 10 m marked for scale.

Figure 23 Photo of Site 2 demonstrating amalgamated channel fill. The amalgamated channels' scours are marked by the yellow lines. Soft-sediment deformation of laminated layers can be seen in the lower left sand body. 10 m marked for scale.

Archer, 1995; Boyd et al., 2006). A tidal influence implies that portions of these stacked, fluvial sandstones were deposited within a lower coastal plain setting, most likely within an estuarine succession. Estuaries are environments that receive sediment from both fluvial and marine sources, and are influenced by tide, wave, and fluvial processes during transgressive successions (Boyd et al., 2006; Dalrymple et al., 1992).

The deformed layers are a result of soft-sediment deformation in a water saturated environment. The deformed deposits found at Site 2 are formed when unlithified laminated layers behaved plastically. The flame structures likely form through the dewatering of underlying sediments as water was trapped by the sediment associated with the bank collapse and this water escaped upward through the sediment shortly after sedimentation. When denser wet sediments are loaded on top of less dense water saturated underlying sediment, the added weight will force fluids to escape upwards through the overlying layers (Reineck and Singh, 1980). The clast with a fold nose is characteristic of the failure and collapse of unlithified layers (Reineck and Singh, 1980). In conjunction with the flame structures, it is interpreted that the slumping occurred subaqueously resulting in the internal deformation of the clasts.

Figure 24 Photo of the rippled cross-stratification channel fill found within the amalgamated channels of Site 2. Rock hammer for scale.

Figure 25 Photo of laminated layers at the Site 2 location. Meter stick for scale.

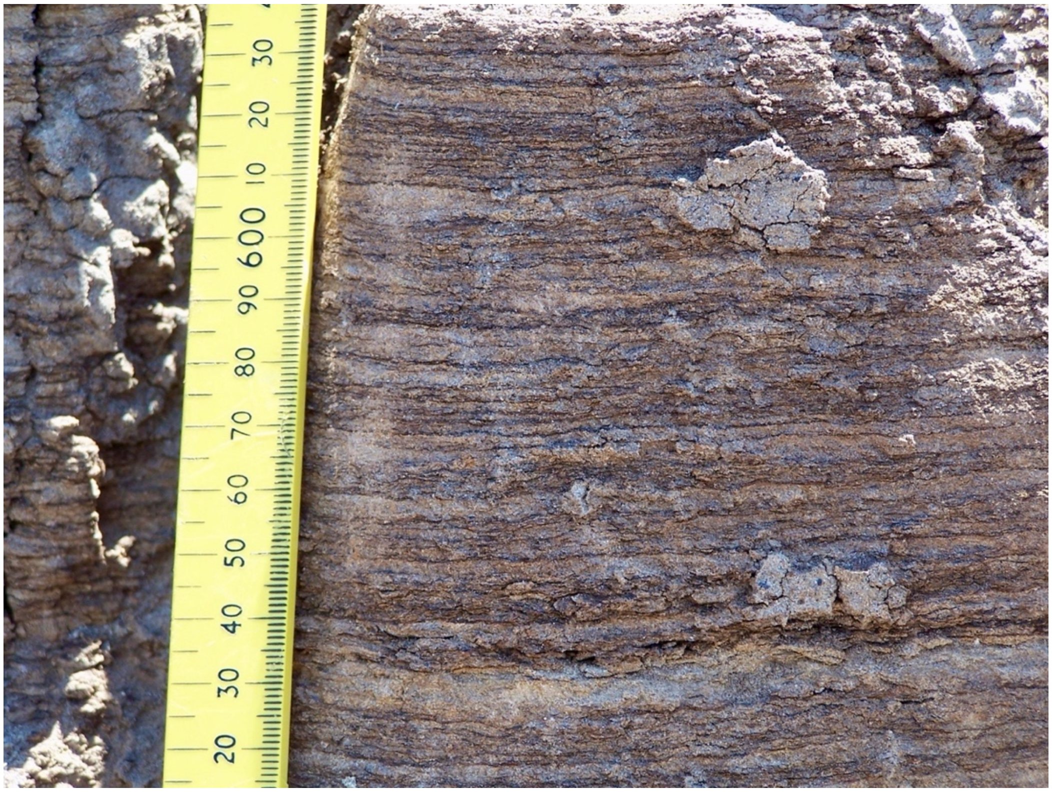

Figure 26 Close-up photo of the rhythmites of laminated layers at the Site 2 location. Meter stick for scale.

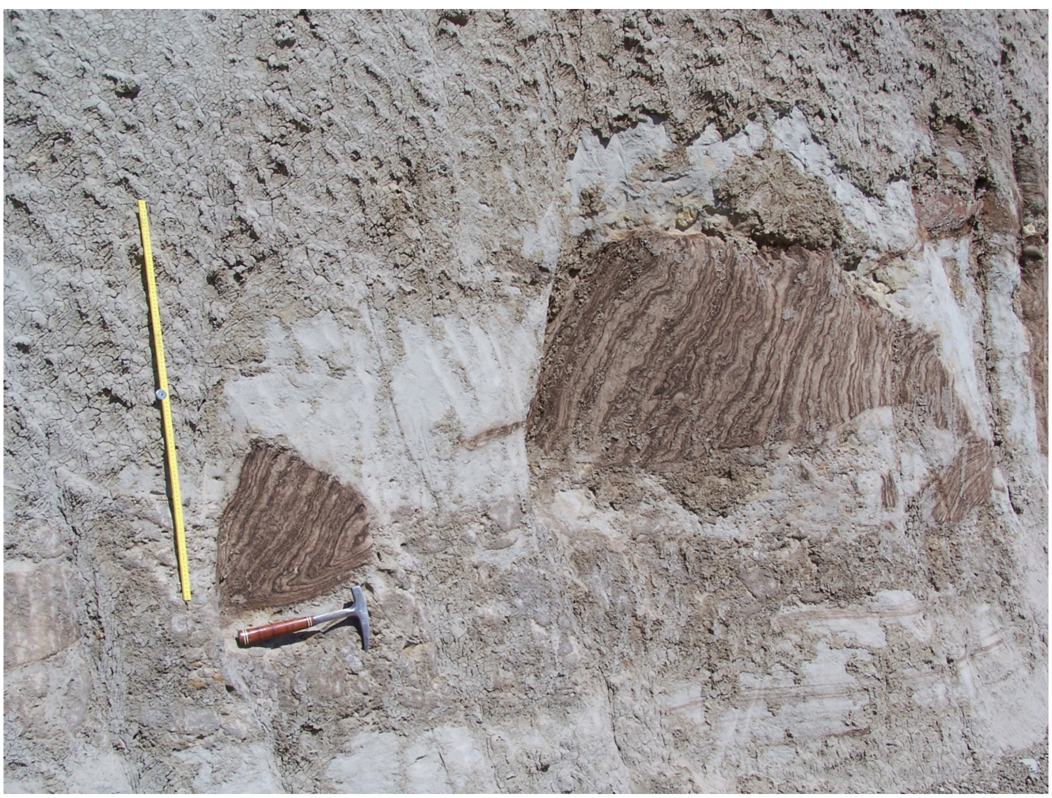

Figure 27 Photo of slump block measuring 1.75 m thick located in Site 2. Rock hammer and meter stick for scale.

Figure 28 Close-up photo of sandstone clast containing an overturned nose in Site 2. Rock hammer and meter stick for scale.

Figure 29 Close-up photo of flame structures in Site 2. Meter stick for scale.

4.2 Wedge-shaped Sandstone

4.2.1 Description

Isolated, very-fine- to fine-grained, wedge-shaped sandstones that thin laterally in the direction of paleoflow were documented in locations including at Site 5, Site 6, and Site 7 (see Figures 30, 31 and 32). The sandstones consist of 2 to 5 meter-thick wedges of sandstone that can be traced laterally over 100 m. They often occur as low-angle dipping beds that downlap onto underlying deposits. These downlapping beds typically thin and fine across outcrop faces in the direction of downlap. They exhibit sharp or erosive lower contacts and sharp or interfingering upper contacts within the variegated facies (see Figure 31). Ripples were observed at Site 5 and Site 6 but were rare. Within the wedge shaped sandstones, grain size fines both upward and laterally in the direction of thinning from fine- to very-fine-grained sandstone.

4.2.2 Interpretation

The thin very-fine-grained sandstone deposits interfingering with the variegated beds are unconfined flows interpreted as crevasse splays as indicated by their sharp bases and gradational lateral contacts (Coleman, 1969). Fining upward and laterally in crevasse splays occur as the unconfined flow decreased in velocity as it spreads laterally and through time as flood waters receded. The crevasse splays can be attributed to the overbank flooding of the sinuous migrating streams, described in section 4.1.

4.3 Variegated Bedding

Figure 30 Photo of Site 6 Overlook. Note that the sand layers (white beds) in the Variegated layers just above the basal coal representing splays that interfinger with the lake deposits.

4.3.1 Description

A distinctive banded, iron-oxide-stained, fine-grained facies termed the "variegated" beds by Archibald (1982) occurs in exposures of the lower Tullock (Ludlow) member of the Fort Union Formation located just above the biostratigraphic K-Pg boundary (Fastovsky, 1987), which is described as the lower-most continuous lignite bed described in the organic facies below. In relation to the sandstone facies described above, the variegated beds occur both stratigraphically below and above the multistory channel sandstone facies in Sites 1 and 3 (see Figure 34). The variegated beds are composed of thin laminated siltstone, gray mudstones,

claystone, and thin very-fine-grained sandstones with occasional crushed plant material. Variegated beds are continuous for distances of over 10 km (Fastovsky, 1987). The variegated facies occur interbedded with the organic accumulated layers and lignite in the lower most sections of all the measured lower Fort Union members within Makoshika State Park (see Figure 31). Fossils of articulated aquatic-vertebrate remains and aquatic plants (C. Hotton, 1986) occur within the variegated beds. The facies can be found extensively throughout the park and offers a contrast in color to the underlying upper Hell Creek layers.

4.3.2 Interpretation

Fastovsky (1987) interpreted the variegated beds as "extensive, quiescent pond deposits." Fine laminae of plant detritus, clay, and silt were deposited by suspension settling. The inference of low-energy, ponded water is supported by the presence of articulated aquatic-vertebrate remains (champsosaurs and turtles) and aquatic plants (C. Hotton, 1986). The ponding resulted in lacustrine deposits associated with a flood plain that occurred marginally to the migrating channels flowing to the east. The interbedded silts and clays were deposited through suspension settling within the ponds. Interbedded very-fine sands were deposited through periodic flooding and progradation of crevasse splays into the lake. The extent of the variegated beds suggests that extensive areas of the floodplains were inundated and that the water table was at or above the floodplain surface throughout much of the early deposition of the Fort Union Formation. Their occurrence at multiple levels both above and below the incised valley fill suggest fluctuating base levels throughout deposition of the Fort Union Formation.

Figure 31 Photo of Site 5. Notice the thin sheet sand deposits (highlighted in yellow) interfingering the variegated bedding (highlighted in orange). The lowermost laterally extensive coal, seen as lignite here (highlighted in black) marks Hell Creek/Fort Union contact (shown by the K/Pg contact to the right of the photo). 10 m marked for scale.

4.4 Organic Accumulation

Figure 32 Photo of lower-most persistent lignite at Site 7.

4.4.1 Description

Facies of organic accumulation is arbitrarily defined as any facies of greater than 5% organic material. This restricts the facies to accumulations of organic litter in contrast to flood-plain material with fine, disseminated organic matter (Fastovsky, 1987). The organic layers have a sharp basal contact and a sharp upper contact when overlain by the variegated beds and a sharp to erosional contact when overlayed by the channel sandstones. Stratigraphically, the organic accumulation is found as a persistent layer below the variegated beds and also occurs interfingering with fine-grained deposits above the variegated beds (See Figures 16 and 32). Previous studies have identified an increase in organic accumulations in the lower Fort Union

Formation as compared to the upper Hell Creek Formation, and this study makes similar observations. The first "persistent" lignite is generally used as the demarcation of the K-Pg Boundary (Calvert, 1912), however exceptions to this generalization are known (Fastovsky, 1987). Within Makoshika State Park the lower-most persistent lignite contains an iridium anomaly and fern spikes have been documented just above the lower-most persistent lignite, which have been used as distinct indicators of the K-Pg boundary (Kroeger, 1993; Hunter et. Al, 1997). A short-lived fern spore spike has been associated with the extinction horizon (Tschudy et al., 1984; Fleming and Nichols, 1990; Nichols 2007). The lignite layers measured were typically less than 1 meter thick (see Figures 18, 30, 31, 32 and 33), but are known to be as thick as 2 meters (Archibald, 1982), and are commonly interbedded with organic-rich black shales composed of clay and plant material. Gypsum was identified in lignites and black shales toward the top of the measured sections at Site 1, Site 3, Site 4, and the Site 5 locations. The organic layers commonly have a sharp basal contact and sharp to erosional upper contact.

Figure 33 Close-up photograph of the lower-most lignite representing the K/Pg Boundary. Backpack for scale.

4.4.2 Interpretation

Lignite forms from an accumulation of plant material. When the plant material accumulates in anoxic waters, decomposition is slowed or stopped (McCabe, 1984). This is consistent with a wetland depositional environment, possibly a mire. Wetland conditions suggest a water table above the sediment surface resulting in standing anoxic waters where plant debris accumulated as a precursor to the lignite. Clastic starvation is essential for the formation of lignite (McCabe, 1984) suggesting that these ponded waters were isolated from coarse sediment influx (McCabe, 1984). The majority of the organic accumulated layers are black shales suggesting periodic influx of clastic material (Flores and Hanley, 1984).

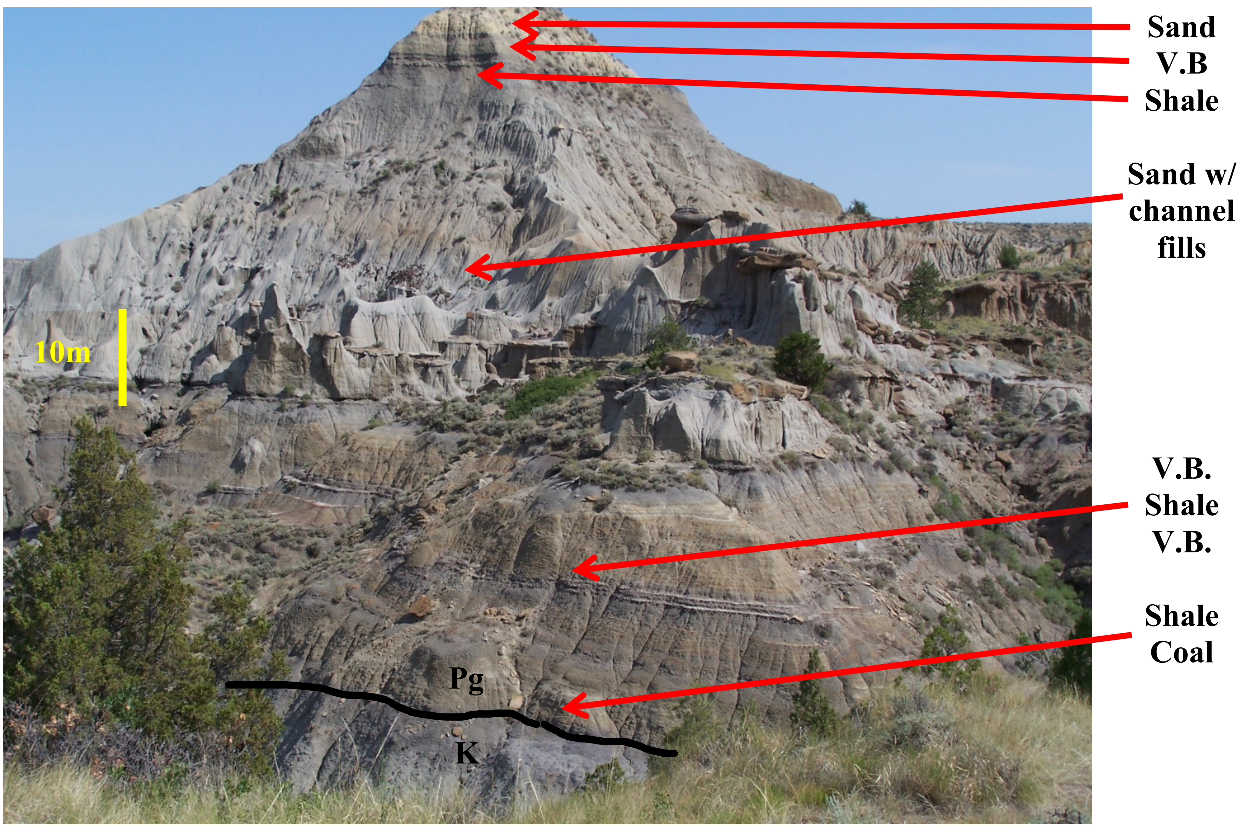

Figure 34 Photo of Site 3 with labelled facies. Organic accumulations of coal and shale, variegated bedding (V.B.) and channel filled sandstones are present. K-Pg Boundary marked by black line.

Amphitheater

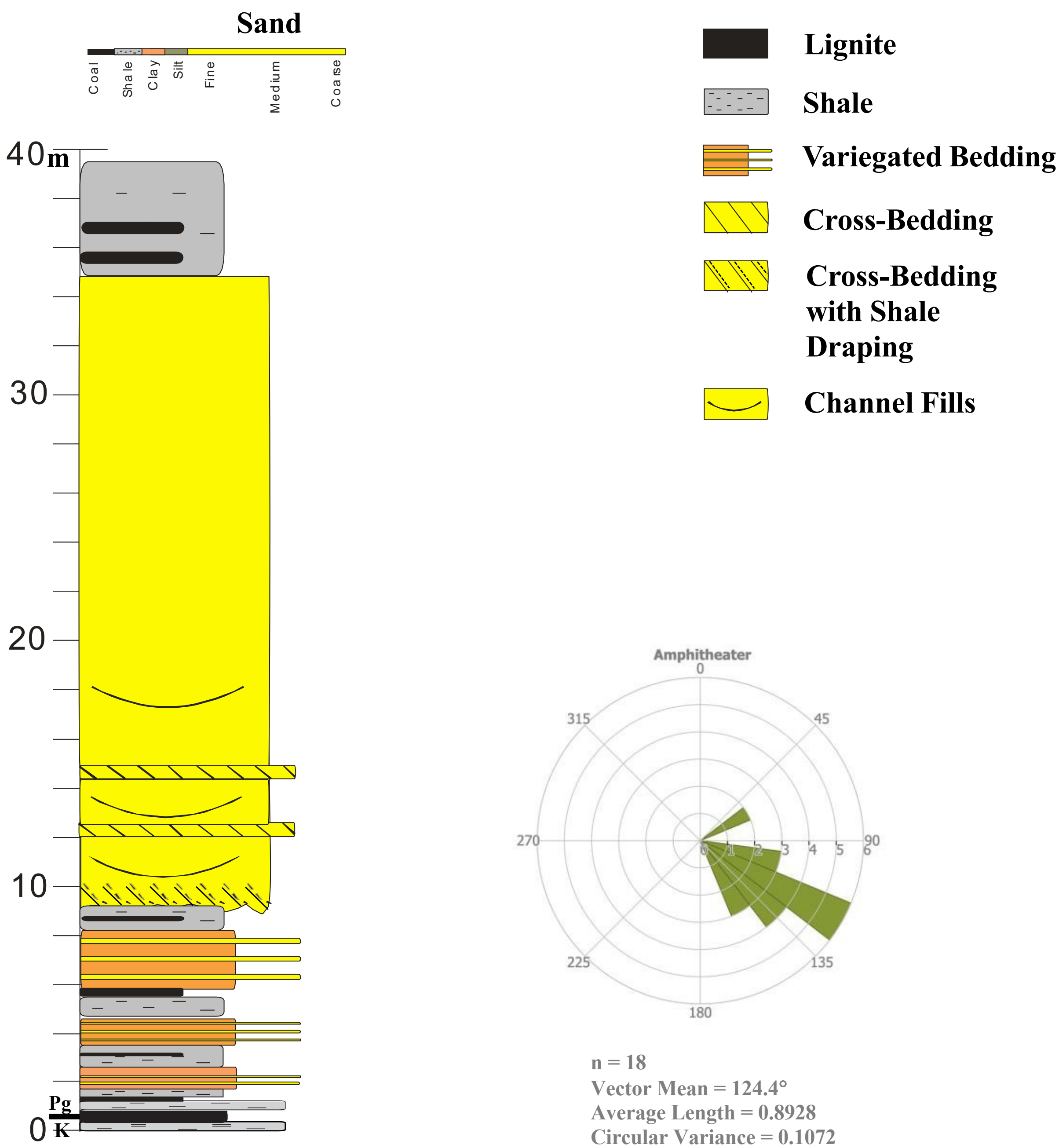

Figure 35 Stratigraphic column from Site 3 displaying the facies found in the lower Fort Union.

4.5 Depositional Environment for the Fort Union Formation

The lower Fort Union Formation facies represent a vegetated wetland landscape located within an extensive floodplain system separated by small meandering channels. Periods of coarse clastic starved conditions led to the development of extensive lakes and mires located between the meandering channels. Extensive ponding due to a high-water table were marked by the deposits of the variegated beds (Fastovsky, 1987). Occasional crevasse splays provided an influx of relatively coarse clastics including very-fine-grained sands and silt that were interbedded with the low-energy swamp and lacustrine deposits. Stream migration across the floodplain occurred and is marked by single-story channel sandstone deposits. Incised valleys filled by fluvial sandstones also occur and indicated fluctuating base levels (see chapter 5) at the time of deposition. The finding of the evaporite gypsum overlaying the rhythmites within the cross-stratified sandstone and lignites at the top of the incised valley fill represent tidal deposition in a lower coastal plain influenced by marine waters such as in an estuary. Variegated beds both below and above the incised valley fill attest to cyclic fluctuations in base level.

5. Fluvial and Sequence Stratigraphy of the Hell Creek and Fort Union Formations

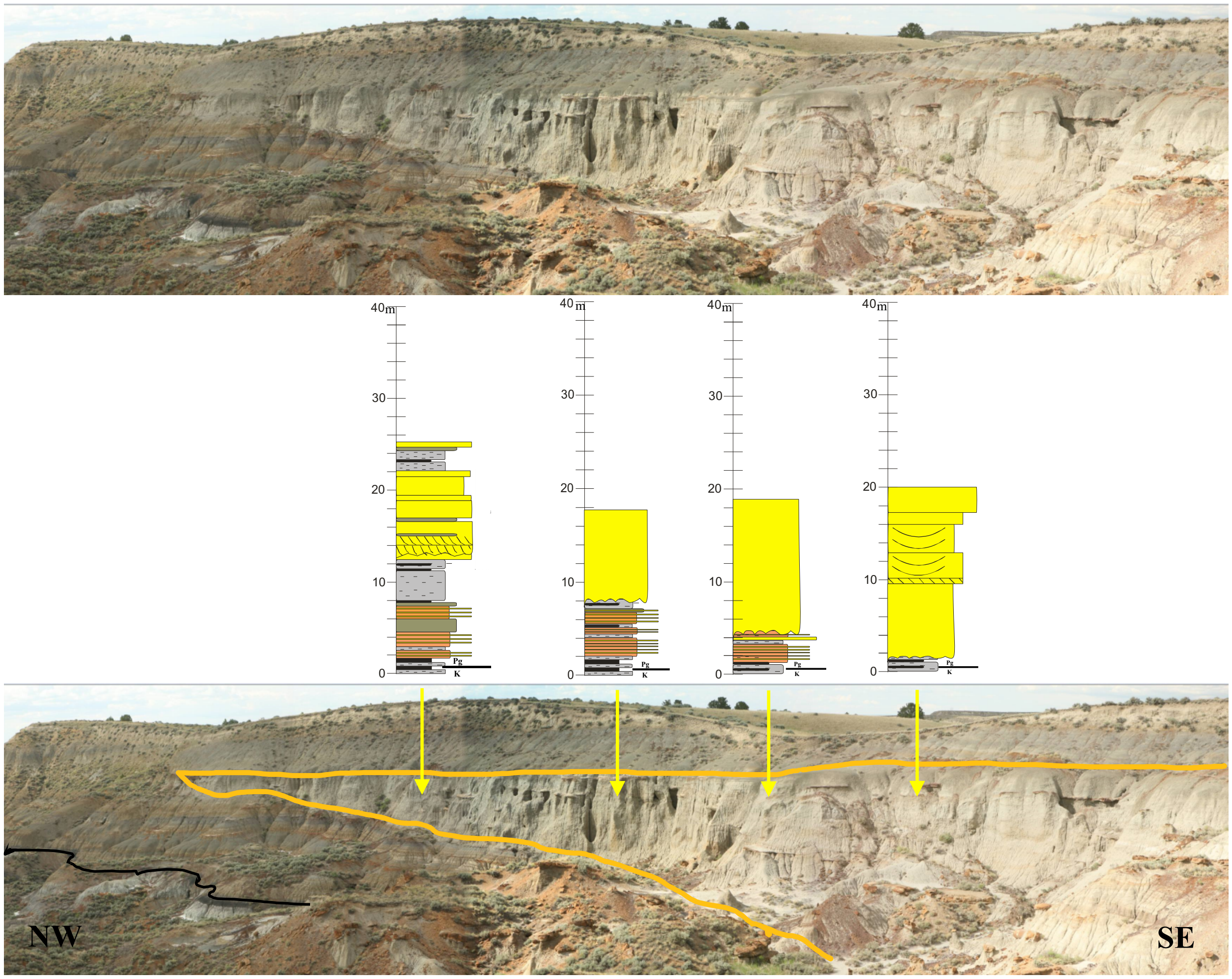

Figure 36 Site 1 VA-VD stratigraphic columns with a panoramic photo of Site 1. Incision outlined in yellow with column locations indicated by arrows. Hell Creek/Fort Union formational contact highlighted in black.

5.1 Fluvial Stratigraphy of the Hell Creek and Fort Union Formations

Below the K/Pg contact, the upper Hell Creek contains thick shales and single storied sandstones as seen in the lower left of Figure 36. This single-story sandstone was not measured but was observed as 3-4 m thick and laterally extensive as were other sandstones observed in the upper Hell Creek deposits elsewhere within Makoshika State Park. These single-story sandstones have been interpreted as single, highly sinuous meandering streams migrating across a vegetated floodplain. In the Site 1 location the shales were not measured but were observed as 10’s of m thick like those elsewhere in Makoshika State Park.

Multistoried bodies occur due to multiple passes of a stream across its flood plain, the shifting of streams into the deposits of a former stream, or due to a drop in base level and incision into underlying deposits. At several locations in the upper Hell Creek Formation, thick multistoried sandstone bodies with an erosional base incising into floodplain deposits below occur forming an incised valley (see Figures 10 and 11). Above these multistoried sandstone bodies and incised valleys, the shales of the upper Hell Creek are interpreted as broad floodplain deposits with the settling of fines from suspension. Other localities within the park show evidence that these shales formed on vegetated floodplains with immature soil development. Soils likely developed in the interfluves outside of the incised valleys. Shales in the upper Hell Creek and the change from incision to sand deposition in the incised valley with overlying shales indicate a rising base level. Whereas erosional surfaces at the base of the incised valley fills that truncate underlying strata record a drop in base level. Therefore, the combination of a cyclic record of incision followed by aggradational deposits suggest fluctuating or cyclic changes in base level at the end of Hell Creek time.

The lowest persistent lignite layer, discussed in previous chapters, represents the K/Pg boundary at the Hell Creek and Fort Union formational contact. The contact between the two formations is sharp throughout Makoshika State Park with the exception of an erosional contact below a Fort Union incised valley found at the Site 1 location. Lignite at the K/Pg boundary indicates that the area occupied by Makoshika State Park was starved of coarse clastics, which allowed for the development of mires across the landscape. Overlying the lignite, the variegated beds fine upward into shale and organic layers and ranges from 4 to 6 m in thickness and they extend laterally for 100's to 1000's of m. The variegated beds are extensive in the lower Fort Union Formation throughout the study area and throughout eastern Montana. The lignite to

variegated bed transition indicates that the water table was rising resulting in flooding of the landscape with the development of extensive shallow lakes on the coastal plain. In such a setting, silt and clay would have settled from suspension during overbank flooding out of the sparse channels scattered across the fluvial surface. Thin fine sands and silts in the variegated beds resulted from periodic flooding that delivered coarse sediment into the lake(s) via crevasse splays. Fine-grained sandstone sheets extending tens to hundreds of meters across the outcrops also occur and either downlap onto the underlying variegated beds or pinch out into the variegated beds. These sandstones are interpreted as overbank splay deposits.

In the Site 1 and Site 3 locations, the variegated beds are overlain by a sharp erosional surface (see Figure 37) or is truncated by an erosional surface that incises into the variegated beds (see Figure 36) and that forms the base of an overlying incised valley sandstone deposits. This surface incises up to and over 12 m downward through the variegated beds and into strata of the upper Hell Creek Formation. The erosional surface at Site 1 forms a flattened U-shaped, trough-like depression at least 0.6 km wide and over 17 m deep which forms a large incised paleovalley (see Figure 36). An incised valley is defined as “a fluvially eroded, elongate topographic low that is characteristically larger than a single channel and is marked by an abrupt seaward shift of depositional facies across a regionally mappable sequence boundary at it base” (Boyd et. al, 2006). The trend of the paleovalley runs 295°-125°, striking NW to SE (see Figure 36).

The sandstone overlying the incision surface measures 17-26 m in thickness but pinches out laterally at Site 1. The sandstone consists of fine- to medium-grained crossbedded sandstone. The paleocurrent directions gives an average flow direction of 113° at Site 1 for the whole sand unit and ranges from 60° and 160° with a vector mean flow direction of 124° at Site 3. Planer

current lineations towards the top of the section V-F (see Appendices B and C) provide a vector mean flow direction of 113°. Stacked, multistoried sandstone channels with shale draped cross-beds are found at the base of the sandstone unit with complex channel stacking observed at Site 3 (see Figure 35) and Site 1 (see cross sections in Appendix A). Towards the bottom of the sandstone unit, channels are amalgamated and range in thickness from 2 to 5 m thick as seen in the Site 2 photo (Figures 23 and 41). The channels contain lateral accretion surfaces which

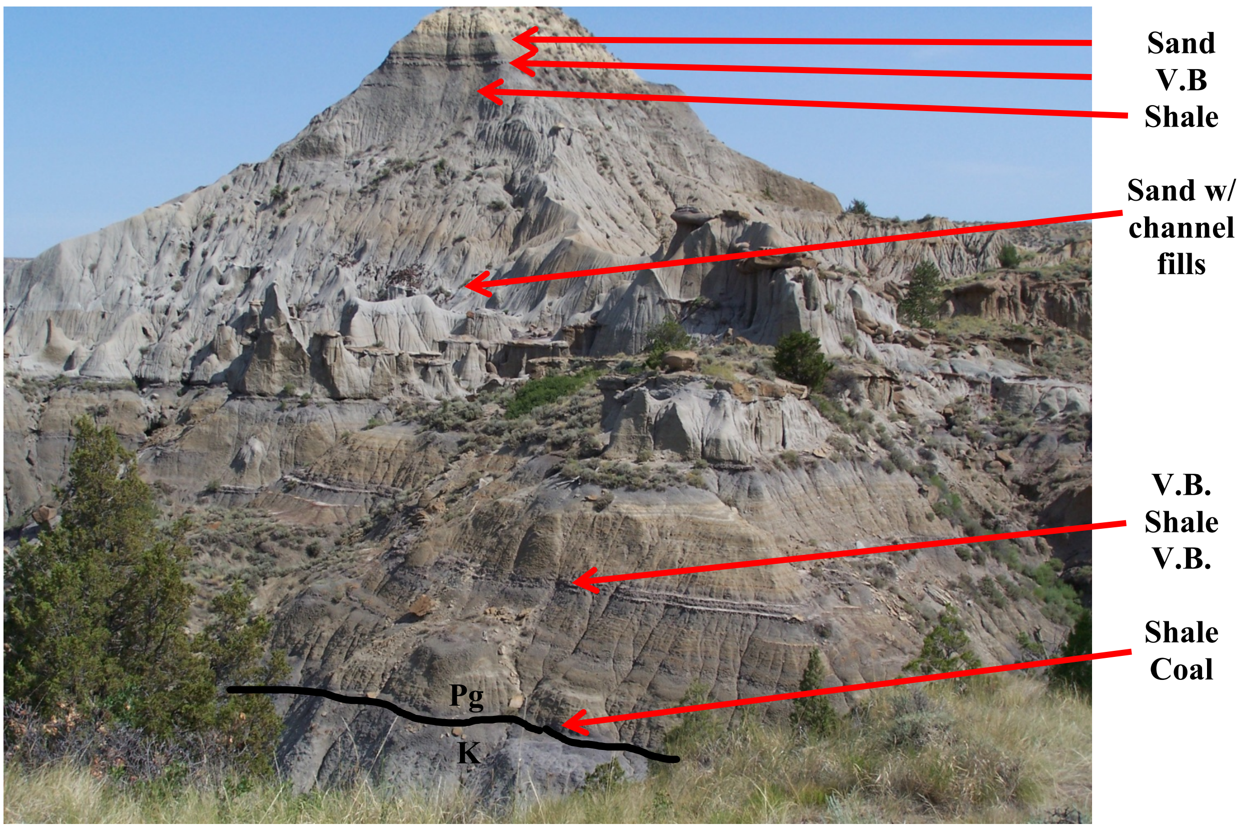

Figure 37 Photo of Site 3 with labelled facies. Organic accumulations of coal and shale, variegated bedding (labelled above as V.B.) and channel filled sandstones are present. K-Pg Boundary marked by black line.

bound crossbedded and cross-laminated sandstones preserved as concretions (see Figure 38). The channels also contain fill characterized by horizontal laminations as seen in Figures 37 and 40 as well as in the stratigraphic column found in Figure 35 and in the Site 1 stratigraphic columns (see appendix A). Toward the top of the sand unit, the channels are more widely dispersed with

lateral accretion deposits preserved in dipping sandstone concretions and also contain horizontally filled laminated rhythmites. The rhythmites are fine- to medium-grain-sized sandstone that alternates with organic-rich shale laminations (see Figure 39). The sandstone and shale define couplets that thicken and thin upward in a fashion that are similar to tidal rhythmites (Archer, 1996). Within the laminations at Site 2, several deformed sandstones structures are

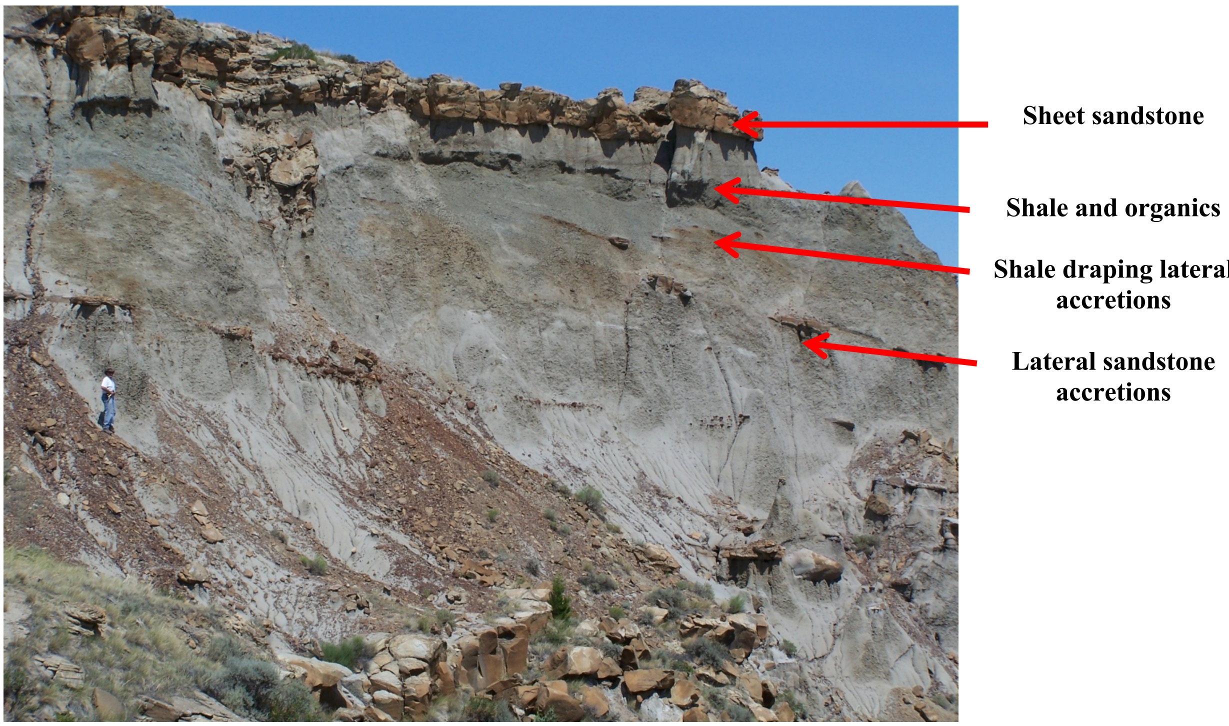

Figure 38 Site 1 Showing the deposits found within the incised valley. Person for scale.

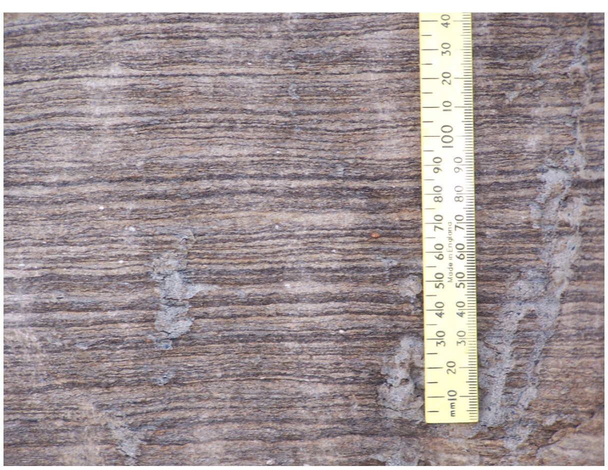

Figure 39 Close-up of Site 2 laminated layers. Note the thickening and thinning sandstone layers.

Figure 40 Close-up of Site 2 scour fill laminations.

found. These structures include flame structures and slump blocks (see Figures 27-29). Overlying the deformed layers are fine-grained sandstones forming stacked channels that occur as multi-lateral and multistoried sandstone body following the definitions of Hirst (1991), Gibling (2006), and Miall (2006) (see Figure 41). At least 5 stacked channel bodies/scours occur that are filled with laminated mudstone. Upward, the stacking gives way to cross bedded lateral accretion deposits with cross-bedding often preserved as concretions. Incision of the cross-stratified sandstone into the floodplain and lacustrine deposits concurring with the pattern of stacked channels and tidally influenced laminations suggest a paleovalley cutting through the region (Boyd, 2006).

Figure 41 Site 2 with deformed laminated layer and stacked channels labelled.

Overlying a sharp contact at the top of the sandstone are evaporite-bearing (gypsum crystals) siltstones, shale with thin lignite beds, and variegated beds (see Figures 36, 37, 45 and

46) suggesting deposition under the influence of sulfate rich marine waters and a return to a high water table.

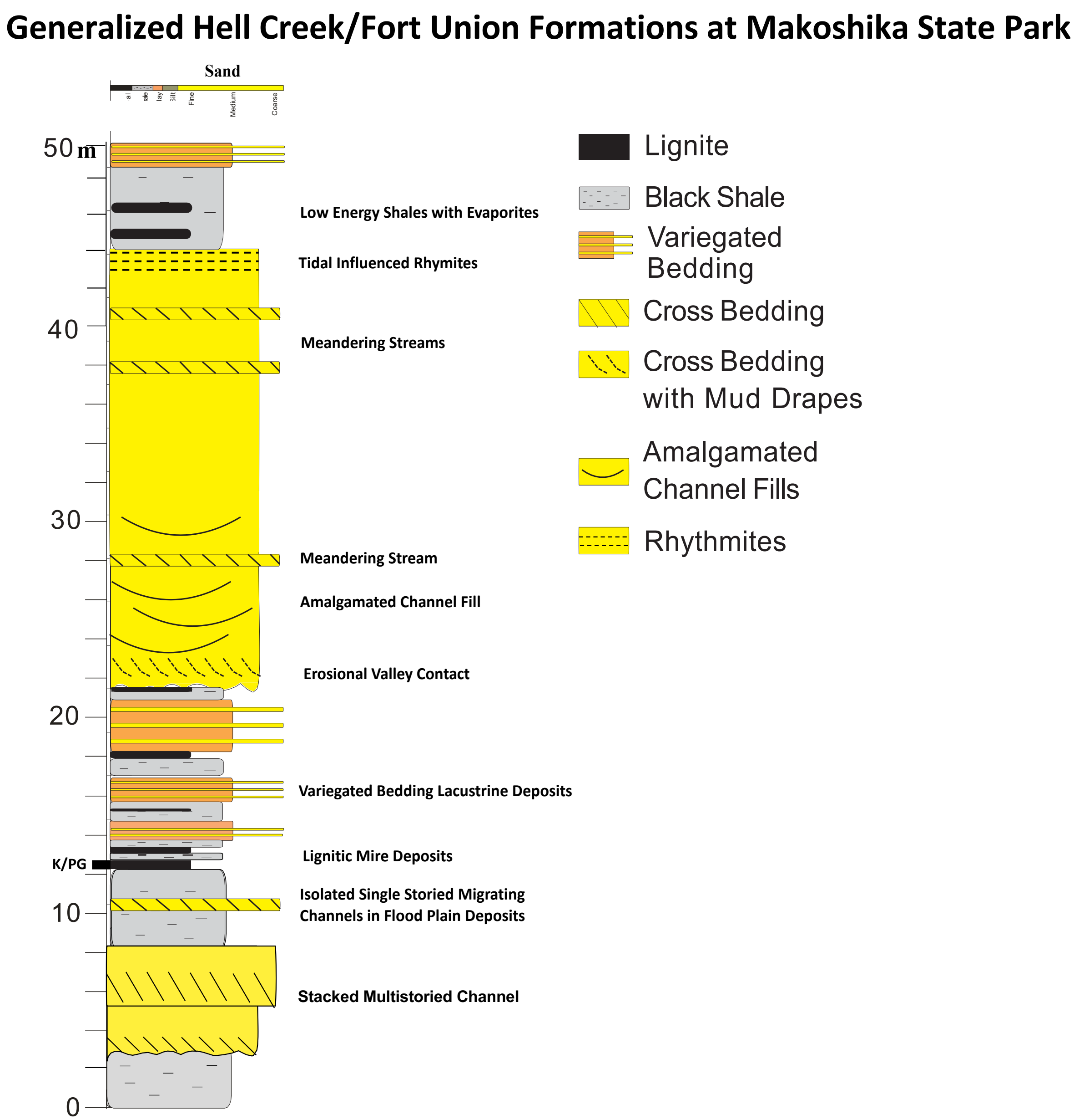

Figure 42 Generalized Hell Creek/Fort Union Stratigraphic column from Makoshika State Park displaying the facies associated with their depositional environments.

5.2 Sequence Stratigraphy of the Hell Creek and Fort Union Formations

Sequence stratigraphy can be used to interpret base level changes in a basin. Base level is an "equilibrium surface… above which a particle cannot come to rest, and below which

deposition and burial are possible" (Sloss, 1962). Catuneanu (2006) states "Sequence stratigraphy analysis can be used to identify the sedimentary response to changes in base level, and depositional trends that emerge from the interplay of accommodation and sedimentation.". Accommodation space is "the space made available for potential sediment accumulation… [such that] … in order for sediments to be preserved, there must be space available below base level" (Jervey, 1988). The erosional base of the multistoried sandstone bodies of the Hell Creek found in Figure 44 and the cliff face near the Site 3 location (see Figure 10), as well as the observed Fort Union Formation sections at the Site 1 and Site 3 locations mark sequence boundaries. As such, sequence stratigraphy will be used to interpret the depositional patterns seen within the transition between the Hell Creek and Fort Union Formation deposits found within Makoshika State Park. The sections described in this study contain sequence boundaries that will be used as the start of the sequence patterns preserved.

An interval of stacked multistoried channel sandstone bodies near Site 6 (Figure 44) represents an interval of low accommodation producing stacked erosively interconnected sandstone bodies. This probably represents deposition on top of an erosion surface akin to an incised valley. If this were the case, this would represent a sequence boundary. Regionally, during much of the deposition of the upper Hell Creek accommodation space was being created at a moderate pace as the upper Hell Creek Formation's deposits represent a relatively high base level with preservation of wide flood plains including isolated meandering streams marked by single-story and lenticular laterally accreting sandstones interspersed with floodplain deposits of shale with pedologic features and plant roots with occasional pulses of clastic material associated with crevasse splays. The incised valley seen on a nearby cliff face from Site 3 indicates that there was a drop in base level late in the Hell Creek time, which resulted in incision. This

represents a second sequence boundary. The multistoried fill within this valley shows the turnaround in accommodation space with negative accommodation and base level fall characterized by the incision surface followed by low positive accommodation characterized by the stacked channel fills filling the incised valley. The upward transition to floodplain deposition at the top of the Hell Creek, just below the boundary lignite suggests an increased rate of the creation of accommodation space due to an increase in the rate of rise of base level (Shanley and McCabe, 1994). These fine-grained facies and description of the Hell Creek Formation deposits, as described in Chapter 3 represent a broad coastal floodplain that ultimately transitioned into a mire at the end of the Cretaceous and at the beginning of the Paleogene. Accommodation space continued to increase as the region became deprived of clastics resulting in development of a mire which produced the lignite that demarks the K/Pg boundary in the region. The peat-lignite-coal continuum develops when areas are starved of clastic sediments and the water table is elevated and located at or just above the land surface. The overlying variegated beds represent extensive lake deposits. Lakes develop when the local water table is above the land surface and mires are drowned allowing lakes to develop. Such settings represent high accommodation settings where space is being created faster than sediment can fill the space (Jervey, 1988; Catuneanu, 2006).

The erosional base of the Fort Union incised valley seen at various sites within Makoshika State Park, and more intensively studied in this thesis due to accessibility, represents another major sequence boundary. Such surfaces occur due to a drop in accommodation (negative accommodation) caused by a drop in base level (relative sea level fall; increased discharge, or uplift; Jervey, 1988; Shanley and McCabe, 1994; Blum and Törnqvist, 2000; Catuneanu, 2006). Initiation of sedimentation above this boundary marks a change to positive

accommodation, thus allowing space to be created to deposit and preserve sediment. Thus, the surface marks a starting point for an accommodation curve, and hence a sequence boundary. A system tract within depositional sequences (unconformity bound package of sediment) represents "a specific sedimentary response to the interaction between sediment flux, physiography, environmental energy, and changes in accommodation" (Posamentier and Allen, 1999). The incision into the underlying variegated bedding, lignite, and deposits at the top of the underlying Hell Creek Formation represents a drop in base level. As base level drops, there will be negative accommodation space and the removal of sedimentary materials. As such, the fluvial downcutting results in the formation of an incised valley (Schumm ,1993; Shanley and McCabe, 1994). The incision is represented in Fluvial Strata A of Figure 43 (also see Figure 44). Down cutting also promotes slumping of materials into the newly formed trough-shaped depression of the incised valley like that observed at Site 2. Such settings indicate a drop in base level, most easily explained by a drop in eustatic sea-level within the Williston Basin.

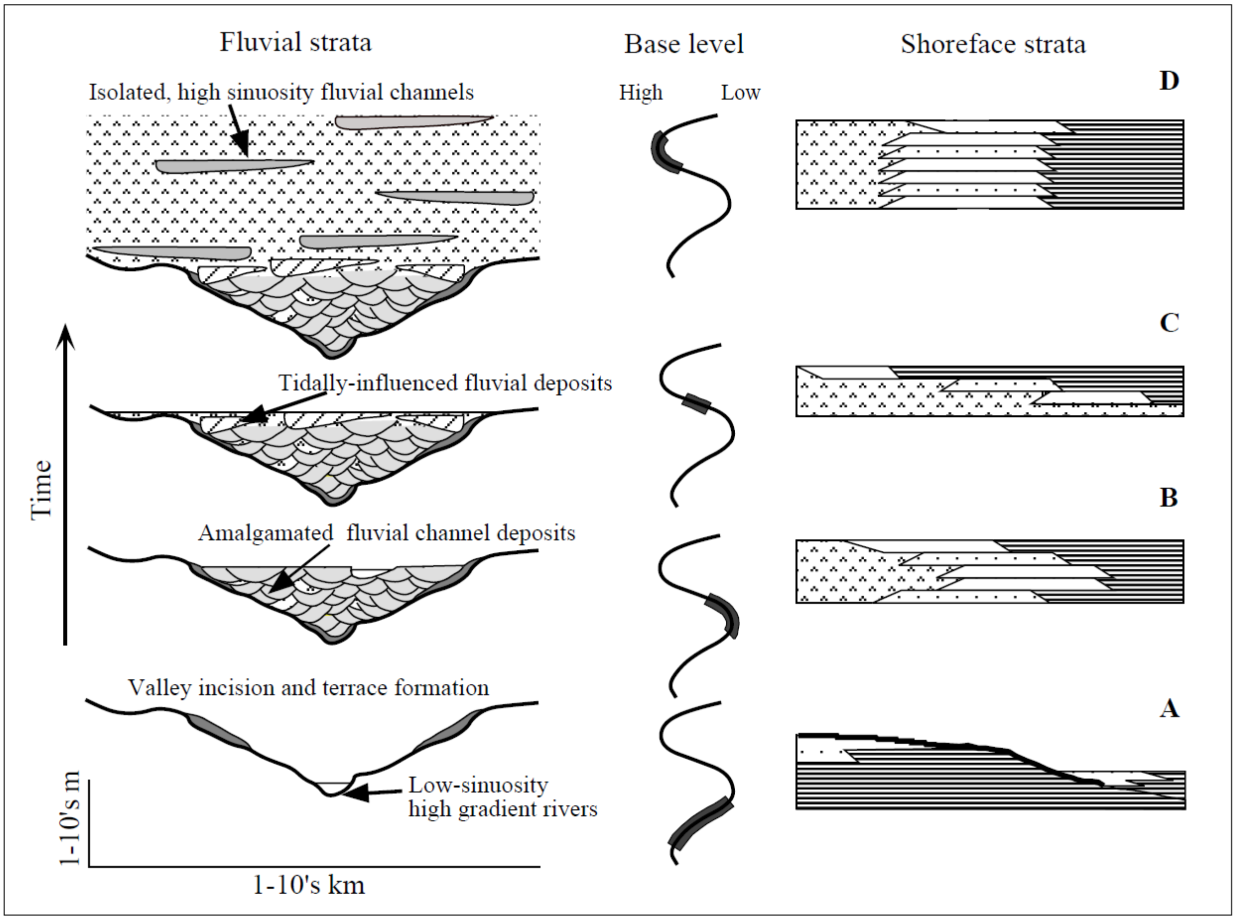

Figure 43 Fluvial deposits as they relate to changes in base level accommodation space. From Shanley and McCabe (1994).

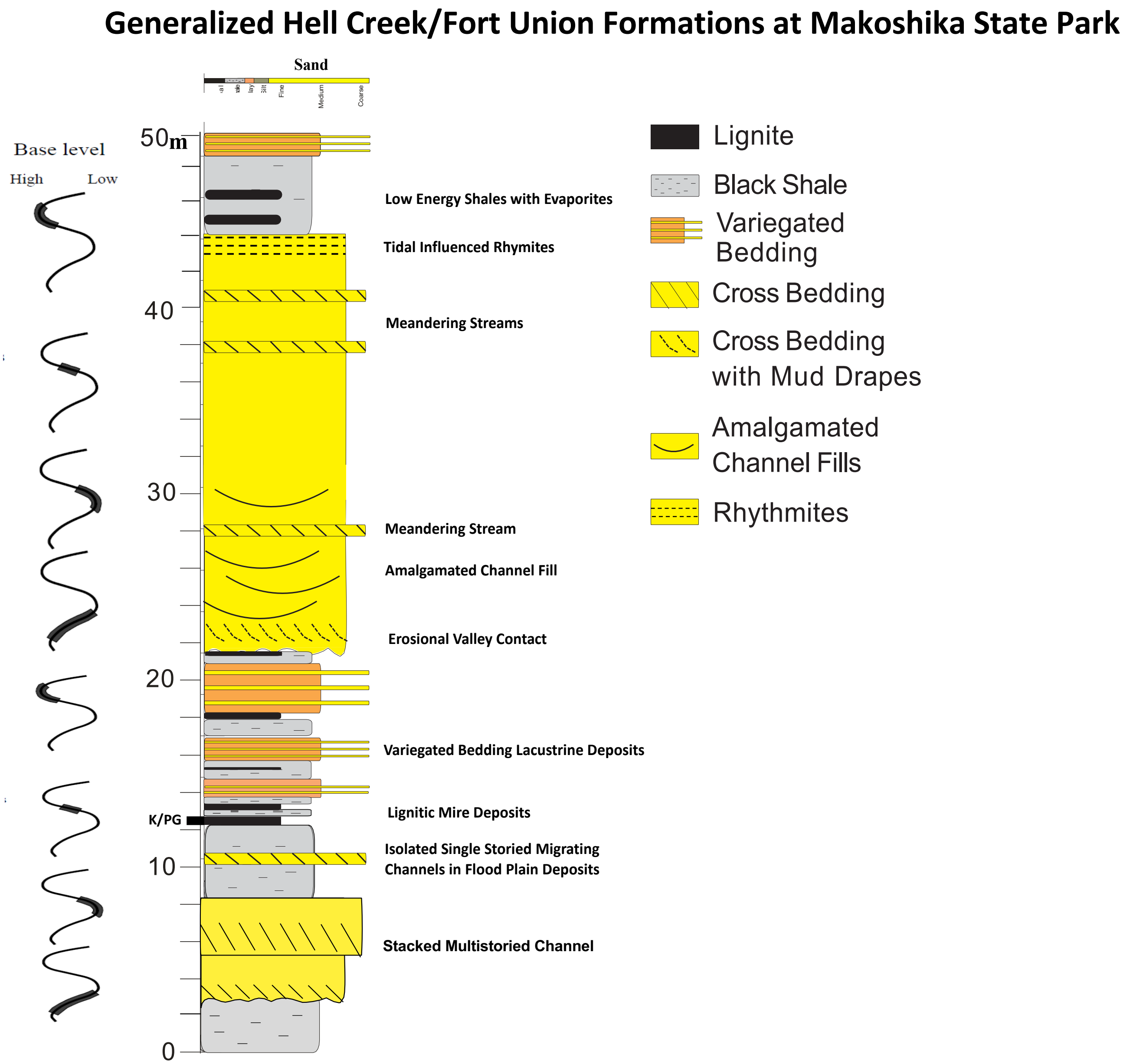

Figure 44 Generalized Hell Creek/Fort Union Stratigraphic column from Makoshika State Park displaying the facies associated with their depositional environments as they relate to base level changes. Base Levels taken from Shanley and McCabe (1994).

In the succession that follows, fluvial architecture and stacking patterns change as the rate of the creation of accommodation space changes. As base level begins to rise slowly and the accommodation space is slowly starting to occur, the sandstone directly above the incision are represented by amalgamated channels (see Figures 43 and 44). With low accommodation space,

the preservation of floodplain deposits was limited. The channels had little room to meander within the valley system. As such, the migrating channels are continuously cutting into previously deposited channel deposits. This resulted in stacked amalgamated channel geometries as seen in Fluvial strata B of Figure 43 (also see Figure 44). and as observed at Site 2 (see Figure 23). Therefore, the amalgamated channels indicate deposition of the streams in a low accommodation setting. A change to low positive accommodation indicates a regional rise in base level.

As base level rises, accommodation space increases. Upward within the incised valley, the amalgamated channels become less common and lateral accretion begins to dominate signaling the establishment of meander streams (see Figures 43 and 44). These sandstones are multistoried and multilateral bodies. Multistoried bodies occur due to multiple passes of a stream across its flood plain, or the shifting of streams into the deposits of a former stream. Stacked bodies suggest that the creation of space for deposition is low, thus allowing only the preservation of channel bodies, or the deepest parts of a channels thalweg with all other sediment deposited higher in the channel or on the flood plain eroded and washed away (Bridge and Leeder, 1979; Shanley and McCabe, 1994). In Shanley and McCabe's (1994) model, this occurs as a result in an increase in the rise of base level or do to an increase in the rate of the creation of accommodation space (Jervey, 1988; Shanley and McCabe, 1994). Additionally, abandoned channels display rhythmites suggesting that deposition may have been influenced by tidal activity where the changing tides impounded river waters during high tide allowing deposition of a fine-grain organic lamina, followed by increased river discharge during falling and low tide allowing for deposition of coarse deposition to complete a coarse/fine rhythmite couplet (see Figure 44).

Continued base level rise would have allowed for the stacking of channel bodies (multistoried deposits) within the incised valley and the observed changes from highly amalgamated channels to highly sinuous meandering channels. When base level rises, the rate of the creation of accommodation space increases allowing for highly sinuous single meandering streams to migrate across a broad floodplain (see Figures 43 and 44), resulting deposits of single-story bodies. Hence, there was space available to preserve floodplain deposits and a return to deposition of the lacustrine variegated beds suggesting that the rate of increasing accommodation continued upward during deposition of strata at the top of the measured stratigraphic section. The variegated beds at this stratigraphic level also occur elsewhere in Makoshika State Park as seen in Figure 45 of Site 4 and Figure 46 of Site 5. The occurrence of gypsum crystals in the shales overlying the incised valley deposits also suggest the influence of sulfate rich waters during deposition, possibly suggesting that deposition of these shales had a marine influence as observed in the Site 2 deposits (see Figure 39 as well as Figures 25 and 26). This combined with preservation of marine deposits in North Dakota (the Cannonball Sea) at the same stratigraphic level, suggests a slow rise in eustatic sea level would have allowed for the creation of accommodation space and initiation of channel deposition.

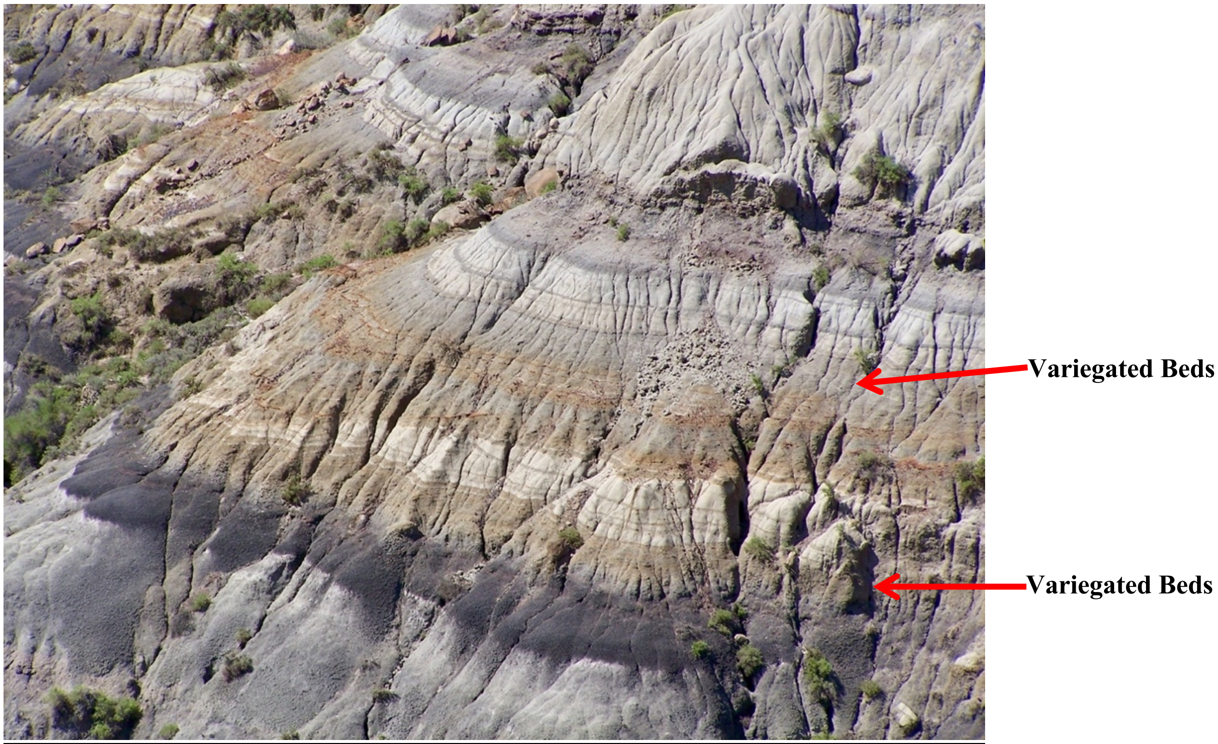

Figure 45 Photo of Site 4. Notice the repeating labelled laminated variegated beds.

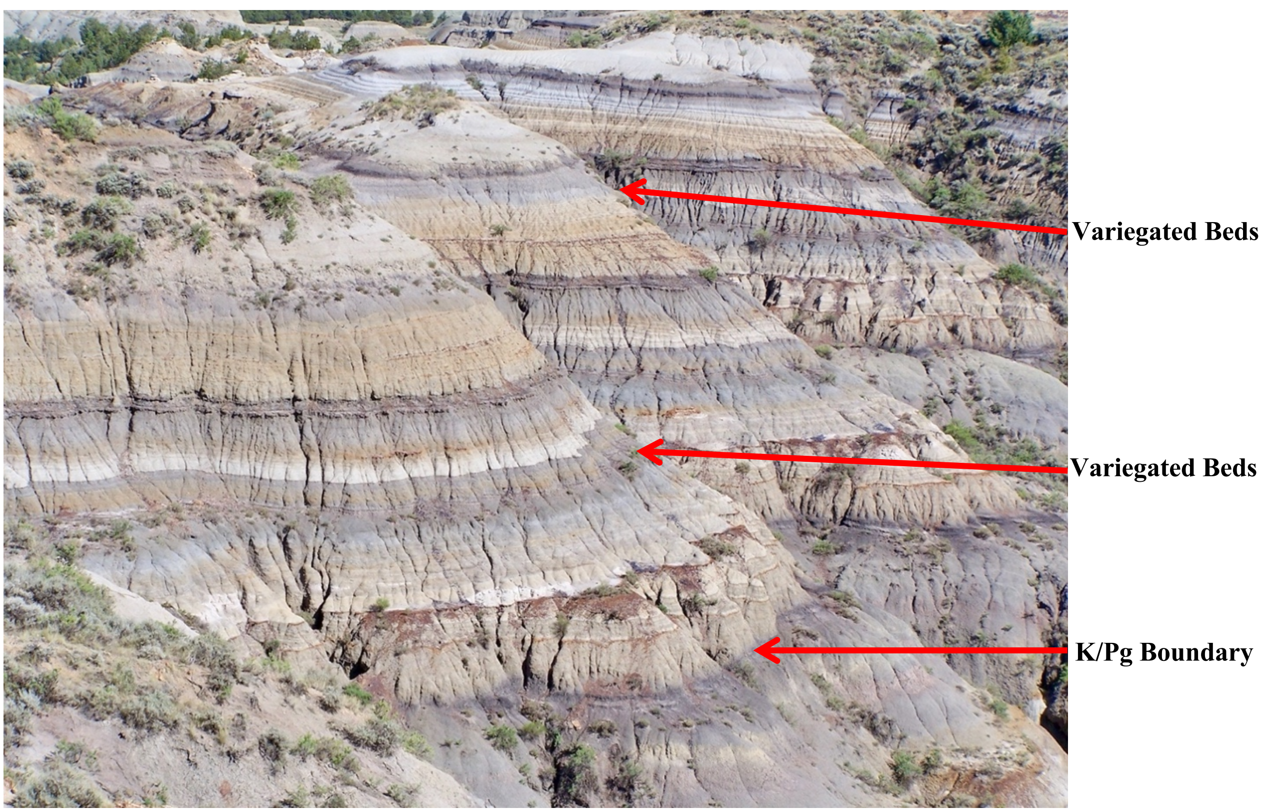

Figure 46 Photo of Site 5. Notice the repeating labelled laminated variegated beds.

6. Discussion of Models for Sedimentation Across the K/Pg Boundary

As discussed in Chapter 1, three main hypotheses have been proposed to explain the changes in depositional style across the K-Pg Boundary. The first suggests that fluctuations in base level of the Cannonball Sea, located just to the east resulted in an elevated water table, which lead to lacustrine development of the Fort Union floodplains (Fastovsky and McSweeney, 1987; Fastovsky and Sheehan, 1994; Johnson et al.,2002). The second hypothesis suggests that Laramide tectonism and lithospheric loading to the west resulted in subsidence induced changes in the position of the shoreline and changes to the position of the water table (Catuneanu et al., 2000), and a third hypothesis suggests that the loss of land plants, due to the K/Pg extinction event across the boundary, resulted in increased erosion, which lead to aggradation within fluvial channels, increased overbank flooding, and ponding of waters on the floodplains (Sheehan et al., 2004; Fastovsky et al., 2008).

The generalized stratigraphic column of the Hell Creek and Fort Union formations at Makoshika State Park in Glendive, Montana, first seen in Figure 44, has been repeated here as Figure 47 in this chapter for reference against the three main scenarios previously hypothesized to explain the changes of sedimentation displayed within the park and elsewhere.

Generalized Hell Creek/Fort Union Formations at Makoshika State Park

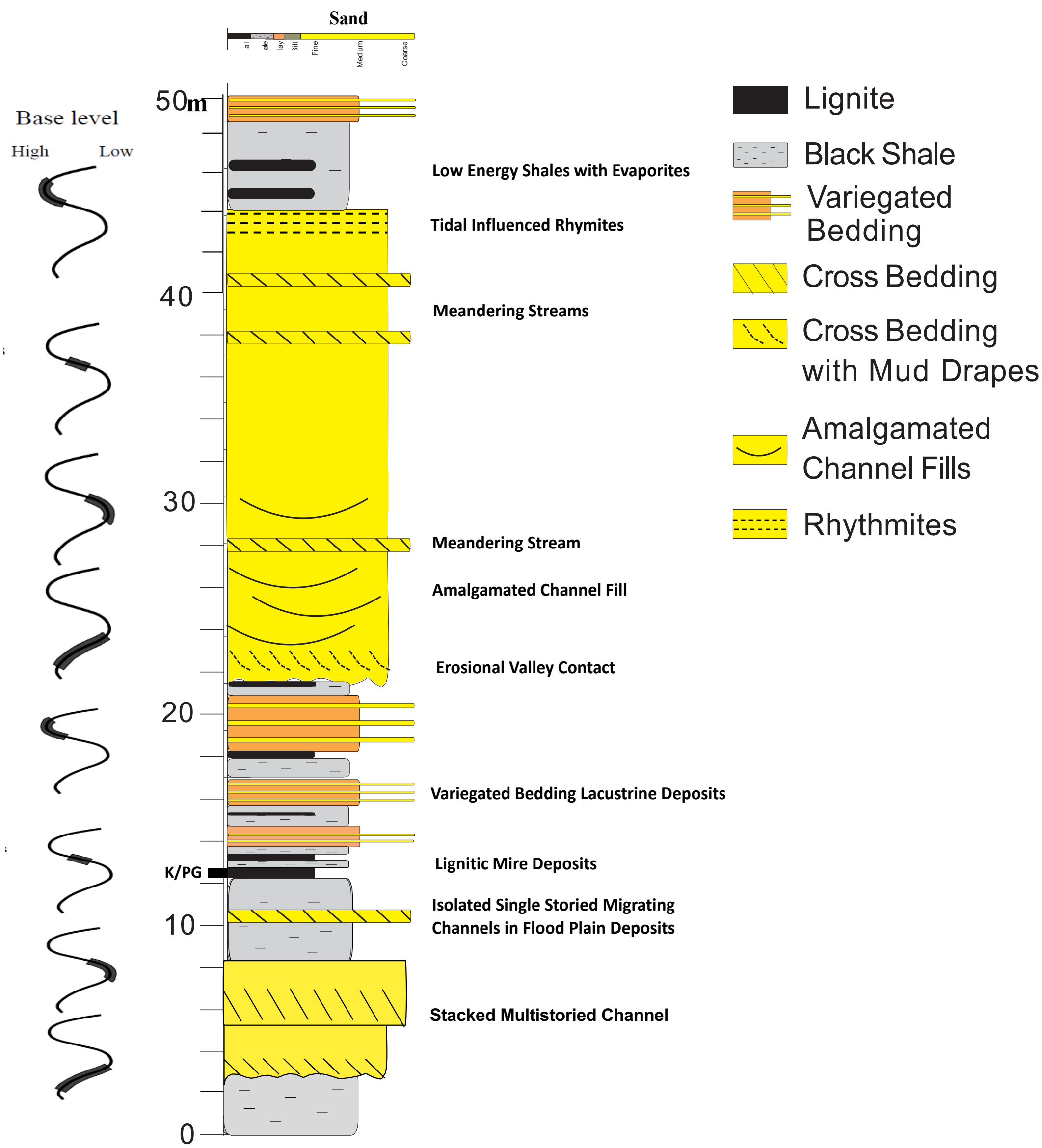

Figure 47 Generalized Hell Creek/Fort Union Stratigraphic column from Makoshika State Park displaying the facies associated with their depositional environments as they relate to base level changes. (Base Levels taken from Shanley and McCabe (1994).

6.1 Base Level Changes due to Transgression of the Western Interior Seaway/Cannonball Sea Hypothesis

The first scenario suggests that a rise in eustatic sea level associated with a marine transgression of the Western Interior Seaway resulted in a rise in the water table leading to a gradually flooded landscape covered by widespread shallow lakes and ultimately marine units

(Fastovsky and Sheehan, 1994). This change would have recorded a gradual change in accommodation space associated with a change in base level. Additionally, if eustatic fluctuations in base level changes occurred within the Western Interior Seaway then cyclical packages of short-term base level fluctuations might be expected in the deposits in eastern Montana and western North Dakota.

When base level rises, accommodation space increases (see Figure 47) resulting in a change in fluvial style. This is often manifest by an increase in the preservation of stream channels above regional unconformities starting first with highly connected fluvial channel bodies or amalgamated stream deposits changing upward to meandering streams to single-story meandering stream deposits isolated in thick floodplains deposits (Shanley and McCabe, 1993). As the transgressive sequence continues, ponding occurs resulting in the increase of fine-grained lacustrine facies through time. If the energy in the location is low enough, it could become sediment starved, and an increase in organics and coal seam abundance and thickness through time would also be expected. If the transgressive sequence continues even further, an increasing marine tidal influence may be reflected in the deposits as was seen as laminated rhythmites found in the upper section of the Site 1 location. (Shanley and McCabe, 1993).

When base level falls, accommodation space decreases which would be reflected in a coarsening-up sequence as the stream's sinuosity decreases across shrinking floodplains and/or transition into confined valleys. Loss of parts of the record due to falling accommodation would occur due to erosion during incision of the valley. This base level fall represents negative accommodation resulting in the incision into the older stratigraphic layers below truncating previous deposits (see Figure 47).

The observations within this study agree with the previous conclusions of a transgressing Cannonball Sea to the east first presented in Fastovsky and Sheehan (1994) and later in Johnson (2002) and Johnson et al. (2002) but going a step further by including evidence of a following (and possibly previous) regressive and transgressive sequences. As seen in the generalized stratigraphic column (see Figure 47) at the Site 1 and Site 3 locations as well at Site 2 and other sites observed in this study, the change in sedimentation deposition and style change that are observed across the K/Pg boundary fit the pattern of sequence stratigraphy due to base level changes for fluvial systems as described by Shanley and McCabe (1994). Additionally, the paleocurrent direction stays consistent throughout the Hell Creek and Fort Union Formations as flow to the east south-east with drainage towards the Cannonball Sea to the east occurred throughout the late Cretaceous and early Paleocene. The observed sequence of facies and environments are independent of the extinction event as they transition across the K/Pg boundary contact.

As Figure 47 shows, the slow rise in base level of upper Cretaceous Hell Creek Formation is marked by single storied laterally accreting sandstone deposits found within a high accommodation setting as a result of a fluvial system consistent with highly sinuous meandering streams migrating across a vast vegetated floodplain. Of note, as seen in Figures 9 and 10, two possible upper Hell Creek thick multistory sandstone deposits sit on an erosional surfaces incising into floodplain deposits below marking perhaps a falls and then rises in accommodation space as it relates to transgressive and regressive cycles of the Western Interior Seaway described as the Breien Member and the Cantapeta marine advances. As base level continues to rise across the K/Pg Boundary and into the Fort Union Formational deposits within Makoshika State Park, ponding increased resulting in the lacustrine deposits represented by the fine-grained

variegated beds. At times the high accommodation, low energy environment became clastic starved as mire conditions created the lignite seams found at the K/Pg Boundary and the overlying lower Fort Union throughout Makoshika State Park.

The next sequence, as shown in Figure 47 above, is marked by a large scale incision, first shown as Figure 33 but repeated below for reference in this chapter as Figure 48, due to the destruction of accommodation space created by the eustatic fall of the Cannonball Sea to the east (Hartman, 1993) ultimately resulting in negative accommodation space and the truncation of underlying deposits. As accommodation space begins to rise again, deposition follows as the incised valley begins to fill with very low sinuous streams that erode into each other within the low accommodation created by the incised valley walls. This produces stacked channel or amalgamated channel bodies. The transgressive sequence continues and accommodation increases allowing for better preserved channel bodies that are characterized by an abundance of lateral accretion surfaces indicating that the stream have become more sinuous as they meander across a wider upper portions of the incised valley or have over-topped the valley walls. The uppermost sandy deposits within the valley display a marine influence with tidally created rhythmites and soft-sediment deformation. The shale deposits that overlay the paleovalley contain gypsum crystals deposited by sulfate rich waters in the substrate, which suggests that the deposition of these shales had a marine influence. In some locations within the park, both floodplain deposits with single-storied laterally accreting channels interfingering with fine-grain low energy deposits and the lacustrine deposits of the variegated beds return.

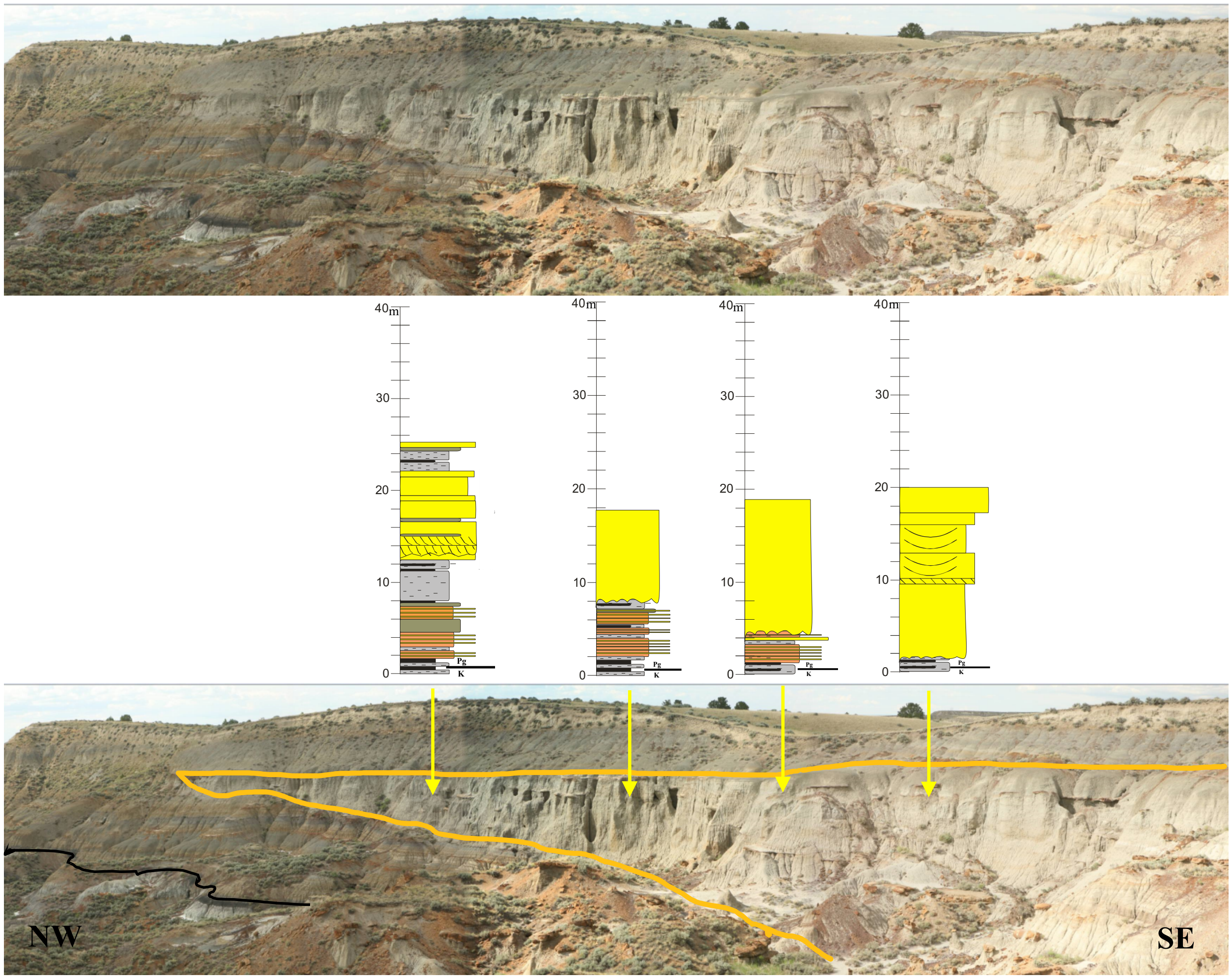

Figure 48 Site 1 VA-VD stratigraphic columns with a panoramic photo of Site 1. Incision outlined in yellow with column locations indicated by arrows. Hell Creek/Fort Union contact highlighted in black.

6.2 Laramide Tectonism Hypothesis

The second scenario suggests that the rise of the Rocky Mountains during the Laramide Orogeny resulted in tectonic loading to the west with associated downwarping to produce a foreland basin. Based on the geometry of a foreland basin (see Figure 49), the greatest accommodation would have been along the edge of the orogenic belt with decreasing subsidence to the east where a flexturally upwarped forebulge would have occurred (Catunaenu et al., 2000). In this scenario, accommodation space would be dependent upon the location of the foreland

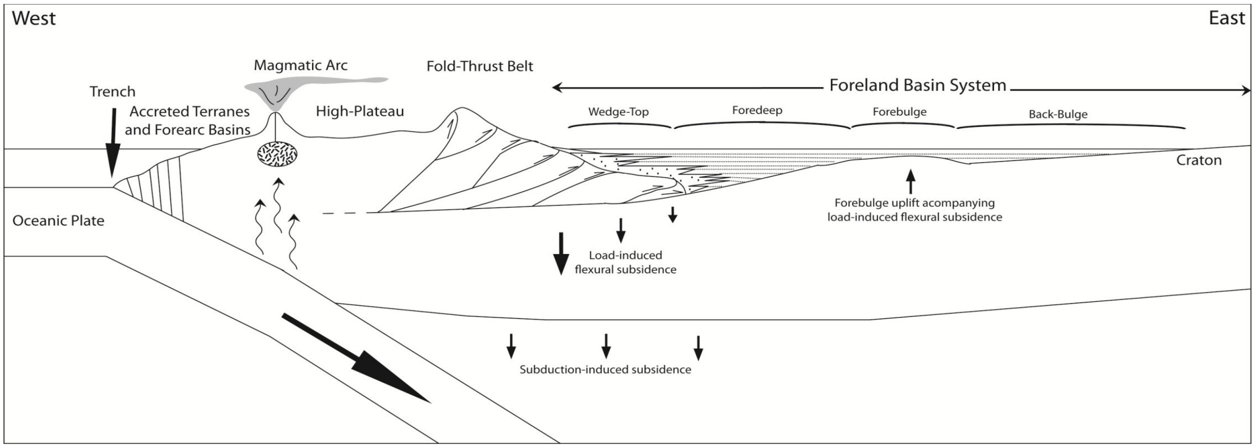

Figure 49 Laramide Foreland geometry in cross-section. From Slattery et al., (2015) modified from DeCelles and Giles, 1996; Miall et al., 2008

basin and the foreland bulge. The change of accommodation space would be gradual at a constant rate over a longer timescale (Catuneanu et al., 1997, 2006). If the deposition is tied to the foreland basin, the associated deposits would be similar to the transgression scenario, however, the highest accommodation in the basin would have occurred to the west with decreasing subsidence/accommodation to the east in the proximity of Makoshika State Park. Stream paleocurrent direction might also be expected to shift with westward drainage into the foredeep depending on the location of the foreland basin and the extend of uplift on the forebulge. Deposition across a rising forebulge would produce a shallow trend for marine deposits and a reduced gradient for fluvial systems and reversal of stream flow with drainage to the west suggesting that a coarsening grain-size would persist across the boundary.

The observations within this study are not consistent with what would be expected due to tectonic loading to the west. There is no evidence of a westward shift in drainage due to differential subsidence caused by tectonic loading to the west as paleocurrent directions in eastern Montana stayed consistently to the east southeast throughout deposition of the Hell Creek and Fort Union Formations. Tectonism also would likely cause a coarsening upward sequence across the K/Pg Boundary as opposed to the fining upwards sequences observed in both the Hell

Creek and Fort Union formations, and the decrease in accommodation would likely have resulted in development of a regional unconformity associated with shifting stream flow. Lastly, tectonism would be gradual and constant with a change in accommodation in one direction, and the time-frame of any cyclic changes would have been over millions of years (Catunaenu, 1997, 2006). The deposition across the K/Pg Boundary in Makoshika State Park shows a repeating pattern of short term, high-to-low-to-high accommodation cycles that are not consistent with solely a tectonic loading influence to the west.

6.3 K/Pg Extinction Hypothesis

The third scenario suggests that the bolide impact of the Cretaceous-Paleogene mass extinction led to a loss of vegetation throughout western North America resulting in an increase in erosion across the landscape. (Sheehan, 2004; Fastovsky, 2008). This theory states the thermal blast associated with the bolide impact would ignite forest fires across western North America. Additionally, the following nuclear winter caused by debris from the bolide in the atmosphere would severely damage vegetation globally. The loss of vegetation would increase runoff and erosion of clastics choking streams with sediment. Widespread flooding would occur due to the choked streams overflowing their banks. The resulting sediments would represent a relatively instantaneous change in the depositional environment and would likely show no signs of the gradual change that may be seen with geologically slower transgression and tectonic loading theories.

The observations within this study are not consistent with what is to be expected in this scenario. Prior to the incision caused by the paleovalley described in this study, there is no evidence of an influx in clastic sedimentation due to the increased erosion described in this scenario. Across the boundary, evidence indicates a change from an environment displaying

increasing accommodation space into a high accommodation environment of low energy and fine-grained deposition associated with lakes and mires. In fact, the multiple lignite deposits that highlight and overlay the K/Pg Boundary would suggest a sediment starved environment. Additionally, the deposits described as a whole show a gradual, and cyclical change of accommodation independent of the K/Pg Boundary as opposed to the instantaneous change that would be expected should the deposits be tied to the plant loss caused by the extinction event. There is also a return to lake deposition above the incised valley which was far removed from the extinction event in time. These deposits are separated by the incision surface of the incised valley, which indicates cyclic changes in accommodation space occurred.

6.4 Discussion

This study supports the hypothesis proposed by Fastovsky and Sheehan in 1994 stating that the change in deposition style across the K/Pg boundary is due to base level changes that resulted from fluctuations in the extent of the Cannonball Sea to the east. Based on this study's observations at Makoshika State Park in Glendive, Montana the transgression scenario is the most likely of the three proposed scenarios based on multiple factors. Using Shanley and McCabe's (1994) sequence stratigraphy due to base level changes for fluvial systems as a guide, the deposition found within Makoshika State Park represent a transgressive sequence that include cyclical short term base level fluctuations. The transition is gradual across the K/Pg Boundary and paleocurrent directions of preserved streams stay constant as they drain east southeast towards the Cannonball Sea located within the Williston Basin.

The evidence presented in this study discount both the Laramide tectonism and extinction event scenarios. As for the Laramide tectonism scenario, tectonically loading to the west should have left evidence that is not displayed in Makoshika State Park. Whilst the changes would be

gradual across the K/Pg Boundary, the effect on sedimentation would be preserved in one of two ways, neither of which are backed by the observations in this study. First, if sedimentation was related to the creation of a foreland basin, the highest accommodation would be to the west resulting in a change of stream paleocurrent directions to shift westward as they drain into the subsided basin. Second, if the sedimentation is influenced by the foreland bulge, a coarsening upward sequence would have been preserved across the boundary as opposed to the fining upward sequence that is present. Finally, tectonism would only cause a shift in accommodation in one direction and would not result in the cyclical pattern preserved within the Site 1 and Site 3 deposits. As for the K/Pg extinction event and the associated loss of vegetation scenario, the result should have left evidence of a sudden change in sedimentation as opposed to the gradual change presented in this study. Additionally, the loss of vegetation would have resulted in an increase in clastic erosion and deposition at, or tangential to, the K/Pg Boundary. This study concludes that sediment starved lacustrine and even mire conditions persisted at and following the K/Pg mass extinction event.

7. Conclusion

The purpose of this study was to answer the following questions as they relate to the testing of three main hypotheses scenarios previously proposed to explain the changes in depositional style across the K-Pg Boundary:

1. What sedimentary facies existed within the Hell Creek Formation deposits of Makoshika State Park? Once the facies are identified, they will be used to interpret the depositional environments of the Late Cretaceous as they related to testing the three hypotheses.
2. What sedimentary facies existed within the Fort Union Formation deposits of Makoshika State Park? Once the facies are identified, they will be used to interpret the depositional environment of the Early Paleogene as they relate to testing of the three hypotheses.
3. How do the facies change across the Cretaceous-Paleogene boundary within Makoshika State Park? Once, a change is identified, the observed evidence will be used to identify the main driver causing a change of sedimentation across the boundary.

Based on the observations of this study, the following conclusions can be made:

- The sedimentary deposition of the Late Cretaceous Hell Creek within Makoshika State Park represent a richly vegetated floodplain with widely separated meandering stream migration. Several possible large scale valley incisions were identified suggesting changes in accommodation space as a result of fluctuations of regional base level.

- The sedimentary deposition of the early Paleogene Fort Union deposits represent an estuary with lacustrine and mire environments that would receive an occasional influx of fine-grained deposition due to crevasse splays of nearby streams. A large scale valley incision cuts into these deposits again suggesting changes in accommodation space as a result of fluctuations of regional base level. The paleovalley is filled with amalgamated channels confined to the lower portion of the valley that transition back into increasingly isolated meandering streams overlain by sedimentation that have a marine influence including tide related rhythmites and the precipitation of evaporites.
- Using the facies to identify the depositional environment changes across the K/Pg Boundary, and applying the concepts of fluvial and sequence stratigraphy, the evidence suggests that only one of the three previously proposed scenarios is likely. The reasoning for each scenario is listed below:
  1) The transgression of the Cannonball Sea to the east is the most likely scenario due to the gradual and cyclical change in deposition related to fluctuations of base level observed below and above the K/Pg Boundary, as well as the consistent east southeast paleocurrent directions preserved in the stream deposits.
  2) The influence on Laramide tectonic loading to the west can be discounted due to the trend in accommodation space recorded through deposition showing an increase in accommodation to the east as opposed to the subsided foreland basin to the west, which would result in a change in paleocurrent direction as the streams shift to drain westward towards the foreland basin. Additionally, if

the deposition was influenced by the uplift of a foreland bulge, a constant coarsening upwards of sediment deposition would exist as opposed to the fining upward sequence followed by cyclical regressional then transgressional sequences that are documented in this study.

3) The K/Pg extinction event scenario can be discounted due to a lack of evidence of the sudden and drastic change in deposition at the boundary as opposed to the gradual change observed in this study. Additionally, this study observed no evidence of an influx of clastic material due to the increase of erosion that would be expected with a sudden and widespread loss of vegetation.

This study concludes that the change in sedimentation across the K/Pg Boundary is due to fluctuating base levels of the Western Interior Seaway. The results of this study increases our understanding, especially of the terrestrial realm, of a much studied and important time in our planet's history and provides a more fully resolved understanding of the landscape evolution associated with the K-Pg Boundary along the western margin of the Williston Basin.

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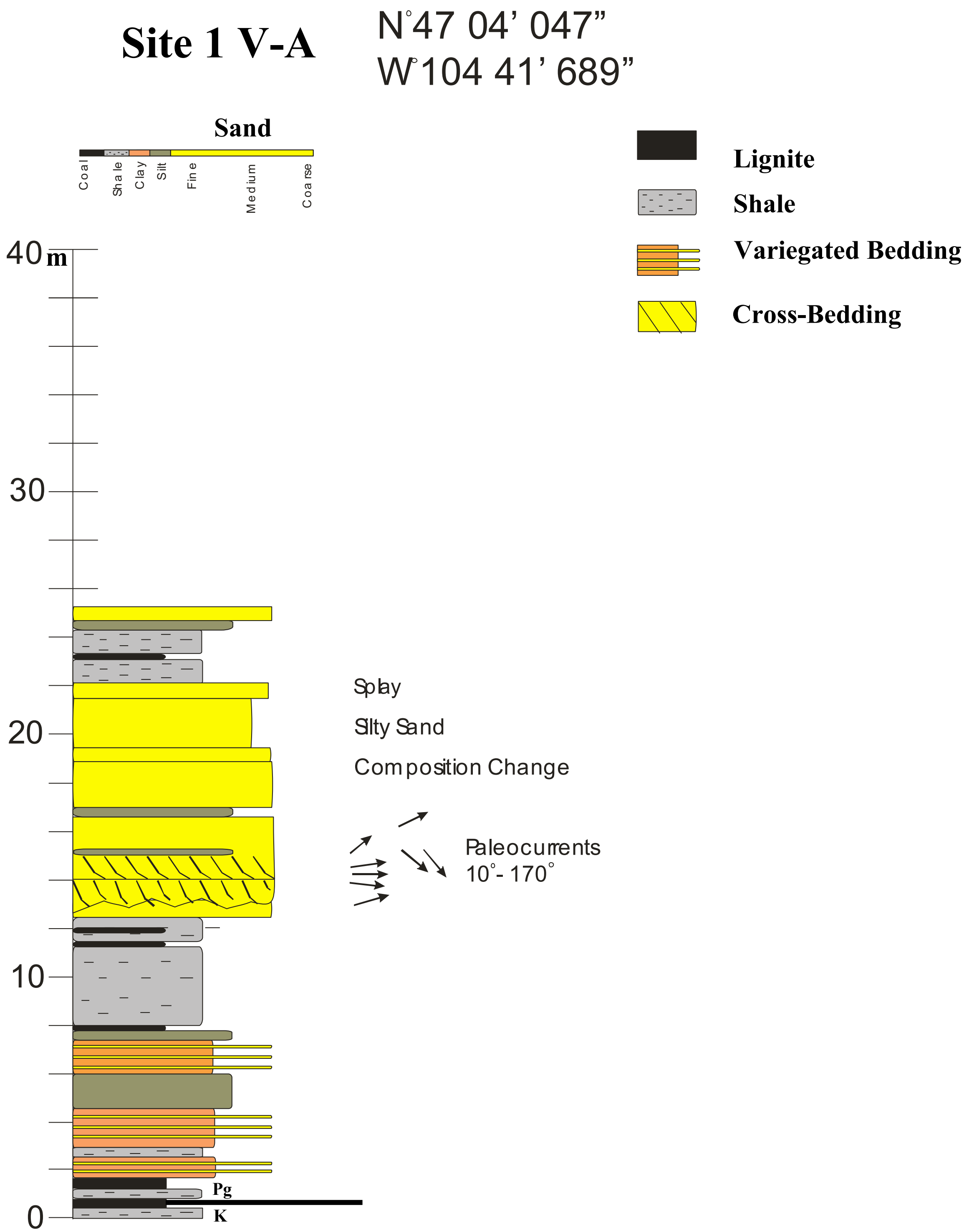
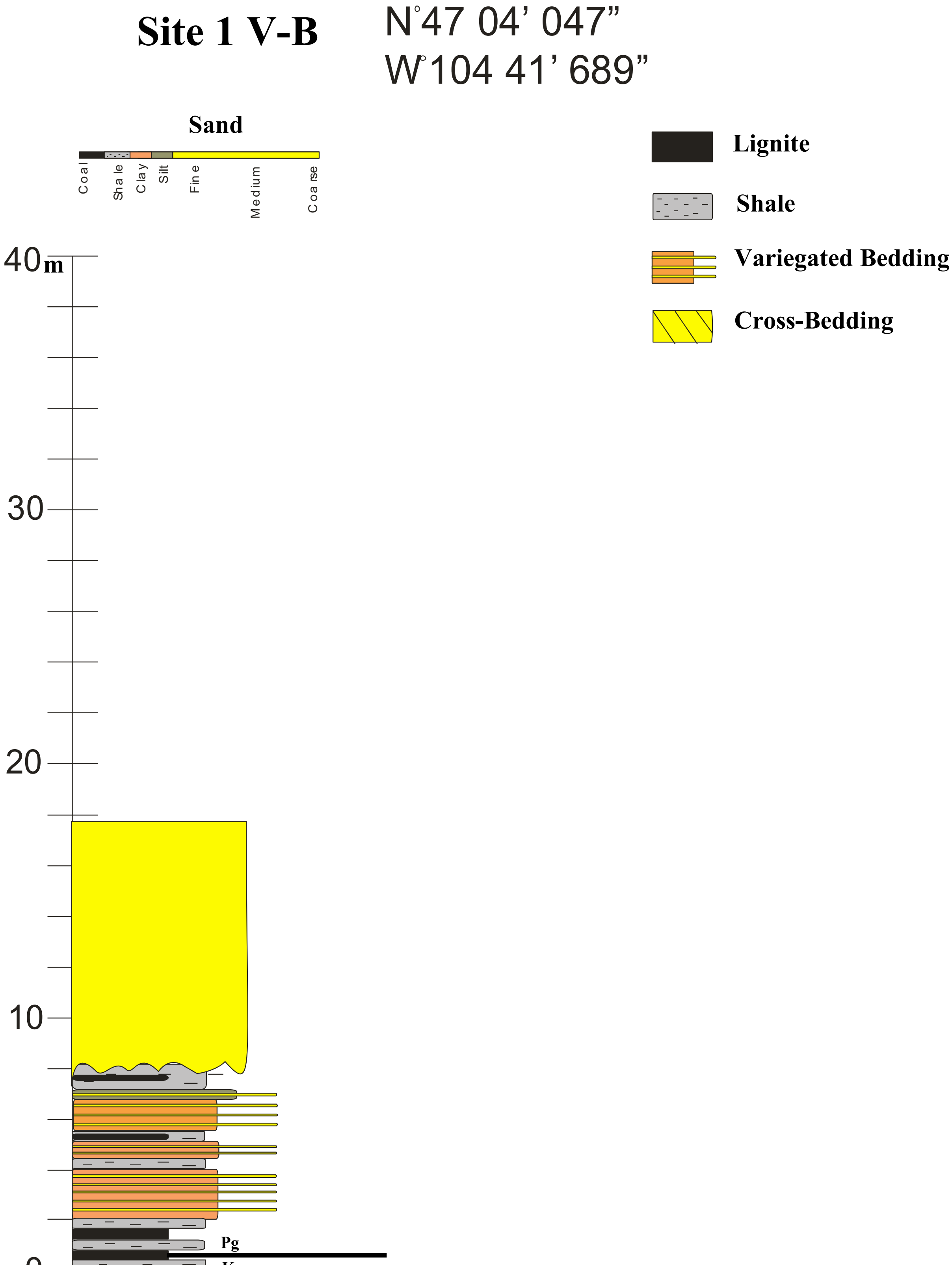
Appendices

Appendix A: Stratigraphic Columns with Measured Section Photographs



Site 1 V-A Stratigraphic column.


Photo of the Site 1 V-A measured location.

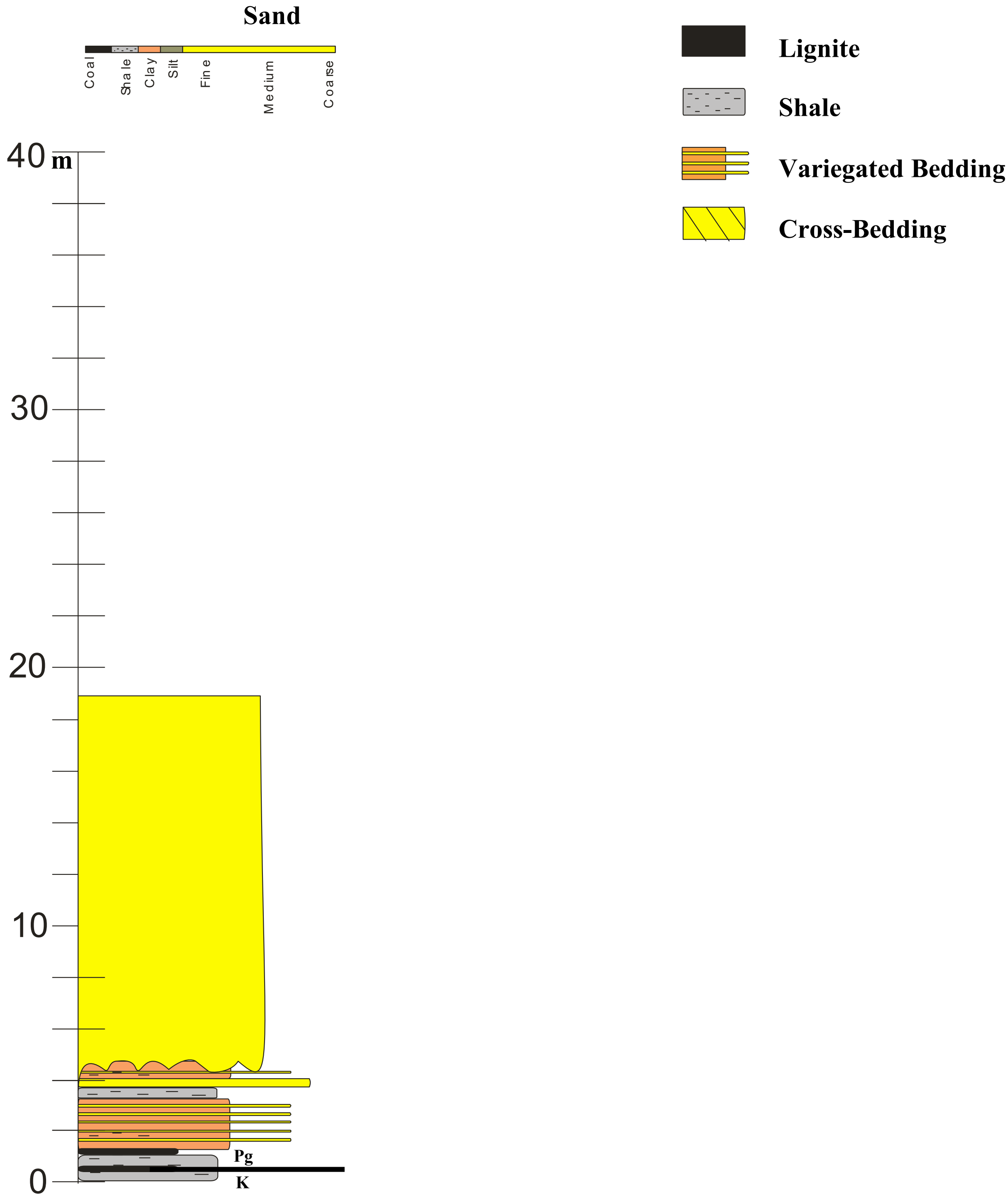


Site 1 V-B Stratigraphic column.


Photo of the Site 1 V-B measured location.

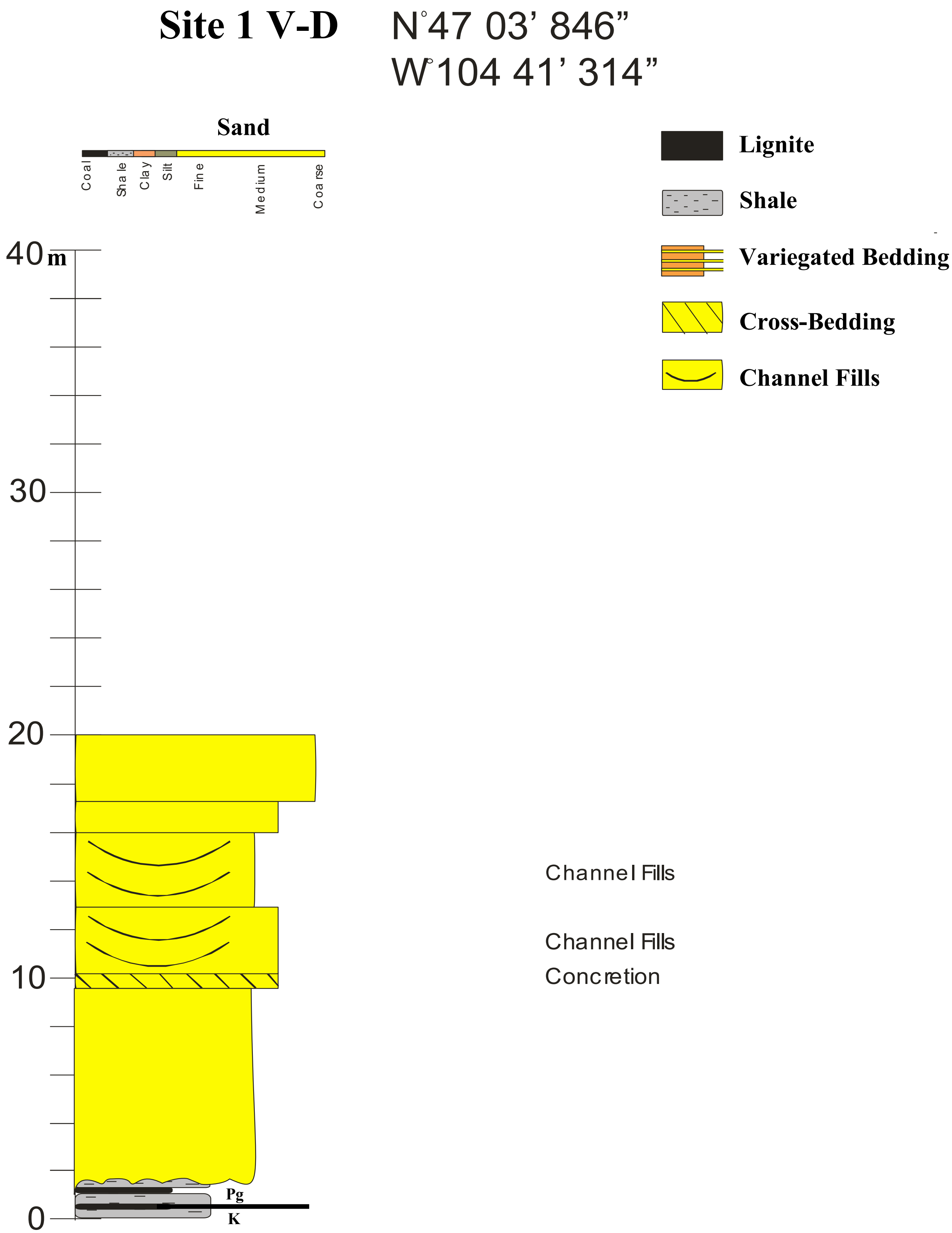
Site 1 V-C

N°47 03' 956"
W°104 41' 485"



Site 1 V-C Stratigraphic column

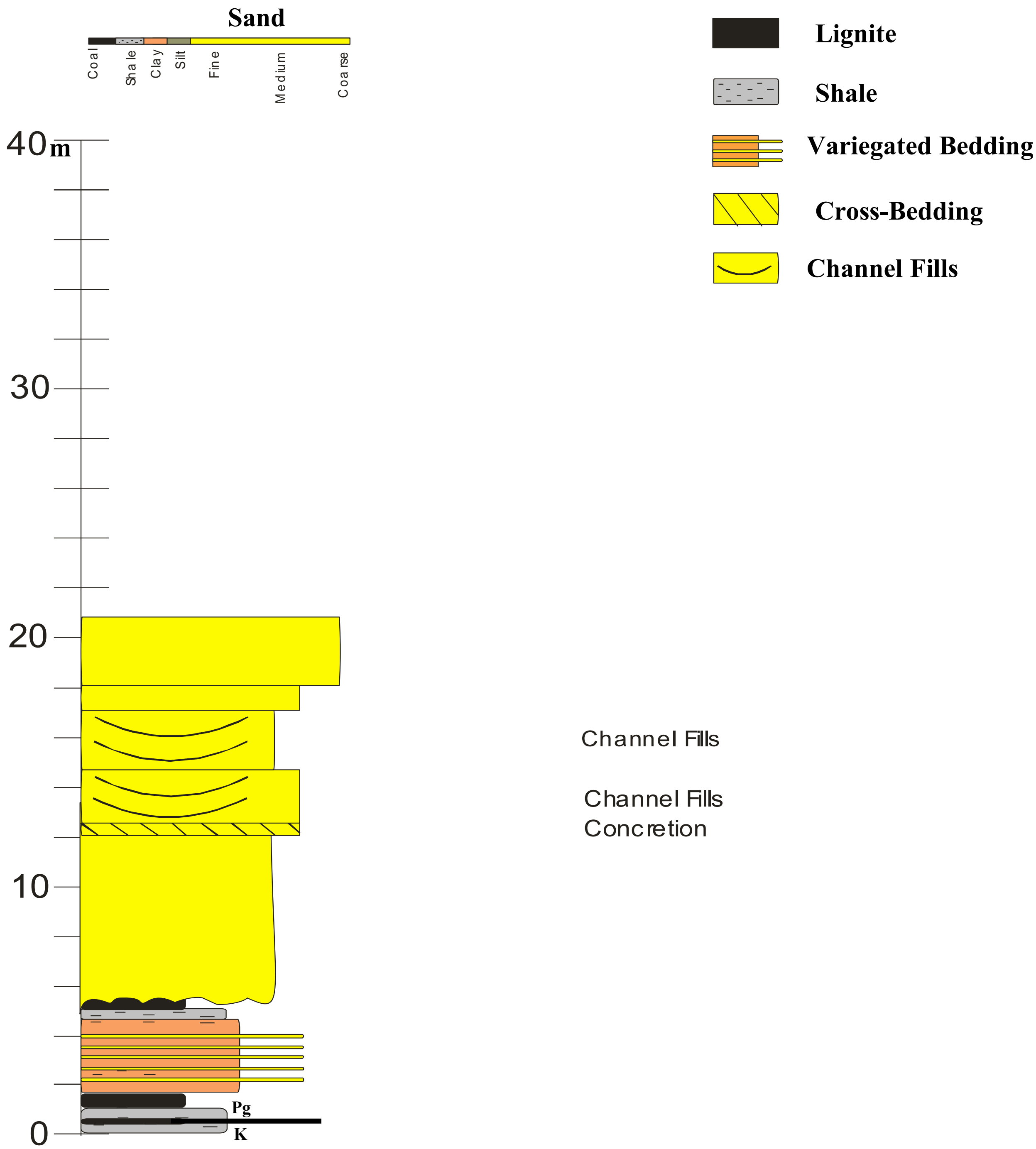

Photo of the measured Site 1 C-V location. People for scale.



Site 1 V-D Stratigraphic column.

Site 1 V-E

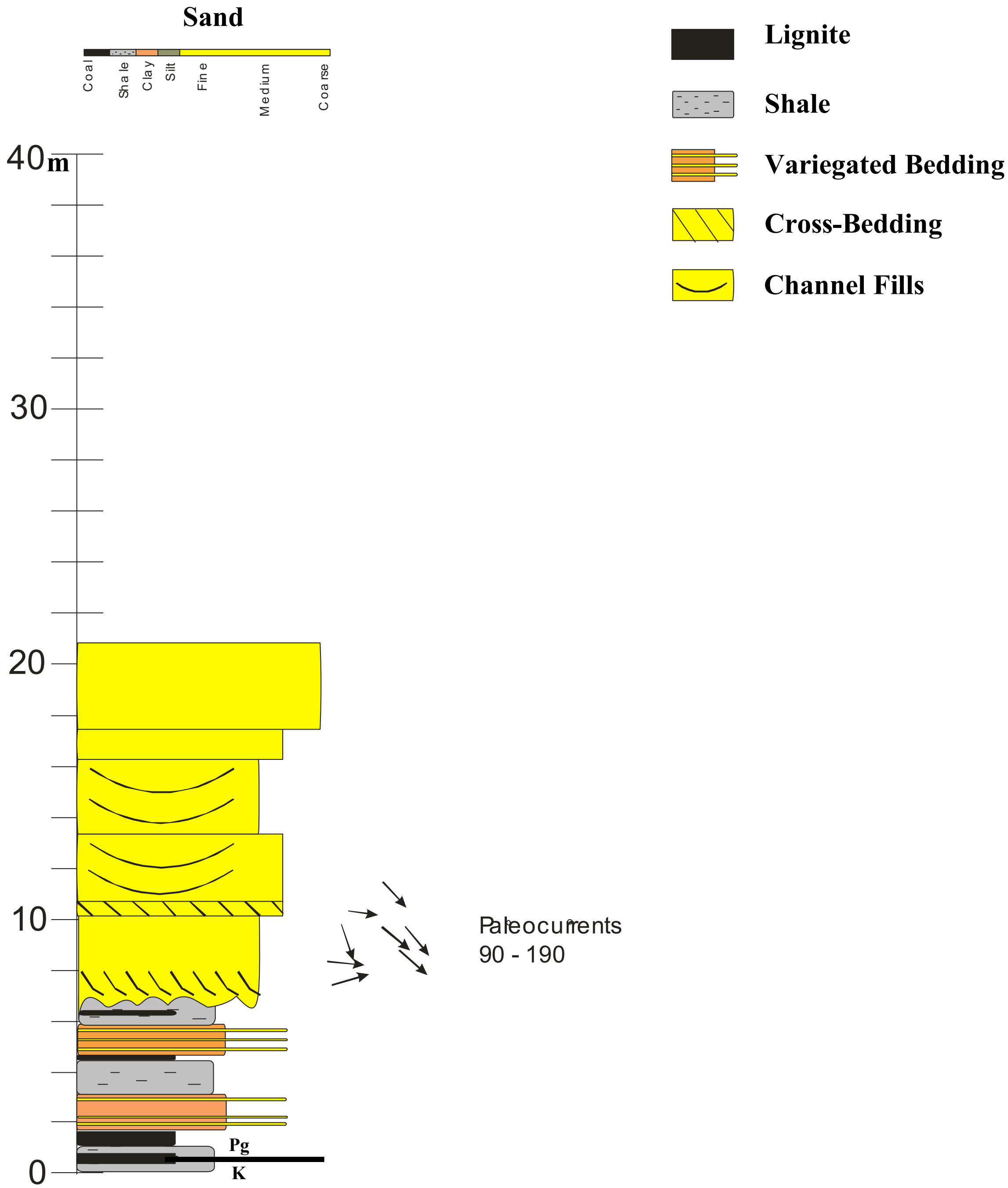
N°47 03' 846"
W°104 41' 314"



Site 1 V-E Stratigraphic column.

Site 1 V-F

N°47 03' 046"
W°104 41' 314"



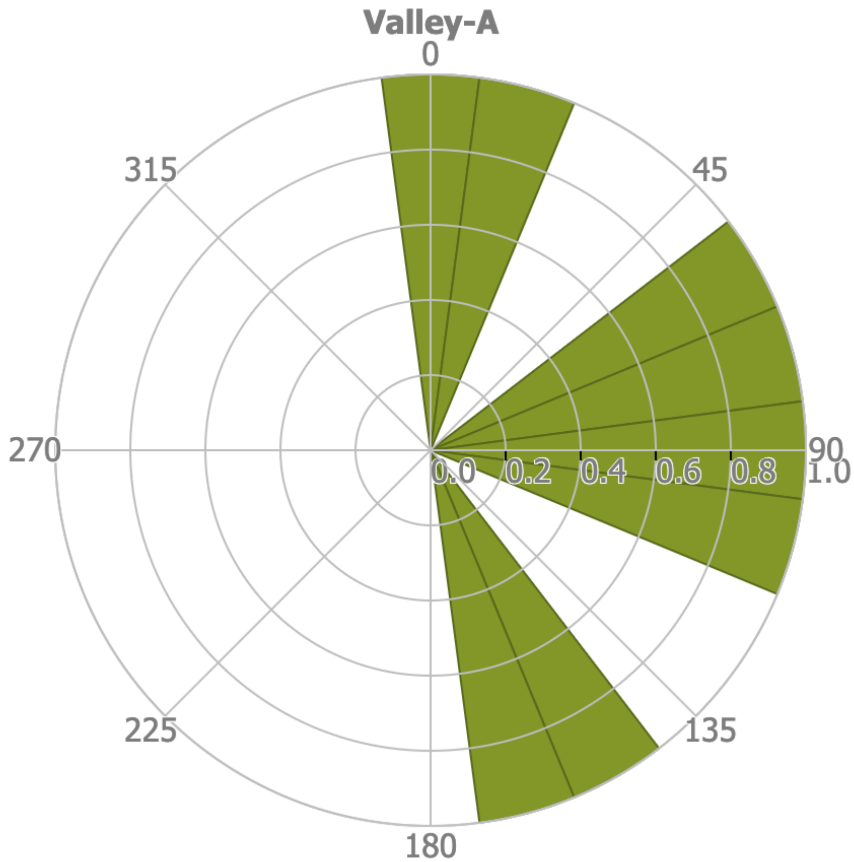
Site 1 V-F Stratigraphic column.


Photo of the Site 1 V-F measured location.

Appendix B: Paleocurrent Measurements

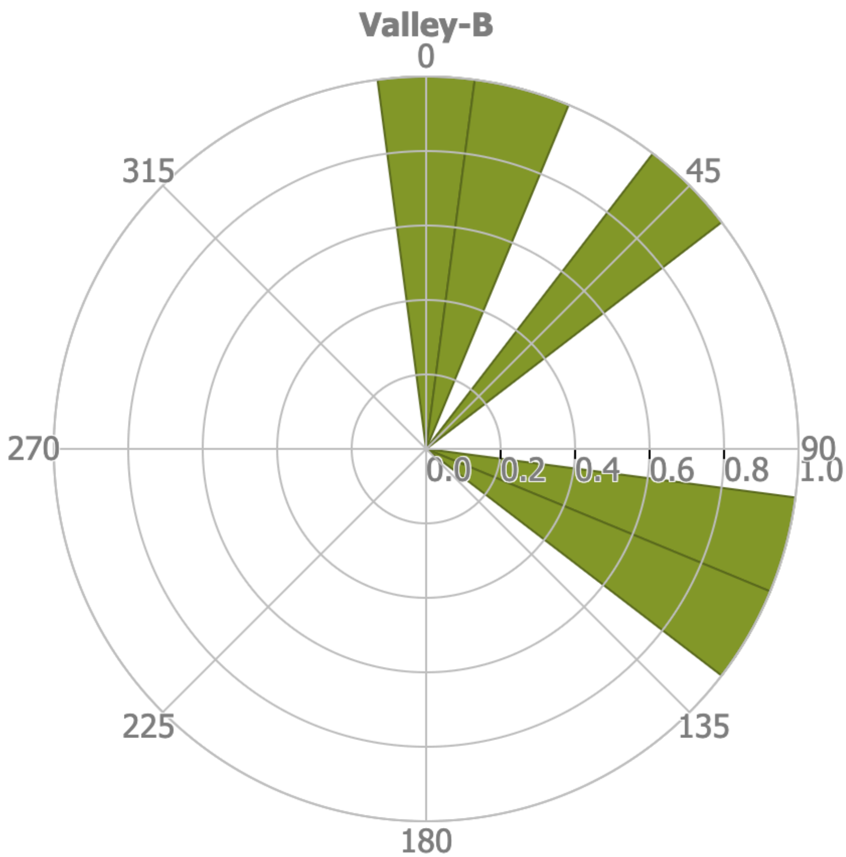
Section	Measurements	N	Vector Mean	Vector Length
Site 1 V-A	70, 110, 90, 80, 10, 20, 170, 150	8	87.2	0.6324
Site 1 V-B	120, 5, 25, 110, 55	5	62.5	0.707
Site 1 V-F	90, 95, 100, 135, 135, 130, 180, 150, 130, 180, 190, 100, 140, 160, 100, 110	16	132.2	0.8564
Site 1 V-H	270, 260, 160	3	235.9	0.6615
Site 3 Amphitheater	120, 120, 160, 120, 125, 70, 145, 60, 160, 160, 140, 145, 125, 105, 105, 140, 105, 120	18	124.4	0.8928
Site 4 Eyeful Vista	125, 120, 120, 95, 85, 120, 75, 65, 90, 105, 95, 120	12	101.4	0.9444
Site 5 Sand Creek Overlook	125, 130, 230, 230, 220, 220, 225, 230, 200, 205, 255, 225, 235	13	214.2	0.8157
Site 7 ELP	95, 110, 115, 115, 95, 85, 85, 125, 155, 90, 105, 110, 115, 85, 120, 150, 155	17	112	0.9244

Appendix C: Rose Diagrams



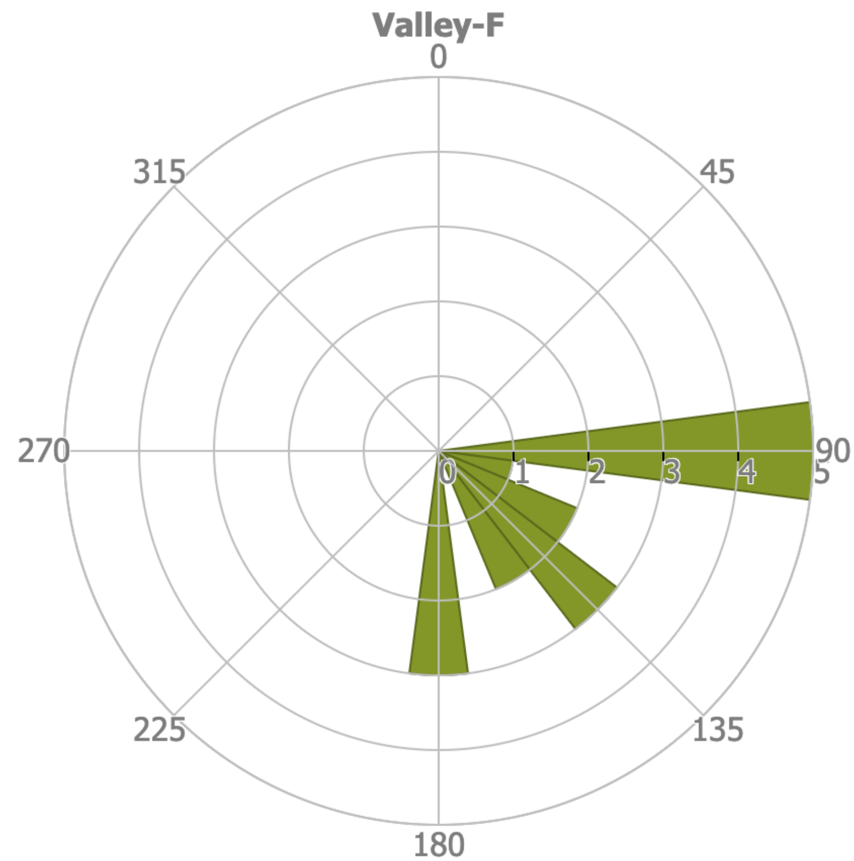
n = 8
Vector Mean = 87.2°
Average Length = 0.6324
Circular Variance = 0.4216

Rose Diagram of the Site 1 V-A location.



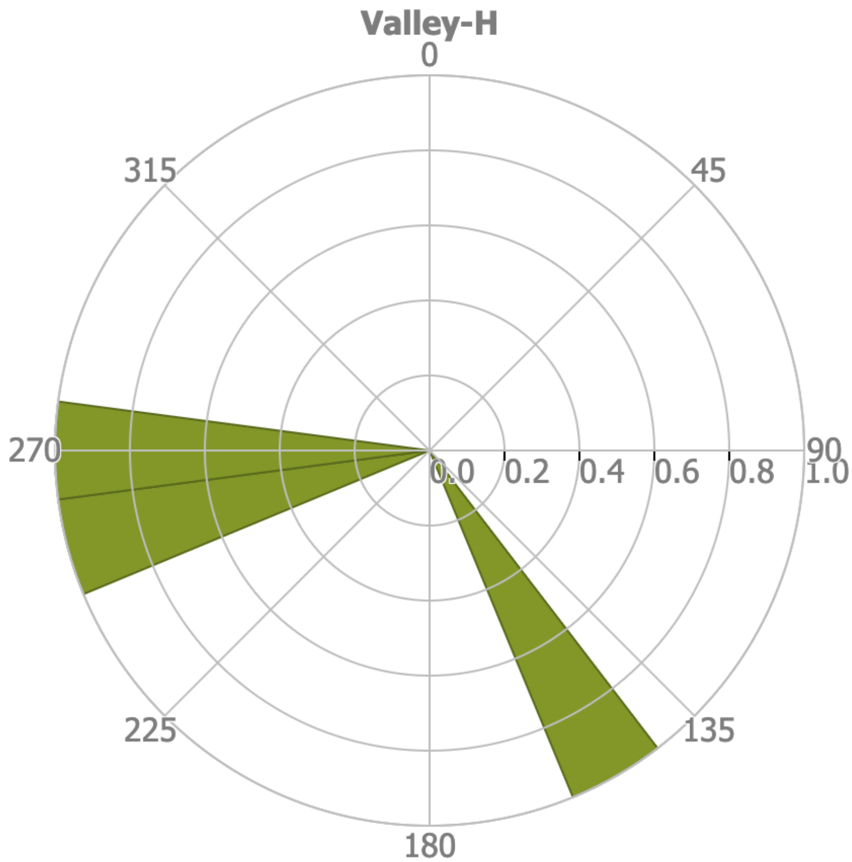
n = 5
Vector Mean = 62.5°
Average Length = 0.707
Circular Variance = 0.293

Rose Diagram of the Site 1 V-B location.



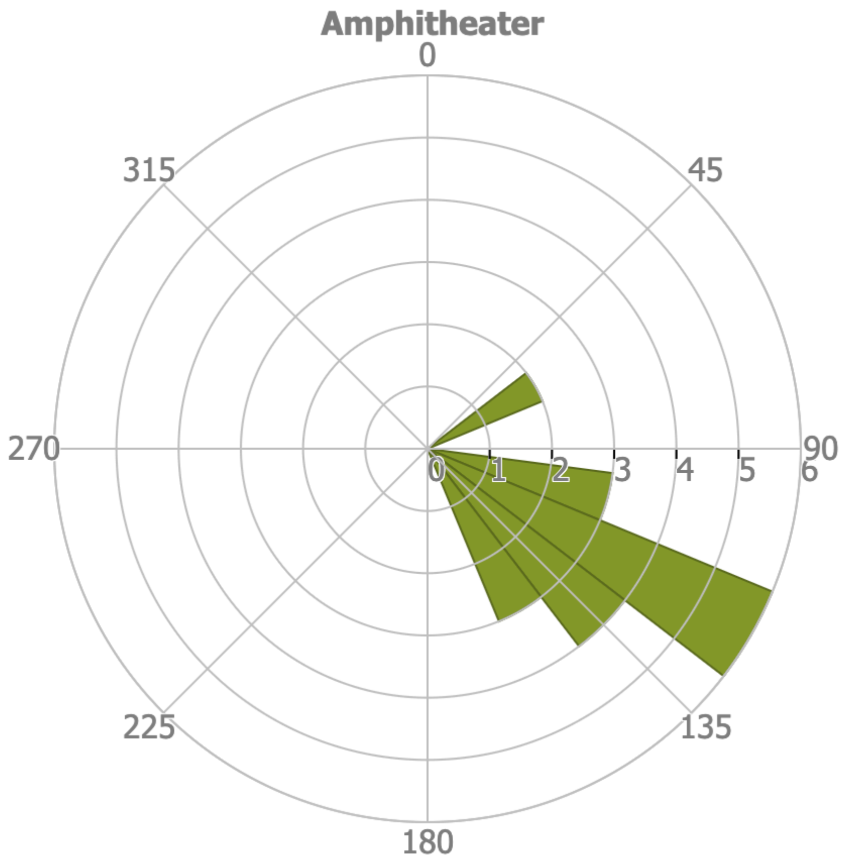
n = 16
Vector Mean = 132.2°
Average Length = 0.8564
Circular Variance = 0.1436

Rose Diagram of the Site 1 V-F location.



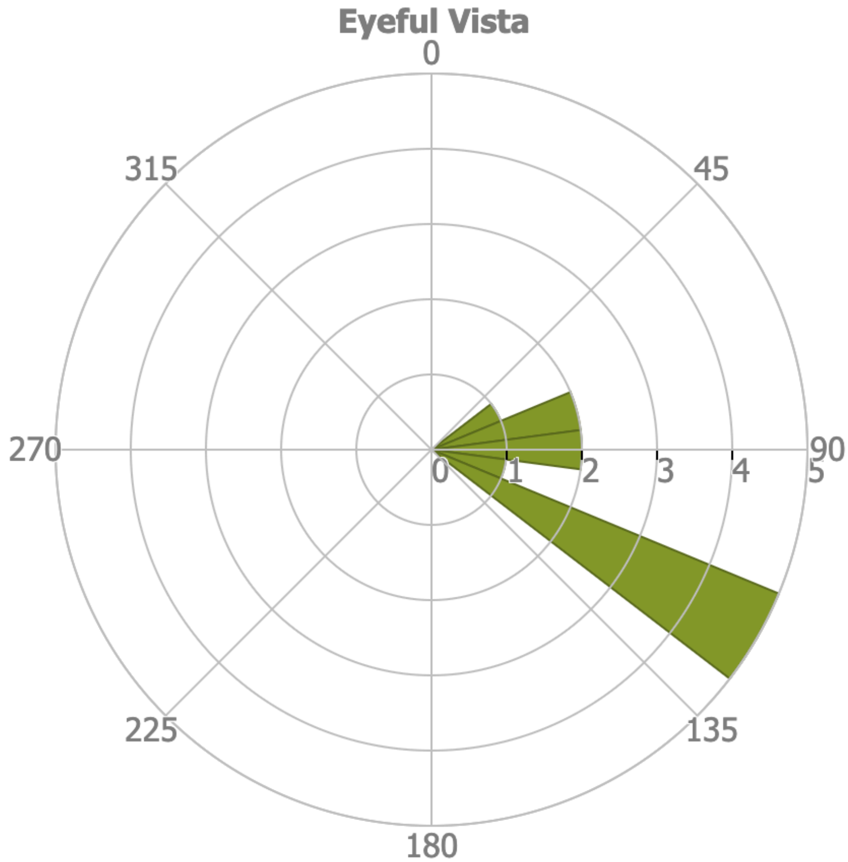
n = 3
Vector Mean = 235.9°
Average Length = 0.6615
Circular Variance = 0.3385

Rose Diagram of the Site 1 V-H location.



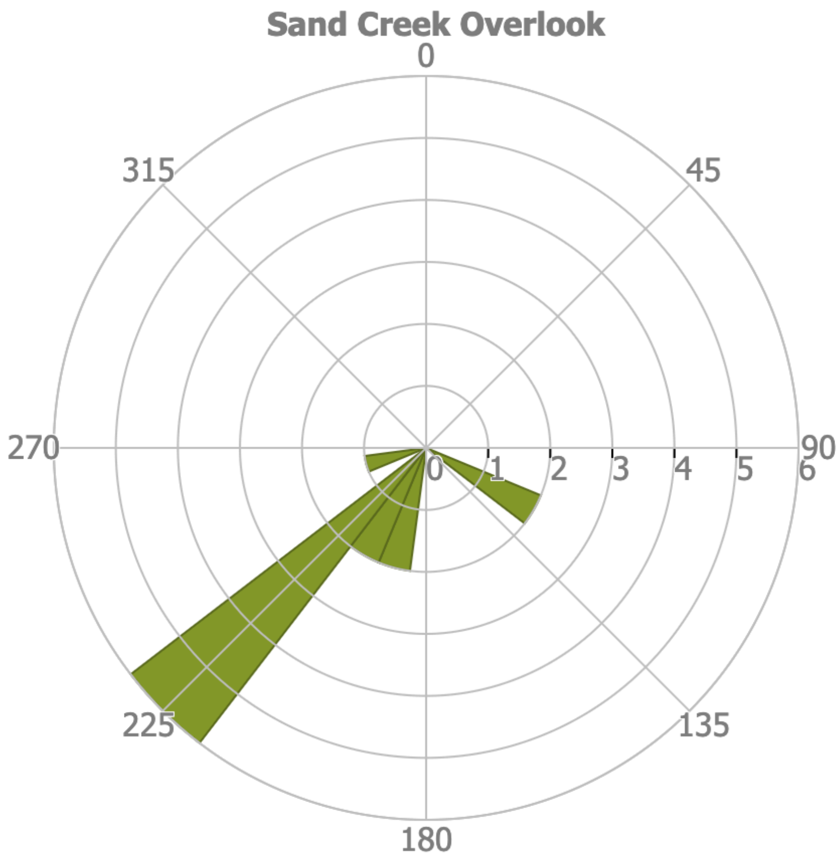
n = 18
Vector Mean = 124.4°
Average Length = 0.8928
Circular Variance = 0.1072

Rose Diagram of the Site 3 Amphitheater location.



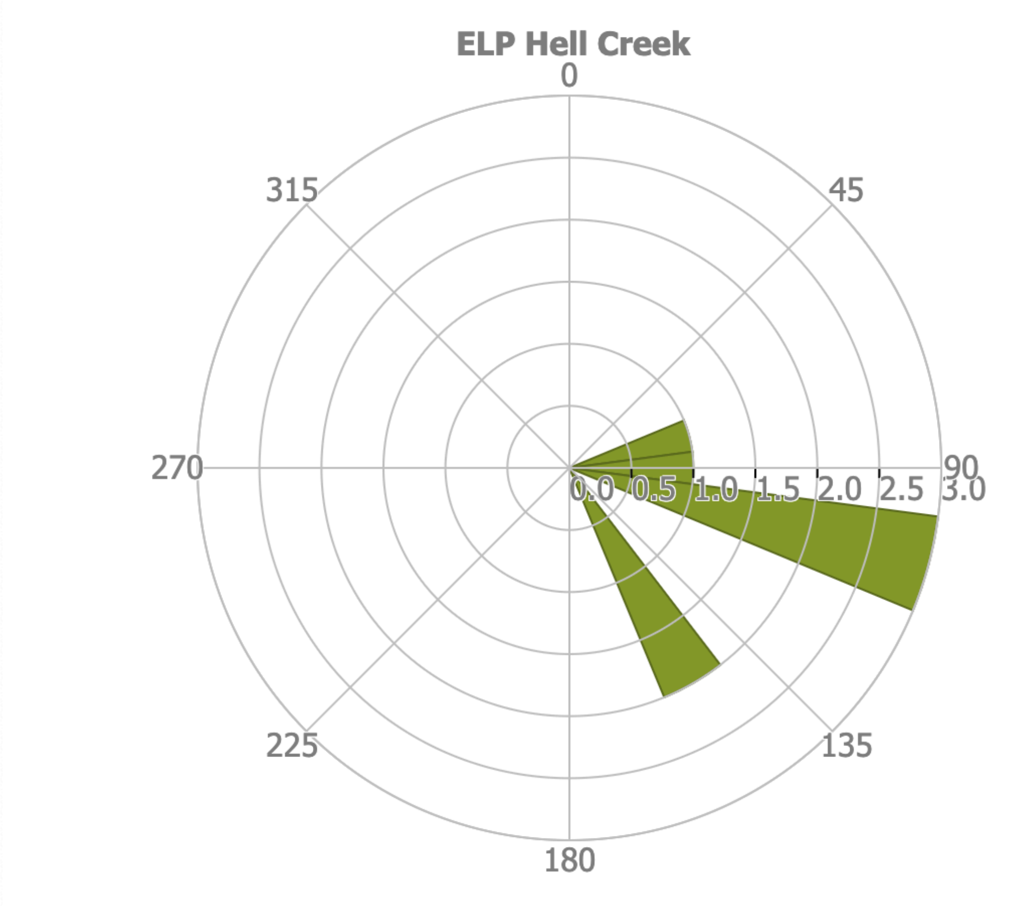
n = 12
Vector Mean = 101.4°
Average Length = 0.9444
Circular Variance = 0.0556

Rose Diagram of the Site 4 Eyeful Vista location.



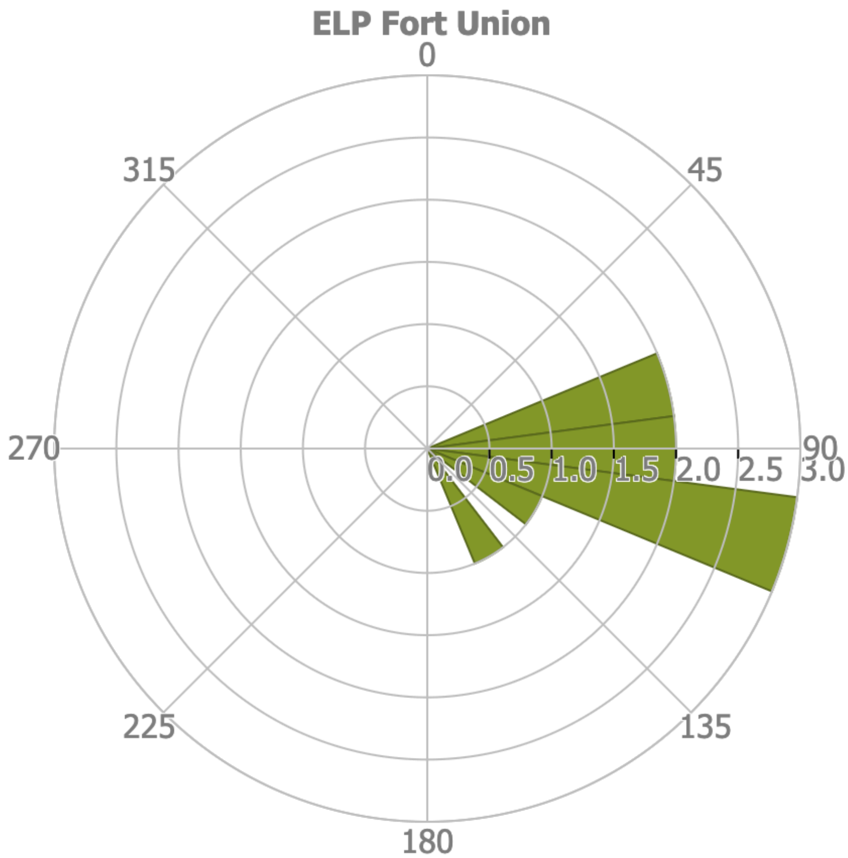
n = 13
Vector Mean = 214,2°
Average Length = 0.8157
Circular Variance = 0.1843

Rose Diagram of the Site 5 Sand Creek Overlook location.



n = 8
Vector Mean = 115.9°
Average Length = 0.6568
Circular Variance = 0.3432

Rose Diagram of the Site 7 ELP Hell Creek location.



n = 9
Vector Mean = 108.5°
Average Length = 0.9348
Circular Variance = 0.0652

Rose Diagram of the Site 7 ELP Fort Union location.