Stratigraphy and depositional environments of the upper Fox Hills and lower Hell Creek Formations at the Concordia Hadrosaur Site in northwestern South Dakota

Mary C. Colson[1], Russell O. Colson[2*], and Ron Nellermoe[3]

[1] *Moorhead Junior High, Moorhead, MN 56560, U.S.A.*

[2] *Department of Anthropology and Earth Science, Minnesota State University Moorhead, Moorhead, MN 56563, U.S.A.*

[3] *Department of Biology, Concordia College, Moorhead, MN 56560, U.S.A.*

[*] *Author to whom correspondence should be addressed:colson@mnstate.edu.*

ABSTRACT

Many of the dinosaur-bearing bone beds in the Hell Creek Formation of the Dakotas and Montana involve multiple species preserved in the upper Hell Creek Formation. In contrast, the Concordia Hadrosaur Site is monospecific with respect to dinosaurian taxa and is situated in the lower Hell Creek Formation in a lithostratigraphic unit we associate with the Little Beaver Creek Member. This member consists of organic-rich sandstones, siltstones, and claystones that are distinctive within the Hell Creek Formation based on their uniformly fine grain size, purplish color, and presence of highly lignitic shale rather than coal. Similar lignitic deposits occur at other marine–terrestrial boundaries of the Fox Hills–Hell Creek Formations in the Little Missouri and Missouri River valleys.

The bone bed at the Concordia Hadrosaur Site (CHS) is associated with an extensive coastal swamp rather than a localized fluvial subenvironment such as river channel, floodplain, or abandoned channel. The bone bed itself lies at the transition from an extensive swamp (represented by highly organic mudstones) to a more fluvially dominated, distributary environment characterized by variegated mudstones, siltstones, and channel sandstones.

The thirty meters of exposed section at the Concordia site include the top of the Fox Hills Formation and lower parts of the Hell Creek Formation. We identify marine silts, muds, and sands, coastal dune sands, coastal swamp muds and silts, and fluvial sands and silts. The sediments are indicative of the marine–terrestrial transition from upper shoreface and foreshore environments to a complex system of coastal dunes, swamps, and distributary channels that formed during the progradation of the Hell Creek sediments into the Cretaceous Fox Hills seaway. Locally, grain size and organic fraction varied due to differences in the proximity to distributary channels, supply of organic material, and water depth.

Despite the concentration of bones dominated by a single species in the CHS bone bed, the high clay fraction of the bone bed matrix, combined with the fact that the lowest part of the bone bed has the greatest clay fraction, indicates that the bones were not introduced by way of a high-energy, catastrophic event, such as a flood. Rather, the bones accumulated in an area of quiet standing water. Although preliminary examination of the bones is consistent with this depositional interpretation, it does not necessarily provide direct support for it.

KEY WORDS: coastal progradation, Cretaceous, *Edmontosaurus*, Fox Hills Formation, Hell Creek Formation, Maastrichtian, North Dakota, South Dakota.

INTRODUCTION

The purposes of this paper are to document the depositional environments across the Fox Hills–Hell Creek formational contact at the Concordia Hadrosaur Site (CHS) and to discuss the relationship of depositional environments to the preservation of this rich bone bed. We describe and interpret nine depositional units exposed at the CHS that span the upper Fox Hills Formation and the lower Hell Creek Formation. Other marine–terrestrial transitions in the lower Hell Creek Formation are also examined.

The CHS is located in a bluff along the Grand River in Corson County of northwestern South Dakota. The bone bed is in the Hell Creek Formation, five meters above its contact with the Fox Hills Formation. The bone bed is 30 cm thick and extends the entire 470-meter length of the bluff. Approximately 2,200 square feet of the bone bed have been excavated at the east end of the bluff, primarily from two quarries, yielding nearly 5,000 hadrosaur bones identified as *Edmontosaurus*. Collected specimens are housed at Concordia College.

Discoveries in the CHS add significantly to our understanding of Late Cretaceous environments in northwestern South Dakota. The CHS is located in eastern parts of the Hell Creek Formation's outcrop area of South Dakota, in a less-studied area than other exposures of the formation (Johnson et al., 2002). It is situated just above the marine–terrestrial transition from the upper part of the Fox Hills Formation into the lower part of the Hell Creek Formation. Sedimentological characteristics of the CHS sandstones, mudstones, and bone bed differ significantly from other Hell Creek dinosaur-bearing sites, which are found mostly in the upper Hell Creek Formation. The sedimentology also differs from other bone-bearing sites in the lower Hell Creek Formation that are within a few miles of the CHS. Those sites are up-section, near the Firesteel Coal, and they contain a greater taxonomic diversity of dinosaurs than does the CHS (Jacobson and Sroka, 1998).

The CHS bone bed differs from typical dinosaur-bearing sites of the Hell Creek Formation in three ways. It is in lower rather than upper parts of the Hell Creek Formation, it has a lower diversity of dinosaurs, and it does not occur in a primarily fluvial deposit. Many of the best-documented vertebrate sites of the Hell Creek Formation occur in its upper part. In eastern Montana, this is due in part to stratigraphic bias in sampling of the upper 50 m of the Hell Creek Formation, where outcrops are less rugged and more easily accessible than outcrops in the lower part of the formation (Clemens, 2002). Another bias may be due in part to greater interest in events related to the Cretaceous–Tertiary boundary as recorded at the top of the formation (Fastovsky and Dott, 1986; Fastovsky, 1987; Nichols and Fleming, 1990; Johnson and Hickey, 1990; Fiorillo, 1998; Johnson et al., 2002). In southwestern North Dakota, Murphy et al. (2002) reported that dinosaurian fossils are found predominantly in the middle to upper parts of the Hell Creek Formation. These remains are found in fluvial strata and include many species (Frye, 1969; Moore, 1976; Butler, 1980; Fastovsky and Dott, 1986; Fastovsky, 1987, 1990; Johnson and Hickey, 1990; Hoganson et al., 1994; Oakland and Pearson, 1995; Fiorillo, 1998; White et al., 1998). White et al. (1998) reported that flood plain and channel deposits in the Hell Creek Formation of eastern Montana and western North Dakota preserve the largest fraction of the total dinosaurian fauna, with members of at least eight families represented.

STRATIGRAPHIC SETTING

Introduction

The Fox Hills–Hell Creek formational transition records the intermingling of marine, brackish, and terrestrial paleo-environments as their representative sediments prograded toward the Cretaceous Western Interior Seaway. The contact between the two formations, and the strata above and below it, have been well studied in western and south-central North Dakota (Frye, 1969; Klett and Erickson, 1977; Wroblewski, 1999; Murphy et al., 2002) and in north-central South Dakota (Waage, 1968; Christians, 1992). Paleogeographically, the Fox Hills and Hell Creek Formations of northwestern South Dakota represent coastal-plain facies (Roberts and Kirschbaum, 1995).

The detailed stratigraphy of lower units in the Hell Creek Formation that contains the CHS is not well documented, and it was simply mapped as undifferentiated lower Hell Creek by Curtiss (1954). Furthermore, the CHS is five miles west of Waage's western-most mapped occurrence of the Fox Hills Formation in the Grand River valley (Waage, 1968, fig. 2). Based on our formational comparison at the CHS with other sites in southern North Dakota and northwestern South Dakota, we place strata of the bluff in the upper Fox Hills and lower Hell Creek Formations. The stratigraphic nomenclature of Frye (1969) is applied to the Hell Creek Formation (Fig. 1), and we use the nomenclature of Waage (1968) for the Fox Hills Formation. Lithostratigraphically, the Concordia Hadrosaur Site is in the Timber Lake and Iron Lightning Members of the Fox Hills Formation and in the Little Beaver Creek Member (Frye's nomenclature) of the lower Hell Creek Formation.

Fox Hills Formation of South and North Dakota

Waage (1968) studied the sedimentology and paleontology of the Fox Hills Formation of the Grand and Moreau River valleys of South Dakota (Ziebach, western Dewey, and eastern Corson Counties). He divided the Fox Hills Formation into three members (Fig. 1) and documented a progressive "freshening" as the marine environments representative of the low-

	North Dakota (Frye, 1969)	
	Little Missouri River Valley	**Missouri River Valley**
Hell Creek Formation	Pretty Butte Member — bentonites, bentonitic shales and thin channel sandstones	
	Huff Member — thick channel sandstones, vertebrate fossils	
	Bacon Creek Member — bentonitic shale, bentonites and thin lignitic shales	Fort Rice Member — lignitic and bentonitic shales, thin sandstones, siderite nodules
	Marmarth Member — thick channel sandstones	Breien Member — glauconitic sand with *Ophiomorpha* and *Ostrea*
	*Little Beaver Creek Member – lignitic sand, interfingers with Fox Hills Formation	Crowghost Member — lignitic and bentonitic shale with a basal lignitic sandstone containing tree stumps. More coal than in Little Beaver Creek Member
Fox Hills Formation	**South Dakota (Waage, 1968)** **Grand River Valley, Moreau River Valley**	
	Iron Lightning Member *Colgate lithofacies — very fine- to medium-grained sand bodies 2–60 feet thick, with the thick sand bodies occurring near the top of the Iron Lightning Member, plant fragments, cross-bedding, *Crassostrea*, *Corbicula* *Bullhead lithofacies — thinly interbedded sand, silt, and clay, fecal pellets in sediment, abundant plant fragments, *Crassostrea*	
	*Timber Lake Member – very fine- to medium-grained poorly consolidated sand with a clayey matrix, sporadic calcite and ferruginous cement (particularly in concretionary masses), *Ophiomorpha* with ferruginous cement	
	Trail City Member Irish Creek lithofacies — largely clay and silt, thinly interbedded, fossiliferous concretions absent Little Eagle lithofacies — clayey silt and clayey sand, bioturbated, abundant mollusks in concretions	

Figure 1. Stratigraphic nomenclature and brief lithologic descriptions for Fox Hills Formation of South Dakota and Hell Creek Formation of North Dakota. Asterisks (*) indicate rock units present at Concordia Hadrosaur Site.

ermost Trail City Member changed up-section to the brackish conditions of the Iron Lightning Member.

Waage divided both the top and bottom members into two lithofacies to accommodate lateral variability within each member (Fig. 1). Waage (1968, p. 158) noted that the Colgate lithofacies is commonly interspersed with, and overlain by, the lignitic clays of the Hell Creek Formation. He interpreted the upper Fox Hills and lower Hell Creek Formations to be deltaic facies. A variant of the Colgate lithofacies found in Emmons County, North Dakota, was documented by Klett and Erickson (1977) and assigned the name Linton Member. The rocks at the CHS offer new details in understanding the complexity of the Cretaceous coastline.

Figure 2. Panorama of 470 meter-long bluff examined, showing areas referred to in text. View is to northeast. Offset on fault between Bone bed sites 2 and 3 is about 4–5 meters. Fault zone is about 10 m wide.

Hell Creek Formation of South and North Dakota

Frye (1969) measured and described the Hell Creek Formation of North Dakota in both the Little Missouri River and Missouri River valleys. He subdivided the formation into members primarily based on variations in the proportions of sandstone, shale, and organic content (Fig. 1). Since completion of Frye's field work, Murphy et al. (2002, p. 10) concluded that the members of the Hell Creek Formation as proposed by Frye are ". . . not recognizable beyond their designated type sections and should not be considered formal members of the Hell Creek Formation." They proposed that the Breien Member is the only regionally recognizable member of the Hell Creek Formation. For the most part, we agree with Murphy et al. (2002), although our evidence suggests that the lowermost part of the Little Beaver Creek Member is also regionally recognizable.

Murphy et al. (2002) noted that the base of the Hell Creek Formation is marked by a 0.3–2.0 meter-thick, organic-rich sandstone, siltstone, or mudstone in the Little Missouri and Missouri River valleys of North Dakota. Frye (1969) also noted that his lowest members at both of these locations are more lignitic than the rest of the formation. At CHS, we observe that the lower Hell Creek Formation is characterized by an organic-rich zone above the Fox Hills Formation. Therefore, we place the lignitic shales, siltstones, and sandstones of the upper one third of the bluff at the CHS in the Little Beaver Creek Member of the lower Hell Creek Formation. We note that the CHS unit is also similar to the Crowghost Member, which Frye (1969) placed above the Fox Hills Formation in the region of the Missouri River in south-central North Dakota.

Characteristics Peculiar to Bone Beds in Lower Hell Creek Formation

The Concordia Hadrosaur Site is a low-diversity bone bed with few species of dinosaur, and its low diversity makes it distinctly different from most other bone beds of the Hell Creek Formation. However, it is not the only low-diversity bone bed to occur in the formation. At the Mason Dinosaur Quarry, near Faith, South Dakota, in Perkins County, personnel from the Black Hills Geological Institute have excavated predominantly *Edmontosaurus* bones from a lignitic bed just above the Fox Hills Formation (Peter Larson, 2002, personal communication; Christians, 1992). At the Stumpf site, near Huff, North Dakota, Hoganson et al. (1994) reported a hadrosaur-bearing bone bed with less diversity than is typical for the Hell Creek Formation. The bone bed at the Stumpf site is three meters above the top of the marine Breien Member, a lithologic association analogous to the location of the CHS and Mason Dinosaur Quarry sites above marine facies of the Fox Hills Formation.

INTERPRETATION OF DEPOSITIONAL ENVIRONMENTS

Introduction

The section at the Concordia Hadrosaur Site is situated in a 470-meter-long bluff along the Grand River, 40 miles southeast of Lemmon, South Dakota (Fig. 2). The 30-

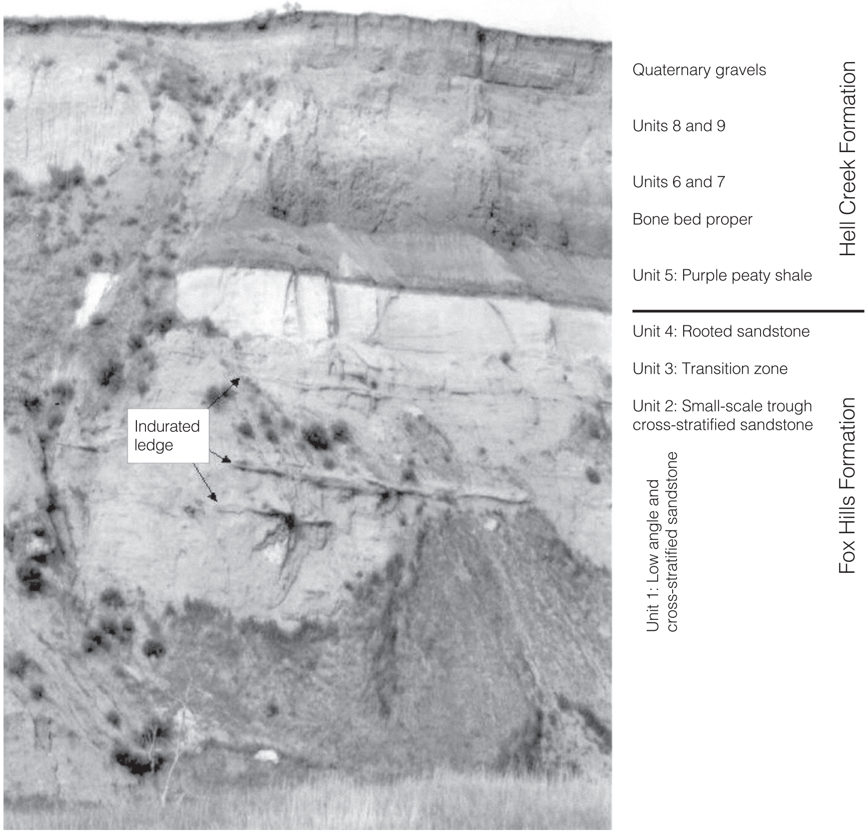


Figure 3. Section at West Ledge of upper Fox Hills Formation and lower Hell Creek Formation as described and interpreted in this report. We place formational contact at top of prominent, white, rooted sandstone. Base of measured section is at lowest exposed rock to right of gully. Thickness from Hell Creek contact to top of bluff is about 13 meters.

meter-thick exposure at the CHS can be divided into nine units based on lithology and sedimentary structures. Units 1 and 4 were described primarily from their exposure at West Ledge (Figs. 2 and 3), and other units were described primarily from their exposure on more easterly parts of the bluff at Bone bed site 3 (BB3), Bone bed site 2 (BB2), Southpoint, or Southbutte (Fig. 2). Unit descriptions are given in Figure 4, along with an interpretation of environments of deposition. Additional details of Unit 5, including the bone bed, are given in Table 1.

Depositional Environments of Upper Fox Hills Formation

We interpret the upper Fox Hills Formation exposed at the Concordia Hadrosaur Site (Fig. 4) to represent a progradational sequence of subtidal, longshore sediments that indicate transition to intertidal conditions and in turn are overlain by supratidal, eolian beach-ridge deposits.

Unit 1 was deposited in a subtidal, nearshore-bar setting. Marine indicators include the presence of glauconite, *Ophiomorpha* in the LAC sandstone, and carbonate pellets of the TCS ledges. The sedimentary and biogenic structures suggest deposition in a nearshore, bar-and-trough setting.

The *Ophiomorpha* burrows probably were made by *Callianassa* (ghost shrimp). Waage (1968) reported an appendage of *Callianassa* preserved in an *Ophiomorpha* burrow in the Fox Hills Formation. *Callianassa*, which is a primary pellet producer in some modern shallow-marine environments (Hill and Hunter, 1976), possibly was the pellet producer for both the laminated sand and TCS layers of Unit 1.

The vertical *Ophiomorpha* networks in the laminated sandstone show short horizontal branches every 20 cm or so. A horizontal branch may be a bypass burrow created by *Callianassa* after an erosional event during which the uppermost part of the burrow was destroyed. Presumably, once a new layer of sand was deposited, the organism reactivated the old burrow tube and extended the original vertical burrow upward (Howard, 1978). Weimer and Hoyt (1964) indicated that *Callianassa* burrows were most abundant below mean sea level at Sapelo Island, off the Georgia coast. The absence of extensive bioturbation and the form of the *Ophiomorpha* networks suggest rapid sedimentation on the upper shoreface (Howard, 1972). The absence of muddy interbeds in Unit 1 also suggests continual agitation in a subtidal environment.

The mud rip-up clasts and coarser sediment of the indurated ledges (TCS layers in Unit 1), the lack of *Ophiomorpha* networks in those TCS layers, and the shift in style of cross-bedding from low-angle to trough cross-bedding may indicate a more energetic environment for the TCS indurated ledges. Common mud clasts and organic fragments may reflect seaward transport of debris when storm-surge water

Table 1. Details of Unit 5 in lower Hell Creek Formation.

Unit 5c 85–105 cm	upper	Upper 15–40 cm. Bones much less common in this zone than in bone bed. Tendons and teeth common. Fewer organic fragments than bone bed, 5–10 volume%.
	middle (bone bed)	Middle 30 cm. Coalified logs below densely packed disarticulated hadrosaur bones. Also present are: internal molds of fresh water mollusks (clams: unionids, *Sphaerium*; snails: *Lioplacodes*, *Campeloma*, *Viviparus*[†]), cones of conifers, leaf imprints, seeds, amber, log fragments (sometimes 80 cm long), bird bones, fish scales, crocodile scutes, tyrannosaurid teeth, turtle, and champsosaur remains. 46% of pollen is *Taxodiaceaepollenites*, a terrestrial cypress (Table 3). Dominant sediment mode is fine to medium clay, with a hint of a second mode at fine silt in some layers. Pulses of coarser sediment are also indicated. 30 to 60 vol% organic fragments.
	lower	Lower 35 cm lignitic shale 20–40 vol% organic fragments.
Unit 5b 210 cm		5–10 vol% organic fragments. Unit tends to weather into small chunks rather than sheets. Small-scale soft-sediment deformation structures in siltier layers.
Unit 5a 260 cm	upper	246 cm. Organic-rich shale and siltstone. 20–60 vol% organic fragments.
	lower	14 cm. Some fine sand grains dispersed within silt and clay (strongly bimodal), but no sand layers or laminae. 25% sand at base, decreasing to 0% at the top. 5–10 vol% organic fragments.

[†] Joseph Hartman, Univ. of ND, 2002, personal comm.

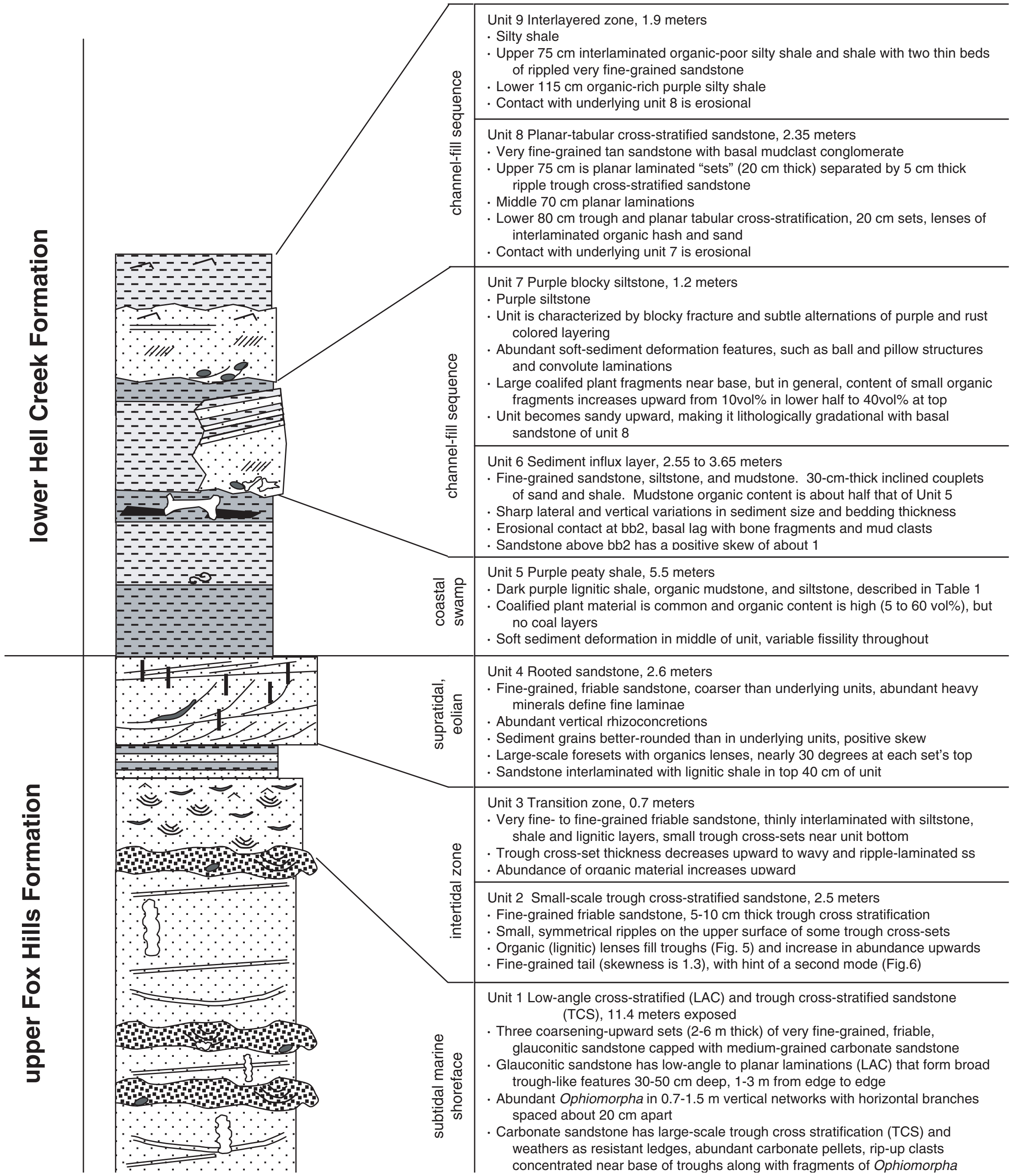
flowed oceanward. Reworked fragments of *Ophiomorpha* in the TCS ledges indicate erosion of the burrowed shoreface bar. The sequence of LAC sandstone to TCS may therefore indicate migration of longshore bars and rip channels during storm events.

The presence of micrite pellets as substantial fractions of the sediment in the TCS layers is puzzling. Where was the carbonate source? *Callianassa* is a well-known pellet producer of the nearshore environment (Weimer and Hoyt, 1964). Pellets are common throughout Unit 1, although carbonate concentrations in the LAC sandstone are much lower than in the TCS ledges. The source of the carbonate for the pellets of the TCS ledges could have been skeletal remains from the brackish-water fauna, like the *Crassostrea*, found at other localities in the upper Fox Hills Formation (Waage, 1968; Christians, 1992). At the Mason Dinosaur Quarry (discussed further in the Discussion section below), transported *Crassostrea* shells occur in thick, cross-stratified beds in the layer equivalent to Unit 1, suggesting that carbonates might have been brought seaward during storms from a more coastward, oyster-bearing environment. This interpretation would explain the association of micrite pellets with mud clasts and organic debris in the TCS layers of Unit 1.

Unit 2 probably was deposited in subtidal channels within the intertidal zone. The suite of sedimentary structures in this unit required an environment in which sand and mud were available, in which there was an abundant supply of organic material, and in which periods of current activity alternated with periods of waning current or quiet water. For example, the presence of both trough cross-sets and smaller ripples along with lenses of organic material (Fig. 5) indicate fluctuating current velocities. The classic environment for alternating flow velocity along with abundant supply of organics is the intertidal zone (Reineck and Singh, 1980). In Unit 2, however, the presence of symmetrical ripples indicates a wave-dominated rather than a tide-dominated intertidal zone. Herringbone cross-stratification, typical of ebb-and-flood tidal cycles, is absent (Reineck and Singh, 1980).

The amount of plant fragments, preserved in Unit 2 as black, organic-hash lenses, increases abruptly and dramatically into the thin organic layers of Unit 3. The increase is consistent with a prograding shoreline and an increasingly terrestrial influence. We interpret Unit 3 to represent laminated sediments in a sheltered low-energy, near-shore environment (perhaps shallow tidal lagoon or tidal pools) that covered a filled subtidal rip channel (Davidson-Arnott and Greenwood, 1976; Reinson, 1984).

As discussed below, magnetite/quartz size ratios in Units 2 and 3 are consistent with some wind transport



Unit 9 Interlayered zone, 1.9 meters
- Silty shale
- Upper 75 cm interlaminated organic-poor silty shale and shale with two thin beds of rippled very fine-grained sandstone
- Lower 115 cm organic-rich purple silty shale
- Contact with underlying unit 8 is erosional

Unit 8 Planar-tabular cross-stratified sandstone, 2.35 meters
- Very fine-grained tan sandstone with basal mudclast conglomerate
- Upper 75 cm is planar laminated “sets” (20 cm thick) separated by 5 cm thick ripple trough cross-stratified sandstone
- Middle 70 cm planar laminations
- Lower 80 cm trough and planar tabular cross-stratification, 20 cm sets, lenses of interlaminated organic hash and sand
- Contact with underlying unit 7 is erosional

Unit 7 Purple blocky siltstone, 1.2 meters
- Purple siltstone
- Unit is characterized by blocky fracture and subtle alternations of purple and rust colored layering
- Abundant soft-sediment deformation features, such as ball and pillow structures and convolute laminations
- Large coalifed plant fragments near base, but in general, content of small organic fragments increases upward from 10vol% in lower half to 40vol% at top
- Unit becomes sandy upward, making it lithologically gradational with basal sandstone of unit 8

Unit 6 Sediment influx layer, 2.55 to 3.65 meters
- Fine-grained sandstone, siltstone, and mudstone. 30-cm-thick inclined couplets of sand and shale. Mudstone organic content is about half that of Unit 5
- Sharp lateral and vertical variations in sediment size and bedding thickness
- Erosional contact at bb2, basal lag with bone fragments and mud clasts
- Sandstone above bb2 has a positive skew of about 1

Unit 5 Purple peaty shale, 5.5 meters
- Dark purple lignitic shale, organic mudstone, and siltstone, described in Table 1
- Coalified plant material is common and organic content is high (5 to 60 vol%), but no coal layers
- Soft sediment deformation in middle of unit, variable fissility throughout

Unit 4 Rooted sandstone, 2.6 meters
- Fine-grained, friable sandstone, coarser than underlying units, abundant heavy minerals define fine laminae
- Abundant vertical rhizoconcretions
- Sediment grains better-rounded than in underlying units, positive skew
- Large-scale foresets with organics lenses, nearly 30 degrees at each set’s top
- Sandstone interlaminated with lignitic shale in top 40 cm of unit

Unit 3 Transition zone, 0.7 meters
- Very fine- to fine-grained friable sandstone, thinly interlaminated with siltstone, shale and lignitic layers, small trough cross-sets near unit bottom
- Trough cross-set thickness decreases upward to wavy and ripple-laminated ss
- Abundance of organic material increases upward

Unit 2 Small-scale trough cross-stratified sandstone, 2.5 meters
- Fine-grained friable sandstone, 5-10 cm thick trough cross stratification
- Small, symmetrical ripples on the upper surface of some trough cross-sets
- Organic (lignitic) lenses fill troughs (Fig. 5) and increase in abundance upwards
- Fine-grained tail (skewness is 1.3), with hint of a second mode (Fig.6)

Unit 1 Low-angle cross-stratified (LAC) and trough cross-stratified sandstone (TCS), 11.4 meters exposed
- Three coarsening-upward sets (2-6 m thick) of very fine-grained, friable, glauconitic sandstone capped with medium-grained carbonate sandstone
- Glauconitic sandstone has low-angle to planar laminations (LAC) that form broad trough-like features 30-50 cm deep, 1-3 m from edge to edge
- Abundant *Ophiomorpha* in 0.7-1.5 m vertical networks with horizontal branches spaced about 20 cm apart
- Carbonate sandstone has large-scale trough cross stratification (TCS) and weathers as resistant ledges, abundant carbonate pellets, rip-up clasts concentrated near base of troughs along with fragments of *Ophiomorpha*

Figure 4. Description of nine units recognized at Concordia Hadrosaur Site with paleoenvironmental interpretations.

of sediment. We believe that some of the sediment deposited in this marine environment may have been windblown from a coastal dune complex. There is the suggestion from the slight bimodality of the sediment distribution (Fig. 6) that more than one process influenced grain size. As a modern example, windblown sandy layers are present in organic-rich lagoonal and marsh sediments associated with beach ridges of the prograding coast of Nayarit, Mexico (Reineck and Singh, 1980, p. 356).

We interpret Unit 4 to have been deposited in an eolian, coastal-dunes environment. Unit 4, overlying the lagoonal deposits of Unit 3, is coarser grained, better sorted, and better rounded than the underlying sand of Units 1 and 2. This change in sedimentary character is consistent with eolian origin (Bigarella, 1972, p. 14, 38–40; Reineck and Singh, 1980, p. 238). The positive skewness of Unit 4, typical of eolian deposits due to the inability of winds to transport the larger particles, clearly distinguishes it from the marine sandstone of Unit 1. River sands are also expected to have a positive skew because of the deposition of a fine fraction as river velocity waned. However, river sands are typically less well sorted and rounded than eolian sands, and Unit 4 is distinguished from fluvial sands higher in the section (Unit 6) by better rounding and sorting (Table 2).

Other features of Unit 4 that are consistent with eolian deposition include the distinctly common presence of opaque heavy minerals. The steep cross bedding seen at the top of the foresets (25–30 degrees) also is consistent with eolian deposition (Selley, 1985, p. 95; Reineck and Singh, 1980, p. 239). Eolian coastal sand dunes are commonly rooted (Reineck and Singh, 1980).

To add support to the interpretation of an eolian environment of deposition, we examined the ratio of sizes of magnetite grains to other grains (primarily quartz) in the sediment. We assumed that magnetite and quartz grains in the sand are, on average, hydraulic equivalents. But because magnetite and quartz have different densities, the buoyancy factor of the transporting medium will have different effects on each. Thus, their ratio of sizes can indicate the medium of particle transport, whether water or air (Blatt et al., 1980, p. 118; Hand, 1967). Results of this analysis, indicating that the rooted sandstone of Unit 4 is indeed eolian, are given in Figure 7.

We are unsure whether the roots present in Unit 4 represent plant growth on the active sand dunes or roots that formed when plants grew down into the sand after a swamp, in which the overlying lignitic sediments were deposited, covered the dune. However, the increasing abundance of root traces upward in the unit supports the latter interpretation. The bimodal distribution of sand and clay at the base of Unit 5a (sample P709-SB-1) seems consistent either with sand blown into a swampy area adjacent to coastal dunes or sand from the substrate being mixed into the sediment of Unit 5 by bioturbation. The proportion of sand decreases rapidly upward in Unit 5 and is gone by about 14 cm above the contact. Other evidence for interaction between the eolian coastal dune environment of Unit 4 and coastal swamp environment of Unit 5 was reported by Frye (1969), in which roots extend from fossil tree stumps of a lignitic shale into a sandstone layer at the base of the Crowghost Member in south-central North Dakota. At the Mason Dinosaur Quarry, a persistent patterned mottling in the sandstone

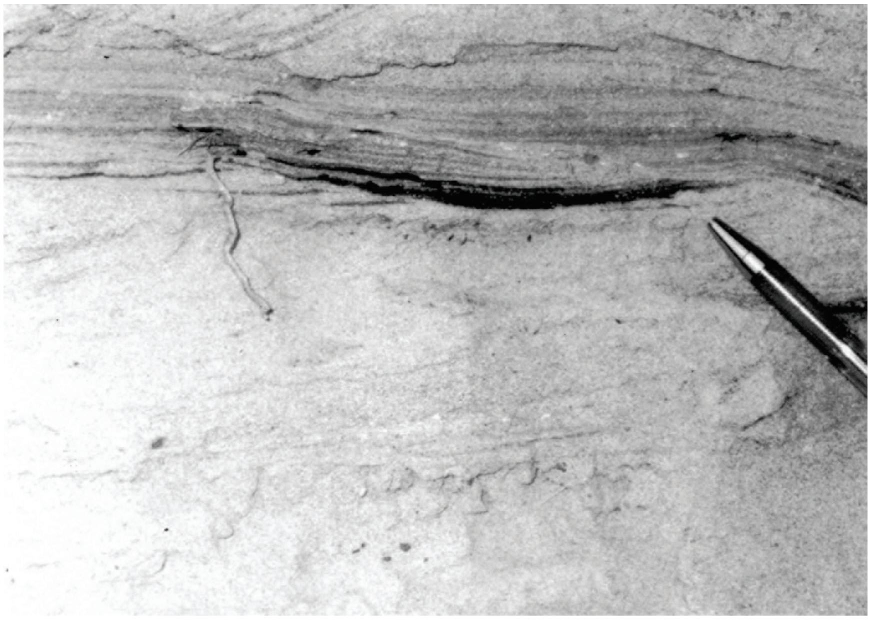


Figure 5. Ripples in Unit 2, small-scale trough cross-stratified sandstone at Southpoint. Pen points to a trough, filled with laminated organic hash and clay, between two symmetrical ripples.

directly under the lignitic material of the Hell Creek (equivalent to Unit 4 at CHS) is indicative of rooting.

In summary, as rivers provided sediment to the Late Cretaceous shoreline, waves and longshore currents reformed the sediment into nearshore bars (Unit 1), with low-energy tidal lagoons or pools (Unit 3) and rip channels (Unit 2), and a shoreline dominated by eolian dunes (Unit 4).

Depositional Environments of Lower Hell Creek Formation

We interpret the lower Hell Creek Formation exposed at the CHS to have been deposited in a coastal swamp dissected by, and ultimately overrun by, distributary channels or rivers.

Unit 5 was deposited in a coastal swamp. Its organic content is consistent with a swampy environment characterized by a significant sediment influx that resulted in the deposition of organic mudstone rather than coal deposits (Carr, 1991). The pollen and organic content indicate a typical Maastrichtian terrestrial swamp flora (Table 3) in a temperate to subtropical swamp (am Ende, 1991). Presence of champsosaur, crocodile, and dominant hadrosaur fossils in Unit 5c further supports the interpretation of a swamp environment (Erickson, 1999). There does not appear to be any obvious evidence for marine influence on Unit 5, even though it occupies a transitional position from the marine bar- and beach-ridge sequence of the Fox Hills Formation to the obviously fluvial environments of the Hell Creek Formation (Units 6, 7, 8, and 9).

Within Unit 5, layers of papery-weathering lignitic shale are commonly underlain by a layer of blocky or crumbly, organic-rich mudstone and overlain by a layer of less organic-rich siltstone or silty shale. Moore (1976) and Carr (1991) noted that changes in mud, organics, and silt can simply reflect the vagaries of sediment supply and subsidence rate or the location of the water table relative to the ground surface. This triplet set of organic mudstone, more organic-rich lignitic shale, and siltstone with less organics is likely related to water-table level, with mud accumulating when the sediment surface is below the water table, peat when the water table and sediment surface are roughly coincident, and siltier sediments when the sediment surface rises above the water table during periods of sediment influx.

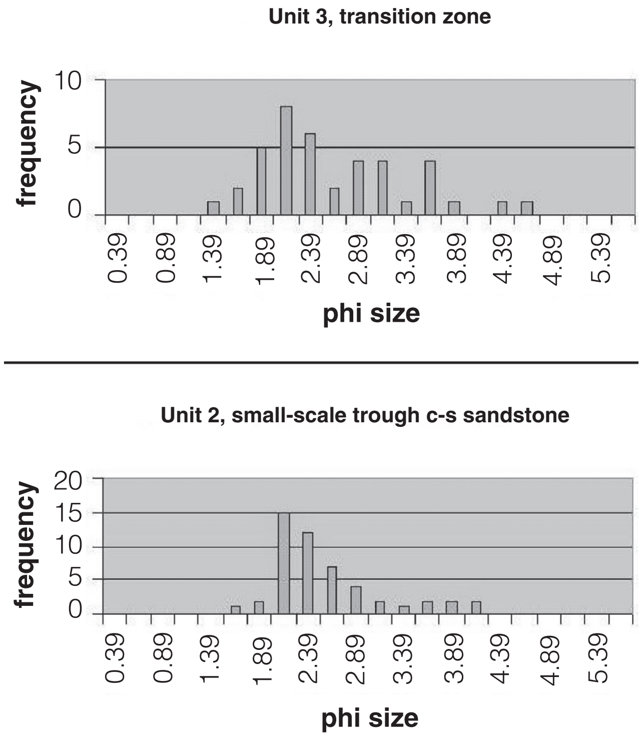


Figure 6. Sediment-size distribution determined by measuring randomly selected particles in disaggregated sediment under a microscope, for samples 708-SB-2 (from Unit 2, Small-scale cross-stratified sandstone) and 707-WL-3 (from Unit 3, transition zone).

Table 2. Sorting and rounding.

	Sorting	Rounding (average)
Unit 3 707-WL-3	0.85	2.2
Unit 4 708-WL-1 and 2	0.6	2.6
Unit 6 712-BB2-9	1.2	1.6

Note: Simple sorting (Inman, 1952), 5=rounded, 1=angular, Determined by observation and measurement of loose grains under a microscope.

All of Unit 5 is interpreted to represent a widespread, coastal-swamp environment that experienced both lateral and temporal changes in water depth and sediment. Johnson et al. (2002) discussed a near-marine interpretation for the Hell Creek Formation as well. They proposed that the easternmost Hell Creek Formation, with the

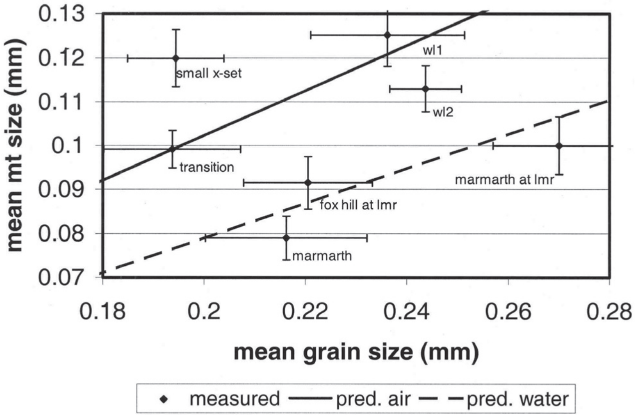


Figure 7. Measurements of magnetite and sediment average sizes compared to ratio of sizes expected for transport either in medium of air or water. Average particle sizes were determined by measuring sizes of randomly selected particles under a microscope. Sizes for magnetite particles were determined by measuring particles separated magnetically from the sample and identified as magnetite under a microscope.

Hydraulic equivalence is defined as follows: let HN = (D•V-B•V)/(A•F), In which HN = hydraulic number, D = density of particle, V = volume of particle, B = buoyancy force of medium per unit volume, A = cross-sectional area of particle, and F= force of transporting medium exerted per unit area. Then hydraulic equivalence is achieved if HN(magnetite) = HN(sediment). Sediment density is assumed to be approximately that of quartz. Lines on graph illustrating expected (pred. = predicted) relationships for hydraulic equivalence in either air or water are calculated from this relationship.
Locations of samples:
fox hill at lmr: upper Fox Hills Formation from Little Missouri River (Frye, 1969, sec. 9, Bowman Co., ND; LM12).
small x-set: Unit 2 at east end of CHS (708-SB-2).
transition: Unit 3 at West Ledge of CHS (707-WL-3).
wl1: Rooted sandstone West Ledge (708-WL-1).
wl2: Rooted sandstone West Ledge (708-WL-2), wl1 and wl2 are from two different cross sets of Unit 4 and are 30 cm apart vertically.
marmarth: lowest Marmarth sandstone from about 4 miles south of bone bed (SS4).
marmarth at lmr: lowest Marmarth Sandstone from Little Missouri River (Frye, 1969, sec. 8, Slope County, ND; LM5).

organic-rich beds of the lower part of the formation (and those organic beds associated with the Breien Member and Cantapeta Tongue), formed in a near-coastal setting.

Units 6, 7, 8, and 9 represent two sets of channel-fill, point-bar migration, floodplain sequences. Evidence supporting this interpretation includes the fining-upward character of the two sets, the erosional surface and lag at the lower boundary of each, fine couplets of sand and silt, which we interpret as inclined heterolithic cross-stratification (Thomas et al., 1987), and features of soft-sediment deformation.

The cross-bedded sandstone of Unit 6, above Bone bed site 2, is a fluvial-channel deposit, with the trough cross-stratified conglomerate lag of bones, ossified tendons, plant debris, and mud clasts representing deposition in the deepest part of the channel. The erosional surface causes the thickness of Unit 5c in that location to vary by as much as 10–20 cm. Load casts, 10 cm in diameter, occur in the top 10 cm of Unit 5c.

The coarse fraction disappears upward in Unit 6 at Bone bed site 2. The thickness of cross-bedded sets also decreases upward, with trough cross-stratification at the bottom, planar–tabular cross-sets in the middle, and interbedded planar- and ripple-laminations at the top. Decreased size of the cross-sets was caused by filling the channel with point-bar sediments (Walker and Cant, 1984; Selley, 1985).

The uppermost 1.75 m of Unit 6, with its couplets of very-fine sand and silt or shale replete with soft-sediment deformation, is interpreted to be inclined heterolithic stratification and to have been deposited as inclined layers on a point bar, where a single sand–silt couplet may represent a single flood event (Thomas et al., 1987). The dewatering and ball-and-pillow structures represent rapid deposition on unstable substrates. In the top meter of Unit 6, the thickness of the silt/shale part of the couplets increases, reflecting deposition during waning floodwaters higher up on the point bar. The top of Unit 6 is a 10 cm-thick layer with iron concretions and organic fragments, and it represents an area of organic accumulation, perhaps a low or swampy spot on the floodplain. Unit 7 represents continued deposition on a floodplain.

Unit 6 has much greater lateral variability than Unit 5, both in type and thickness of sedimentary units, again consistent with channel-related deposition. The mudstone above Bone bed site 3 is different from the mudstone of the bone bed itself (Fig. 8) and can be correlated to the sandstone/inclined heterolithic stratification above Bone bed site 2 (Fig. 9). This correlation is supported by the pronounced shift in character of the mudstone above Bone bed site 3 as well as by the position of Unit 6 under the laterally continuous Unit 7. Environmentally, Unit 6 above Bone bed site 2 is a channel-fill sequence, and the laterally equivalent Unit 6 mudstone above Bone bed site 3 represents an open-water area of the coastal swamp. Both subenvironments of Unit 6 were located in the more landward regions of the coastal swamp complex. These sharp, lateral changes in lithologic composition indicate rapid facies shifts between subenvironments as might be expected near a distributary channel or in a river flowing into a swampy area.

Units 8 and 9 represent a similar event to that inferred for Units 6 and 7. As in Unit 6, there is a lower erosional surface with basal lag in the sandstone of Unit 8, which fined upward as the lag fraction dropped out. Above the lag, the sandstone weathers into planar-laminated sets alternating with rusty rippled layers. Unit 8 is similar to Unit 6, channel- and point-bar fill. The lowermost 1.2 m of Unit 9 is an organic-rich shale that is overlain with interlaminated silt and shale, suggesting deposition in a ponded area of the flood plain. It lacks the features of soft-sediment deformation typical in Unit 7. Units 6–9 of the CHS bear remarkable similarity to the "classic" depositional style of the Hell Creek Formation as reported by Fastovsky (1987).

Sandy sediments of Units 6–9 are distinctly different from the sand bodies below Unit 5. Sediments have a fine-grained tail typical of river deposits, and they show an absence of the clay-rich pellets that are important in the sands of Units 1, 2, 3 and 4.

In summary, the lowermost Hell Creek Formation represents a coastal swamp with high sediment influx (Unit 5) overlain by deposits of increasingly fluvial character (Units 6–9).

Table 3. Summary of palynomorphs from Unit 5c.

Lycopsida (Club Moss)	
Lycopodium spores	<1%
Filicinae (Ferns)	**11%**
Appendicisporites (?) fragment	<1%
Gleichina sp.	2%
Monolete type spores (Polypodiaceae)	5%
Trilete type spores	4%
Gymnosperm (Conifers)	**46%**
Pinuspollenites (Pine Tree)	<1%
Taxodiaceaepollenites (Taxodium-Cypress)	46%
Angiosperm (Flowering Plants)	**43%**
Alnus (Alder tree)	<1%
Aquilapollenites sp.	2%
Cranwellia rumseyensis	1%
Monosulcate type pollen	2%
Proteacidites	1%
Triporopollenites type pollen	6%
Tricolpopollenites type pollen	24%
Tricolporopollenites type pollen	7%
Wodehouseia spinata	<1%

Note: sample taken from directly below bone bed proper at site of Bone bed site 3 (sample P710-BB3-3). Separation and identification of palynomorphs prepared by James Ruffin and National Petrographic Service, Houston, Texas.

DISCUSSION

Introduction

A model illustrating environments of deposition at the time of formation of the Concordia bone bed is shown in Figure 10. This reconstruction is based on interpretation of the depositional environments for the succession of rocks found at the Concordia bone bed site as shown in Figure 4 and explained in the text above. The bone bed lies at a transition from organic rich mudstones of swamp origin to more river-like deposits above. We infer that the environment in which the bone bed formed was near the inland edge of a coastal swamp where river or distributary influence became more significant. The coastal swamp environment is where the hadrosaurs lived, not simply where hadrosaurian remains were transported by flood after death. This explains the persistently monospecific nature of *Edmontosaurus*-bearing sites in the lower Hell Creek Formation.

Question of Catastrophic Emplacement

Did the bone bed proper in Unit 5c result from bone accumulation in quiet water, perhaps over an extended period of time? Or did it result from a sudden event such as a flood that drowned and buried a large number of creatures at once (Fiorillo and Voorhies, 1999)? Several lines of reasoning argue against a high-energy, sudden event at the CHS. For this discussion, we use "sudden event" to refer to a high-energy event such as a flood that killed and buried animal remains in a period of days, and not to refer to more lengthy phenomena such as droughts or other stressful events that might cause widespread death over a period of months, years, decades, or centuries. This distinction is important because our sedimentological results primarily address whether the emplacement was, for example, in quiet water. Our results have less to say, however, about whether that emplacement occurred over multiple generations (creating a time-averaged deposit of bones resulting from gradual accumulation) or occurred within a single population (perhaps resulting from stresses created by such factors as drought or disease).

The very fine grain size of the sediment of Unit 5c (as much as 70% clay, the remainder being silt) is not consistent with a high-energy, sudden event. Even if the fine-grained rock in which the bones are found represents a pulse of sediment related to a distal flood event, we would expect the coarsest fraction to be at the bottom of this layer, resulting either because this coarsest fraction settled first

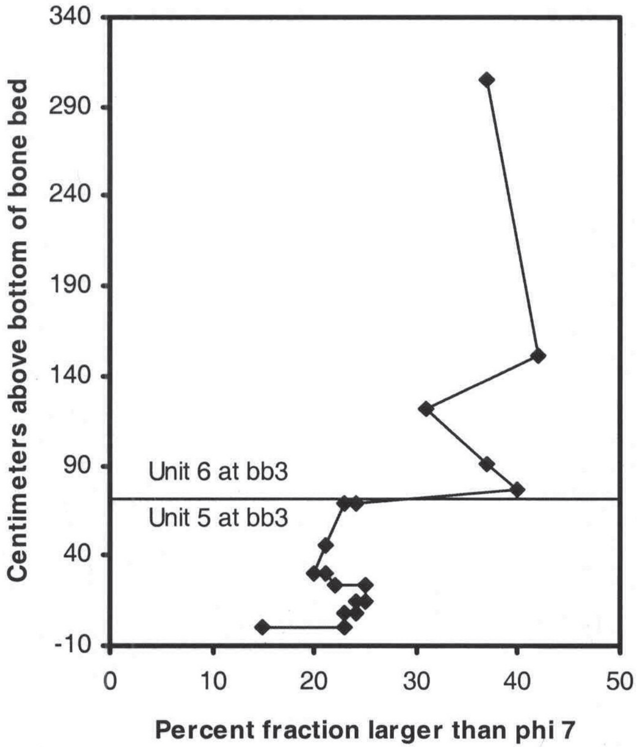


Figure 8. Graph illustrating change in sediment character between Units 5 and 6 in mudstones above Bone bed 3.

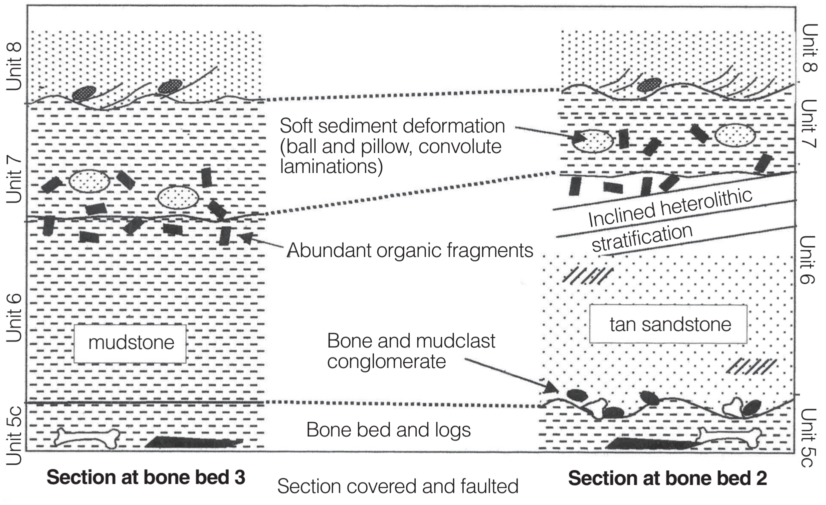


Figure 9. Comparison of lithologic composition and sedimentary structures of Units 5c, 6, and 7 at Bone bed sites 2 and 3. Unit 6 is all mudstone at Bone bed site 3. But at Bone bed site 2, Unit 6 is a classic channel fill of lag, cross-bedded sandstone, and inclined heterolithic stratification. Although Units 5 and 6 at Bone bed site 3 appear similar, they can be distinguished on basis of sediment-size distribution (Fig. 8).

or the sediment size decreased as the energy of the event waned. However, the zone of the bone bed with the highest clay fraction and lowest sand fraction is located at the bottom of the bone bed proper. In addition, recurrent siltier layers within the bone bed proper and the overlying sparse zone are more consistent with episodic and gradual accumulation than with a single catastrophic event.

Even if these deposits represent a distal region of a flood event, and the bones were rafted into a low-energy, swamp environment as carcasses during a flood or storm surge, we would not expect the bones to have been deposited at the bottom of the mud layer, as is the case. Because the sediment size indicates insufficient energy to transport even a very low-energy bedload, any bones rafted into the low-energy swamp environment must have been in the form of floating carcasses, with buoyancy greater than or comparable to the sediment load. Therefore, the clastic sediments would have settled prior to, or at the same time as, the carcasses. If the carcasses somehow settled prior to the sediment load, and they were subsequently buried by sediment from the event that introduced the carcasses, then the burial should have prevented disarticulation of the bones. Yet, the bones are thoroughly disarticulated. We interpret the disarticulation to have occurred as a result of biotic activity that scattered the bones during the progress of more gradual accumulation.

The unweathered and unabraded bones are consistent with rapid emplacement and burial. However, this observation also is consistent with more gradual accumulation in an environment in which the bones experienced little or no subaerial exposure or transport. It is not consistent with the disarticulation of the bones due to remobilization and transport of individual elements from a distal location.

Another argument that the bone bed did not result from a sudden event is related to our interpretation of the small-scale stratigraphy of Unit 5. The mudstone of the bone bed proper rests on the particularly organic-rich, purple "peaty" layers of Unit 5a and 5b. Above, we suggested that the papery-weathering lignitic layers represent a water table coincident with the sediment surface and that the mudstone represents a rise in the water table relative to the sediment surface. Within this interpretation, the mudstone of the bone bed proper represents sediment accumulation during an interval in which the water table was persistently high, rather than during an influx of sediment associated with a flood. This interpretation is consistent with the conformable boundary between the bone bed proper and underlying sediments and with the decrease in organics upward through the bone bed proper.

Although the focus of this paper is not on the taphonomy of the dinosaur bones, we need to consider whether or not that aspect is consistent with our interpretation. For example, does the distribution of sizes of hadrosaur bones suggest a population of individuals all killed in a sudden event (not consistent with our interpretation of the sediments), or does the distribution suggest either long-term attritional accumulation or a shorter-term, stress-induced die-out (both consistent with our interpretation)? Therefore, we address briefly some general taphonomic support for our interpretation that the bone deposit did not occur in a "sudden event" as we define it above.

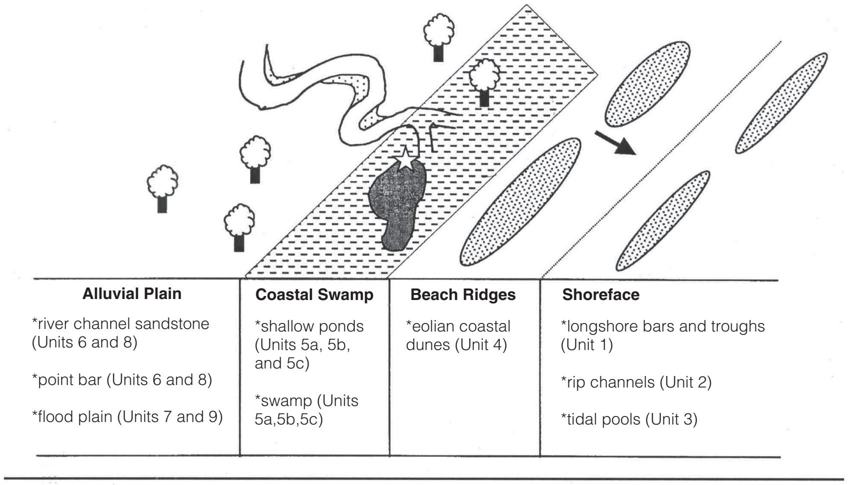


Figure 10. Static depositional model for environments at time of deposition of Concordia hadrosaur bone bed. White star indicates our interpreted location of bone bed.

Figure 11 summarizes the lengths and quantities of femora excavated from the CHS. The distribution of femoral lengths is consistent with deposition of bones resulting from attritional death, with larger, older individuals preferentially represented (Koster, 1987). In a catastrophic death event, younger individuals would be expected to be more common (Voorhies, 1969; Currie and Dodson, 1984). Even if juveniles did not travel with the herd, the distribution of femoral lengths for a sudden-death event should have more younger than older individuals if the population was in either a steady state or was growing. Although the observed distribution might result from sedimentological sorting, such sorting is improbable in this case given the mud matrix. In this analysis, we presume that the length of a femur yields a rough approximation of age. Nevertheless, we recognize that femoral length may not be linearly related to the age of individuals and that this may influence our interpretation. We also point out that in a longer-term, stress-induced die-out, older individuals might be expected to be preferentially vulnerable, thus yielding the pattern we observe. Thus, this pattern, while arguing against the catastrophic death of an entire population (as is consistent with our sedimentological interpretations), does not address whether the bone accumulation resulted from attritional accumulation over decades or centuries (a time-averaged deposit) or as a stress-induced accumulation over a much shorter period.

In Figure 11, we compare femoral dimensions with those reported for the Mason Dinosaur Quarry (Christians, 1992). The MDQ is located about 50 miles south of CHS and occupies the same stratigraphic position near the Fox Hills–Hell Creek formational contact. We discuss the MDQ in more detail below, but note here that Christians (1992) interpreted the MDQ as representative of a catastrophic event in which bones and sediment were rapidly deposited during one or possibly two episodes of crevasse splay or overbank flooding. That interpretation differs considerably from what we apply to the CHS site.

Nature of Fox Hills–Hell Creek Formational Contact at CHS

The contact between sandstones of the Fox Hills Formation and the purple-brown, fissile lignitic shale of the Hell Creek Formation is easily traced upstream from the CHS until it is no longer exposed. It is also traceable several miles downstream. Although the abrupt change in lithologic composition and color that make this contact prominent might lead one to initially suspect a significant hiatus, evidence at the CHS suggests a conformable contact.

The nature of the Fox Hills–Hell Creek formational contact is regionally variable. The contact at the Little Missouri River valley is unconformable, as indicated by several feet of relief on the Colgate Member of the Fox Hills Formation (Frye, 1969). At the CHS, we observed a few inches of relief at the top of Unit 4 (the rooted sandstone) west of the fault at the west side of the CHS. We also observed a few inches of relief at the contact at the Mason Dinosaur Quarry. In the Missouri River valley, the contact between the Hell Creek and Fox Hills Formations is reported by Frye (1969) to be conformable because the two units interfinger with one another. Murphy et al. (2002) reported that the contact is regionally conformable but with local scouring. In contrast, Johnson et al. (2002) suggested that a major unconformity exists between the Fox Hills and Hell Creek Formations over their entire outcrop areas.

Despite some indication of exposure or erosion, we conclude that the contact at CHS does not represent a significant depositional hiatus. Rather, we suggest that the contact portrays relatively continuous deposition during a progressive shift of adjacent, near-shore environments. The relief at the contact between the rooted sandstone of Unit 4 and the purple "peaty" shale of Unit 5 could have resulted from transitory relief expected on eolian dunes.

The contact between Unit 4 of the Fox Hills Formation and Unit 5 of the Hell Creek Formation can be traced over a substantial area. If Unit 5 represented widespread, renewed deposition after a significant hiatus, it would more likely rest on different facies in different regions because of variable erosion in each area. We observed the equivalent of these units not only at the Concordia Site and at the Mason Dinosaur Quarry, 42 miles (72 km) to the south, but also at the type section of the Little Beaver Creek Member of Frye (1969) in western North Dakota, 110 miles (183 km) to the west. In addition, a similar transition is seen between the Fox Hills Formation and the Crowghost Member (which we believe to be laterally equivalent to the Little Beaver Creek Member) of the Hell Creek along the Missouri River 75 miles (125 km) to the northeast. This regional similarity was also observed by Frye (1969) and Murphy et al. (2002). Murphy et al. (2002, p. 16) noted that in both the Little Missouri River and Missouri River valleys "There is a remarkable similarity in character of this basal carbonaceous bed (thickness and lithology) from southwestern to south-central North Dakota."

Although this persistent character could have been caused by a major event following a significant depositional hiatus, it is also consistent with development of a regionally extensive coastal swamp adjacent to the retreating sea. The age of the Fox Hills–Hell Creek formational boundary appears to be younger toward the east, as based on macrofossils, consistent with the latter interpretation (e.g., Johnson and Hickey, 1990).

We offer the following arguments from the CHS and nearby sites as further support for the interpretation that these paleoenvironments collectively migrated with the prograding shoreline along the Cretaceous Western Interior Seaway.

1. At Southbutte, we observed a transitional zone between the rooted sandstone of Unit 4 and the overlying purple "peaty" shale of Unit 5. This transitional zone

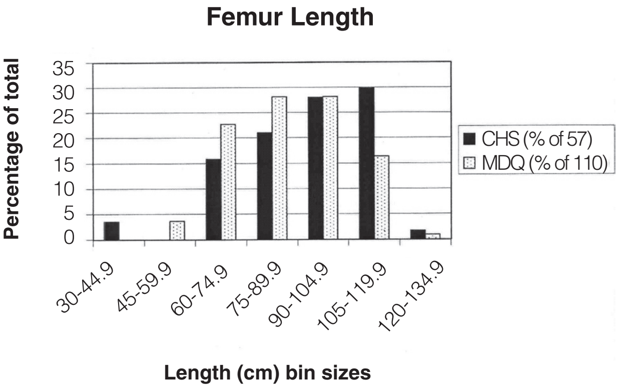


Figure 11. Distribution of lengths of *Edmontosaurus* femora excavated at Concordia Hadrosaur Site (CHS; data from Nellermoe, Gould, and Larson, in prep.) and at Mason Dinosaur Quarry (MDQ; data from Christians, 1992). More frequent occurrence of larger bones is consistent with an attritional accumulation but less consistent with catastrophic accumulation of a complete population.

consists of a 40 cm-thick layer of interlaminated, lignitic mudstone and sandstone containing root traces like those in the rooted sandstone. The interlayered nature of this zone, along with the upward increase in fraction of lignitic mudstone, is consistent with a transitional boundary between the rooted sandstone and the purple "peaty" shale. In addition, a 14–20 cm-thick, mixed sand and organic-rich zone occurs at the bottom of Unit 5 all along the outcrop. However, this zone provides less conclusive evidence than the interlaminated sandstone and lignitic mudstone, because it could simply be the result of bioturbation regardless of whether or not the rooted sandstone and purple lignitic shale were separated by a significant hiatus.

2. The Concordia site is a reasonably complete section of shoreface–coastal swamp–terrestrial fluvial facies succession similar to modern analogs like the chenier plain of Louisiana or the coastal beach ridges of Nayarit, Mexico (Reineck and Singh, 1980) and ancient analogs such as described by Carter (1978). Such a conformable sequence would not be expected if a significant hiatus existed and if the sections above and below the contact were genetically unrelated. For example, the more shoreward parts of the Fox Hills Formation might be missing, or the more fluvial deposits of the Hell Creek Formation might rest directly on the former.

3. The presence of a strikingly similar section at the Fox Hills–Hell Creek formational contact 42 miles south at the Mason Dinosaur Quarry further supports interpretation of conformable relationships. If there had been a significant hiatus, different amounts of erosion at the two sites likely would have resulted in the Hell Creek Formation resting on a different facies at the Mason Dinosaur Quarry. If, on the other hand, these rocks represent fairly continuous deposition during migration of adjacent and genetically related environments, this similarity would be expected. Similarities and differences between the Concordia site and the Mason Dinosaur Quarry site are shown in Table 4. We note that Murphy et al. (2002) indicated that this association at the Fox Hills–Hell Creek formational contact is not pervasive in the subsurface.

4. A similar sequence of sediments is seen in the lower Fort Rice Member above the Breien Formation in the Hell Creek Formation of south-central North Dakota. Marine, glauconitic sands are overlain there by lignitic shales that are similar in character to our Unit 5 at CHS. A similar lignitic shale also underlies the Breien Member in the top of the Crowghost Member. The similar association of marine deposits and lignitic shale both at the Fox Hills–Hell Creek formational contact and at the stratigraphically higher, upper and lower contacts with the Breien Member suggests that the relationship is genetic and not an artifact of a regional hiatus between the Fox Hills and Hell Creek Formations. Combined with the regional persistence of a unit comparable to our Unit 5, the association supports our interpretation that this transition (i.e., coastal swamp/marine shoreface) is typical of the paleoenvironmental settings adjacent to the seaway. Our interpretation of this association is shown conceptually in Figure 12.

5. There are no obvious soil structures or features at the top of the rooted sandstone at the CHS that would indicate subaerial exposure for an extended period, although we did note that mottling and root structures are indicative of some degree of exposure.

6. Johnson et al. (2002) noted that coal deposits typically are developed in the shoreward beds of regressive sequences. They also argued, however, that deposits in the lower Hell Creek Formation are not actually coal bearing and thus are not typical of regressions. Nevertheless, a high sediment supply, leading to organic-rich mudstones rather than coal-bearing deposits, would have been expected within the rapidly prograding Cretaceous shoreline of the Dakotas.

The strongest evidence for a significant hiatus between the Fox Hills and Hell Creek Formations cited by Johnson et al. (2002) occurs in regions west of the CHS, where unconformities have been widely reported before. The evidence includes the apparent absence of subchrons C30r and C31r in southwestern North Dakota and the absence of *Aquilapollenites striatus* in lower parts of the Hell Creek Formation in that region. Although evidence for a hiatus in southwestern North Dakota does not directly conflict with the conclusions in the present report, part of our argument rests on the regional consistency of sediments at the Hell Creek–Fox Hills formational contact. Given this consistency, we would not expect a significant hiatus along the Little Missouri River in that area, despite the obvious relief in the contact that we observed there. We note that the key C30r interval that is missing along the Little Missouri River is particularly short in duration. It may have been missed by sampling or, more probably, it was simply not preserved in the Hell Creek Formation because of the intermittent and scouring nature of fluvial deposition.

Question of Stratigraphic Position and Fluvial-swamp Versus Coastal-swamp Deposition

We point out two significant implications of the stratigraphic location of the Concordia bone bed. First, the bone bed is in lowermost parts of the Hell Creek Formation, not in its upper levels as are most of the other well-known bone beds (Fastovsky, 1987). Second, the bone bed is more likely associated with a regionally extensive coastal swamp that was tied to the position of the Cretaceous shoreline rather than to a local variation in a fluvial environment. Evidence for the latter conclusion is two-fold. First, lignitic shales and mudstones rest conformably on marine-coastal strata at the CHS. Second, the widespread and pervasive character of the lignitic shales and mudstones of Unit 5 is not consistent with a localized fluvial swamp, such as interpreted for the coals of the upper Hell Creek Formation. Those coals are thin (10–40 cm thick) and are not regionally persistent (Fastovksy, 1987). The thickness and persistence of Unit 5 is consistent with a widespread, persistent swamp near a coast where the water table was controlled by sea level.

CONCLUSIONS

1. The hadrosaur bone bed at the Concordia Hadrosaur Site does not represent a sudden-death event in a primarily fluvial environment. Rather, the deposit represents an accumulation over an extended period (months to years, rather than days) in a hadrosaur-dominated coastal swamp.

Table 4. Comparison between Mason Dinosaur Quarry (MDQ) and Concordia Hadrosaur Site (CHS).

Similarities	Differences
Units 4 and 5: An erosional contact between lignitic mudstone (Unit 5, CHS) and overlying fluvial sediments (Units 6-9, CHS) exists above the bone bed at both sites. The bone horizon (predominantly *Edmontosaurus*) is seen 1.5-3 meters above the Fox Hills-Hell Creek contact in peat-rich clay and siltstone at both locations (Unit 5, CHS). Bone bed is thin but extensive at both locations, extending at least a hundred meters. At both locations, the Fox Hills–Hell Creek contact is between a fissile, dark brown lignitic shale layer (Unit 5, CHS) and a yellow-mottled fine sandstone containing randomly oriented organic fragments (Unit 4 rooted sandstone, CHS).	**Units 4 and 5:** The mudstone and claystone overlying the lignitic shale directly above the Fox Hills at the MDQ are substantially less peat-rich than at the Concordia site Lignitic shale zone is thin (30 cm) at MDQ, thick at CHS (5 m). No rhizoconcretions are seen in the sandstone below the lignitic shale at MDQ. Although, rhizoconcretions are not seen everywhere in the rooted sandstone of Unit 4 at the CHS.
	Units 2 and 3: There are no obvious intertidal deposits at the Ruth Mason Quarry such as Units 2 and 3 at CHS.
Unit 1: Planar laminated to broadly cross-stratified fine sand of the upper Fox Hills (like Unit 1 of CHS) occurs at both locations below the bone bed. Indurated layers exist at both locations within the planar laminated fine sandstone (like Unit 1, CHS). These indurated layers contain high proportions of calcite in both locations, unlike the less-indurated sandstone. At both sites the indurated layers (in Unit 1 at CHS) contain evidence of transport, including rip-up clasts and clast lags, or at MDQ, accumulations of disarticulated, convex up, oyster shells.	**Unit 1:** The calcite-rich layers at MDQ consist of dense oyster accumulations, whereas at the Concordia site, the calcite layers consist of micrite pellets. *Ophiomorpha* were seen at the Concordia site, but not at the MDQ. Clay layers and peat layers are found below the planar laminated fine sand at MDQ. Rocks below the laminated fine sand are not exposed at CHS.

2. The succession of rocks at the Concordia Hadrosaur Site records the marine–terrestrial transition that occurred during progradation of the sediments of the future Hell Creek Formation into the Fox Hills seaway. Facies progressively change from those representing upper shoreface and foreshore environments to others representing coastal dunes, coastal swamps, and, finally, distributary channels and rivers.

3. Within this changing sequence of paleoenvironmental settings, the hadrosaur-dominated bone bed lies at the transition from an extensive coastal swamp to a fluvially dominated, distributary environment.

ACKNOWLEDGMENTS

We thank Karl Leonard at Minnesota State University Moorhead for insightful comments made in the field and on the manuscript. We thank Ray Rogers at Macalester College for his informal pre-review of the manuscript, and Tom Bown, an anonymous reviewer, and Donald Boyd for particularly useful comments and suggestions, as well as Jay Lillegraven for his handling of the manuscript. We thank Joseph Hartman at the University of North Dakota for identification of mollusks.

REFERENCES CITED

am Ende, B. A., 1991, Depositional environments, palynology, and age of the Dakota Formation, south-central Utah, *in* Nations, J. D., and Eaton, J. G., eds., Stratigraphy, depositional environments and sedimentary tectonics of the western margin, Cretaceous Western Interior Seaway: Boulder, Geological Society of America Special Paper 260, p. 65–83.

Bigarella, J. J., 1972, Eolian environments: Their characteristics, recognition, and importance, *in* Rigby, J. K., and Hamblin, W. K., eds., Recognition of ancient sedimentary environments: Tulsa, SEPM Special Publication 16, p.12–62.

Blatt, H., Middleton, G., and Murray, R., 1980, Origin of sedimentary rocks: Englewood Cliffs, New Jersey, Prentice-Hall, 782 p.

Butler, R. D., 1980, Stratigraphy, sedimentology and depositional environments of the Hell Creek Formation (Late Cretaceous) and adjacent strata, Glendive area, Montana [Ph.D. dissert.]: Grand Forks, University of North Dakota, 270 p.

Carr, D. A., 1991, Facies and depositional environments of the coal-bearing upper carbonaceous member of the Wepo Formation (Upper Cretaceous), north-eastern Black Mesa, Arizona, *in* Nations, J. D., and Eaton, J. G., eds., Stratigraphy, depositional environments and sedimentary tectonics of the western margin, Cretaceous Western Interior Seaway: Boulder, Geological Society of America Special Paper 260, p. 167–188.

Carter, C. H., 1978, A regressive barrier and barrier-protected deposit: Despositional environments and geographic setting of the late Tertiary Cohansey Sand: Journal of Sedimentary Petrology, v. 48, p. 933–950.

Christians, J. P., 1992, Taphonomy and sedimentology of the Mason Dinosaur Quarry, Hell Creek Formation (Upper Cretaceous), South Dakota [Master's thesis]: Madison, University of Wisconsin, 91 p.

Clemens, W. A., 2002, Evolution of mammalian fauna across the Cretaceous–Tertiary boundary in northeastern Montana and other areas of the Western Interior, *in* Hartman, J. H., Johnson, K. R., and Nichols, D. J., eds., The Hell Creek Formation and the Cretaceous–Tertiary boundary in the northern Great Plains: An integrated continental record of the end of the Cretaceous: Boulder, Geological Society of America Special Paper 361, p. 217–245.

Currie, P. J., and Dodson, P., 1984, Mass death of a herd of ceratopsian dinosaurs, *in* Reif, W. E., and Westphal, F., eds., Third symposium on Mesozoic terrestrial ecosystems: Tübingen, Short Papers, p. 61–66.

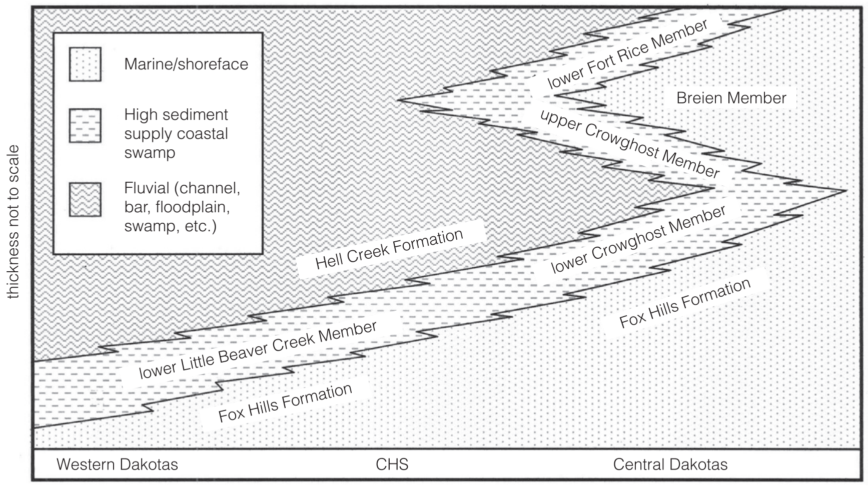


Figure 12. Conceptual interpretation of facies relationships from eastern Montana to south-central North Dakota, based on observed lithologic similarities in Little Beaver Creek, upper and lower Crowghost, and Fort Rice Members (defined by Frye, 1969).

Curtiss, R. E., 1954, Areal geology of the Black Horse Butte Quadrangle (15 minute): South Dakota Geological Survey, scale 1:62500, 1 sheet.

Davidson-Arnott, R. G. D., and Greenwood, B., 1976, Facies relationships on a barred coast, Kouchibouguac Bay, New Brunswick, Canada, *in* Davis, R. A., and Ethington, R. L., eds., Beach and nearshore sedimentation: Tulsa, SEPM Special Publication 24, p. 149–168.

Erickson, B. R., 1999, Fossil Lake Wannagan (Paleocene: Tiffanian), Billings County, North Dakota: North Dakota Geological Survey Miscellaneous Series no. 87, 9 p.

Fastovsky, D. E., 1987, Paleoenvironments of vertebrate-bearing strata during the Cretaceous–Paleogene transition, eastern Montana and western North Dakota: Palaios, v. 2, p. 282–295.

______ 1990, Rocks, resolution, and the record: A review of depositional constraints on fossil vertebrate assemblages at the terrestrial Cretaceous/Paleogene boundary, eastern Montana and western North Dakota, *in* Sharpton, V. L., and Ward, P. D., eds., Global catastrophes in Earth history: An interdisciplinary conference on impacts, volcanism and mass mortality: Boulder, Geological Society of America Special Paper 247, p. 541–548.

Fastovsky, D. E., and Dott, R. H., Jr., 1986, Sedimentology, stratigraphy and extinctions during the Cretaceous–Paleogene transition at Bug Creek, Montana: Geology, v. 14, p. 279–282.

Fiorillo, A. R., 1998. Measuring fossil reworking within a fluvial system: An example from the Hell Creek Formation (Upper Cretaceous) of eastern Montana, *in* Tomida, Y., Flynn, L. J., and Jacobs, L. L., eds., Advances in vertebrate paleontology and geochronology: Tokyo, National Science Museum Monographs, p. 243–251.

Fiorillo, A. R., and Voorhies, M. R., 1999, Bonebed taphonomy: Distinguishing mass death assemblages from time-averaged accumulations [abs.]: Journal of Vertebrate Paleontology, v. 19, supplement to no. 3, p. 44A.

Frye, C. I., 1969, Stratigraphy of the Hell Creek Formation in North Dakota: North Dakota Geological Survey Bulletin 54, 65 p.

Hand, B. M., 1967, Differentiation of beach and dune sands using settling velocities of light and heavy minerals: Journal of Sedimentary Petrology, v. 37, p. 514–520.

Hill, G. W., and Hunter, R. E., 1976, Interaction of biological and geological processes in the beach and nearshore environments, northern Padre Island, Texas, *in* Davis, R. A., and Ethington, R. L., eds., Beach and nearshore sedimentation: Tulsa, SEPM Special Publication no. 24, p. 169–187.

Hoganson, J. W., Campbell, J. M., and Murphy, E. C., 1994, Stratigraphy and paleontology of the Cretaceous Hell Creek Formation, Stumpf Site, Morton County, North Dakota [abs.]: North Dakota Academy of Science Proceedings, v. 48, p. 95.

Howard, J. D., 1972, Trace fossils as criteria for recognizing shorelines in the stratigraphic record, *in* Rigby, J. K., and Hamblin, W. K., eds., Recognition of ancient sedimentary environments: Tulsa, SEPM Special Publication no. 16, p. 215–225.

______ 1978, Sedimentology and trace fossils, *in* Basan, P. ed., Trace fossil concepts: Tulsa, SEPM Short Course, no. 5, p. 11–42.

Inman, D. L., 1952, Measures for describing the size distributions of sediments: Journal of Sedimentary Petrology, v. 22, p. 125–145.

Jacobson, R. J., and Sroka, S. D., 1998, Preliminary assessment of a Hell Creek dinosaurian fauna from sites in Corson County, South Dakota [abs.]: Journal of Vertebrate Paleontology, v. 18, supplement to no. 3, p. 53A.

Johnson, K. R., and Hickey, L. J., 1990, Megafloral change across the Cretaceous/Tertiary boundary in the northern Great Plains and Rocky Mountains, U.S.A., *in* Sharpton, V. L., and Ward, P. D., eds., Global catastrophes in Earth history: An interdisciplinary conference on impacts, volcanism and mass mortality: Boulder, Geological Society of America Special Paper 247, p. 433–444.

Johnson, K. R., Nichols, D. J., and Hartman, J. H., 2002, Hell Creek Formation: A 2001 synthesis, *in* Hartman, J. H., Johnson, K. R., and Nichols, D. J., eds., The Hell Creek Formation and the Cretaceous–Tertiary boundary in the northern Great Plains: An integrated continental record of the end of the Cretaceous: Boulder, Geological Society of America Special Paper 361, p. 503–510.

Klett, M. C., and Erickson, J. M., 1977, Type and reference sections for a new member of the Fox Hills Formation, Upper Cretaceous (Maastrichtian) in the Missouri valley region, North and South Dakota: North Dakota Geological Survey Miscellaneous Series no. 5B, 24 p.

Koster, E. H., 1987, Vertebrate taphonomy applied to the analysis of ancient fluvial systems, *in* Ethridge, F. G., Flores, R. M., and Harvey M. D., eds., Recent developments in fluvial sedimentology: Tulsa, Third International Fluvial Sedimentology Conference Contributions, SEPM Special Publication 39, p. 159–169.

Moore, W. L., 1976, The stratigraphy and environments of deposition of the Cretaceous Hell Creek Formation (reconnaissance) and the Paleocene Ludlow Formation (detailed), southwestern North Dakota: North Dakota Geological Survey Report of Investigation no. 56, 40 p.

Murphy, E. C., Hoganson, J. W., and Johnson, K. R., 2002, Lithostratigraphy of the Hell Creek Formation in North Dakota, *in* Hartman, J. H., Johnson, K. R., and Nichols, D. J., 2002, The Hell Creek Formation and the Cretaceous–Tertiary boundary in the northern Great Plains: An integrated continental record of the end of the Cretaceous: Boulder, Geological Society of America Special Paper 361, p. 9–34.

Nichols, D. J., and Fleming, R. F., 1990, Plant microfossil record of the terminal Cretaceous event in the western United States and Canada, *in* Sharpton, V. L., and Ward, P. D., eds., Global catastrophes in Earth history: An interdisciplinary conference on impacts, volcanism and mass mortality: Boulder, Geological Society of America Special Paper 247, p. 445–455.

Oakland, L., and Pearson, D. A., 1995, A *Tyrannosaurus rex* from the Hell Creek Formation (Cretaceous: Maastrichtian), Bowman County, North Dakota and observations on its depositional setting [abs.]: North Dakota Academy of Science Proceedings, v. 49, p. 62.

Reineck, H. E., and Singh, I. B., 1980, Depositional sedimentary environments: New York, Springer-Verlag, 549 p.

Reinson, G. E., 1984, Barrier-island and associated strand-plain systems, *in* Walker, R. G., ed., Facies models: Toronto, Geoscience Canada, Reprint Series 1, p. 119–140.

Roberts, J. N. R., and Kirschbaum, M. A., 1995, Paleogeography of the Late Cretaceous of the Western Interior of middle North America: Coal distribution and sediment accumulation: U.S. Geological Survey Professional Paper 1561, 115 p.

Selley, R. C., 1985, Ancient sedimentary environments: Ithaca, New York, Cornell University Press, 317 p.

Thomas, R. G., Smith, D. G., Wood, J. M., Visser, J., Calverley-Range, E. A., and Koster, E. H., 1987, Inclined heterolithic stratification — terminology, description, interpretation and significance: Sedimentary Geology, v. 53, p. 123–179.

Voorhies, M. R., 1969, Taphonomy and population dynamics of an early Pliocene vertebrate fauna, Knox County, Nebraska: Contributions to Geology, University of Wyoming, Special Paper 1, 69 p.

Waage, K. M., 1968, The type Fox Hills Formation, Cretaceous (Maastrichtian), South Dakota: Peabody Museum of Natural History Bulletin 27, Yale University, 179 p.

Walker, R. G., and Cant, D. J., 1984, Sandy fluvial systems, *in* Walker, R. G., ed., Facies models: Toronto, Geoscience Canada, Reprint Series 1, p. 71–89.

Weimer, R. J., and Hoyt, J. H., 1964, Burrows of *Callianassa major* Say, geologic indicators of littoral and shallow neritic environments: Journal of Paleontology, v. 38, p. 761–767.

White, P. D., Fastovsky, D. E., and Sheehan, P. M., 1998, Taphonomy and suggested structure of the dinosaurian assemblage of the Hell Creek Formation (Maastrichtian), eastern Montana and western North Dakota: Palaios, v. 13, p. 41–51.

Wroblewski, A. F.-J., 1999, Stratigraphy, sedimentology, and paleontology of the Hell Creek Formation (Maastrichtian), Bowman County, North Dakota [abs.]: American Association of Petroleum Geologists Bulletin, v. 83, p. 1190.

MANUSCRIPT RECEIVED: MAY 30, 2003

REVISED MANUSCRIPT RECEIVED: MARCH 18, 2004

SECOND REVISED MANUSCRIPT RECEIVED: MAY 27, 2004

MANUSCRIPT ACCEPTED: OCTOBER 29, 2004