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Hell Creek Formation: A 2001 synthesis

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INTRODUCTION

In the 94 years since Barnum Brown (1907) described the Hell Creek Formation, this rock unit has yielded magnificent dinosaurs and diverse plants and animals from the last Cretaceous terrestrial ecosystem. Fossils collected from near the Cretaceous-Tertiary (K-T) boundary in the Hell Creek Formation have been used to argue catastrophic extinction, gradual extinction, and even the survival of dinosaurs into the Tertiary. The contributors to this volume have attempted to carry the understanding of these uppermost Cretaceous strata to the next level by exploring the lesser studied eastern half of the outcrop area, utilizing new techniques, attempting to study the entirety of the fossilized biota, and applying an integrated approach wherever possible.

From east to west, the preserved remnants of the Hell Creek Formation extend nearly 700 km (Fig. 1). Most of the previous published work on the formation and its fossils was based on outcrops in Garfield and McCone Counties, Montana, around the margins of the Fort Peck Reservoir, and around the margins of the Cedar Creek Anticline near the Montana–North Dakota border. The exposures in North Dakota received some attention in the late 1960s, but interdisciplinary efforts began there primarily in the late 1980s (Johnson et al., 1989). The Hell Creek Formation in South Dakota has yielded spectacular dinosaurs such as the *Tyrannosaurus rex* "Sue," but very little scientific effort has been applied there, and few publications are available. In this summary chapter, we attempt to synthesize and integrate the major findings of the other chapters in this volume.

STRATIGRAPHY

The Hell Creek Formation is exposed in Montana, North Dakota, and South Dakota. Equivalent and contiguous strata in Wyoming are known as the Lance Formation and in Canada as the Frenchman and Scollard Formations. In this volume, authors have focused on the areas that bear the Hell Creek name, primarily those on the margin of the Williston Basin in Montana and the Dakotas (Fig. 1).

The complete thickness of the Hell Creek Formation has been measured at only a few locations. Several factors have contributed to this apparent oversight. The formation is mostly horizontal and is usually thicker than the topographic relief that has been incised into it. This, combined with the lateral discontinuity of beds, a bentonitic surface weathering that obscures bedding, and an upper contact that in places is difficult to identify, has created a situation where it is difficult to make accurate measurements. For these reasons, many have estimated the thickness of the formation rather than directly measuring it. Estimates in the Fort Peck Reservoir area have ranged from a maximum of 170 m in Garfield County, Montana (Brown, 1907) to a minimum of 41 m in McCone County, Montana (Collier and Knechtel, 1939). The most recent work in McCone County reported thicknesses of 51–85 m (Rigby and Rigby, 1990). Murphy et al. (this volume) report six localities in North Dakota where they measured the entire thickness of the formation. At two sites in southwestern North Dakota, the formation is 100 m thick and at four sites in the central North Dakota the formation ranges from 50 to 70 m thick.

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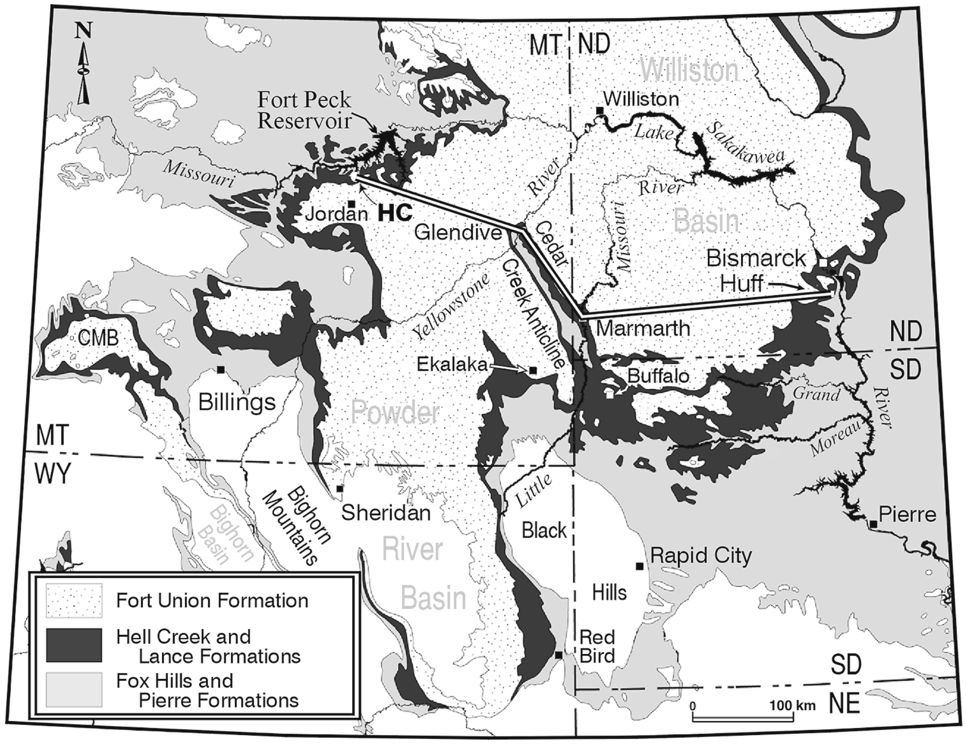

Figure 1. Map of northern Great Plains showing outcrop of Hell Creek and equivalent and adjacent strata. Type area of Hell Creek Formation is marked as HC. Line of cross section for Figures 2 and 3 is marked.

The greatest degree of integration of diverse Hell Creek data has been achieved in sections in southwestern North Dakota. These sections were used to provide a lithostratigraphic framework for magnetostratigraphy, geochronology, chemostratigraphy, palynology, megafloral paleobotany, paleoentomology, and vertebrate paleontology. Patterns revealed by this integration provide new hypotheses that can be tested across the entire outcrop of the formation.

A cross section of the formation presented in Figure 2 extends from the type area of the Hell Creek on the south bank of the Fort Peck Reservoir, to the north end of the Cedar Creek Anticline at Glendive, Montana, to the south end of the anticline near Marmarth, North Dakota, to the Missouri River south of Bismarck, North Dakota. Along this transect, the formation thins, ranging from 80–120 m in the west to 50–70 m in the east. Over the 500 km course of this transect, the top of the formation is always within a few meters, above or below, the K-T boundary, and as such, it can be roughly viewed as diachronous on a local fine scale, but essentially isochronous on the regional scale (Nichols and Johnson, this volume; Hotton, this volume; Fastovsky, 1987).

The easternmost outcrops of the Hell Creek Formation document that the formation interfingers with marine strata. Murphy et al. (this volume) place the marine sediments of the Breien Member of the Hell Creek Formation into stratigraphic context relative to the top of the formation. They also name a new marine deposit, the Cantapeta advance, a unit 10 m below the top of the formation, that contains *Ophiomorpha* burrows and was clearly deposited under the influence of marine conditions. This is the youngest evidence of Cretaceous marine deposition in the northern Great Plains. It is significant because it reduces the stratigraphic separation of the highest Cretaceous marine beds and the lowest Paleocene marine beds to a mere 15 m and raises the probability that a marine K-T boundary may be in the subsurface in the eastern Williston Basin. Hoganson and Murphy (this volume) describe the dimensions and vertebrate fauna of the Breien Member of the Hell Creek Formation. Hartman and Kirkland (this volume) document the previously unpublished invertebrate fauna collected by Charles Frye in the 1960s and interpret variations in salinity based primarily on molluscan associations through the end of the Cretaceous as represented by the Fox Hills and Hell Creek Formations. Collectively, these papers show that the Breien Member was marine, and its fauna was closely related to the marine fauna of the underlying Fox Hills Formation. In addition, brackish and marine mollusks from Hell Creek strata overlying the Breien Member indicate a younger and more complex history of the Western Interior Seaway near the end of the Cretaceous.

MAGNETOSTRATIGRAPHY

Both Lund et al. (this volume) and Hicks et al. (this volume) present papers on the magnetostratigraphy of the Hell Creek Formation. Lund et al. compare two sections at Glendive, Montana, with two sections south of Bismarck, a separation of more than 300 km. Hicks et al. studied six sections along

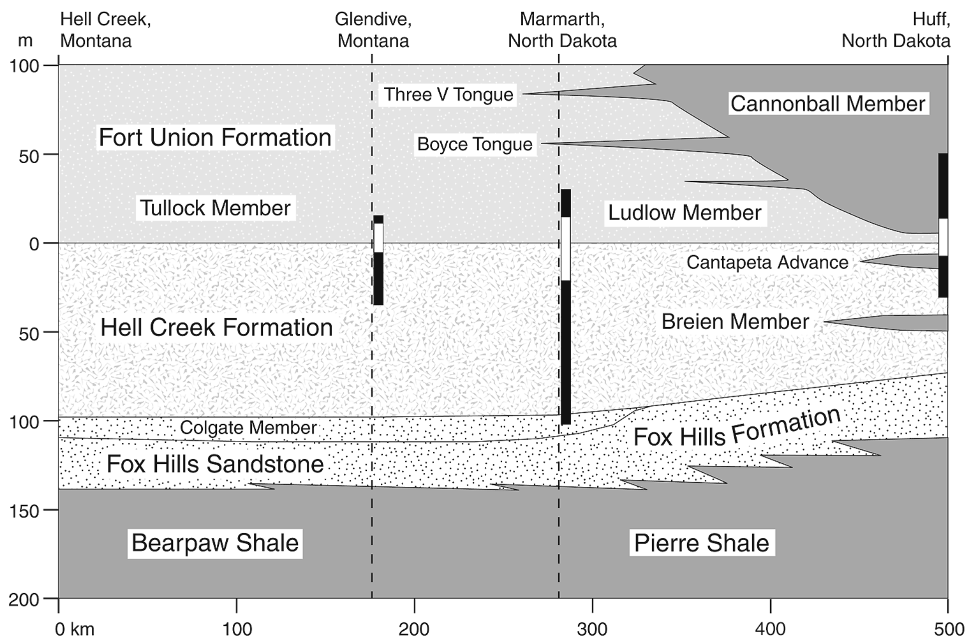

Figure 2. Stratigraphic cross section from Hell Creek to Glendive, Montana, to Marmarth, to Huff, North Dakota showing thickness of Hell Creek and adjacent strata. Black and white bars show position and results of paleomagnetic sections of Hicks et al. (this volume) near Marmarth and Lund et al. (this volume) near Glendive, Montana, and Huff, North Dakota. Datum is top of Hell Creek Formation. The Firesteel lignite seam divides the lower and upper Hell Creek Formation in South Dakota, south of the line of section.

a 45 km length of the Little Missouri River. Both groups identified three polarity subchrons that they interpret as C29n, C29r, and C30n. In all 10 sections, the palynologically defined K-T boundary occurs in a reversed interval interpreted as C29r. The thickness of C29r and the position of the K-T boundary relative to the base of the subchron are variable, but in general, the K-T boundary occurs in the basal third of the subchron. Lund et al. interpret this variation to represent a diachroneity of the top of the Hell Creek Formation and argue that the top of the formation is older to the east than to the west. Hicks et al. see this same amount of variation in the position of the K-T boundary within their local transect, but argue that local diastems within the Hell Creek are responsible for the variation. In the most complete marine sections, the K-T boundary occurs slightly above the middle of C29r (Smit, 1999).

Obradovich (*in* Hicks et al., this volume) recalibrates the age of the K-T boundary to 65.51 Ma by normalizing many recently determined radiometric ages to a uniform standard. The K-T boundary and the beginning and end of magnetic polarity subchron C29r represent time lines. Using estimated durations for the Cretaceous and Paleocene portions of C29r (D'Hondt et al., 1996), the age of the K-T boundary (Hicks et al., this volume), and the thickness of rock between those time lines, it is possible to estimate a sediment accumulation rate for the Hell Creek Formation. Both Lund et al. and Hicks et al. use variants of this method and the assumption of a uniform sediment accumulation rate to make estimates of the duration of the entire formation. Lund et al. estimate a duration of 2.5 m.y., whereas Hicks et al. estimate 1.36 m.y. The difference in these estimates is due to three variables: (1) variable formation thickness, (2) different estimations for the duration of C29r, and (3) different thicknesses or accumulation rates of the Cretaceous portion of C29r. The shorter duration is supported by the absence of C30r in two tightly sampled sections of the lower Hell Creek Formation in Bowman County, North Dakota. Nonetheless, the difference between the two estimates illustrates the need for better age control at the base of the formation.

CHEMOSTRATIGRAPHY

Arens and Jahren (this volume) present analyses of stable carbon isotopes from sedimentary rock samples in four sections in southwestern North Dakota. The $\delta^{13}C$ shift of 1.5‰–2‰ that marks the K-T boundary in marine sections was detected in all four sections, but not always in precise correlation with the palynologically defined K-T boundary. Additional variations of $\delta^{13}C$ throughout the formation have the potential to define an isotope stratigraphy, allowing for independent correlation between sections of the Hell Creek Formation. The differences between these results and the palynological record suggest that chemostratigraphy needs to be refined at more sites where the K-T boundary clay layer is present.

PALYNOLOGY AND PALEOBOTANY

Nichols (this volume) documents the palynology of the entire Hell Creek Formation, and Nichols and Johnson (this volume) use palynology to locate the K-T boundary in 17 sections. In several sections north of Marmarth, North Dakota, they identify a zone as thick as 3 m at the base of the Ludlow Member of the Fort Union Formation that contains Cretaceous palynomorphs. They name this the Fort Union strata of Cretaceous age. Pearson et al. (this volume) have discovered a partial ceratopsian skeleton in this unit. Hotton (this volume) addresses the K-T boundary in the Fort Peck Reservoir region and argues that dramatic changes in the palynoflora at the K-T boundary support the impact hypothesis. Kroeger (this volume) uses palynology to discuss sedimentological facies within the Hell Creek.

Johnson (this volume) describes the megafloral paleobotany of the Hell Creek and lower Fort Union Formations and recognizes 380 megafloral morphotypes. Of this total, 328 morphotypes occur in the Hell Creek Formation. This is more than three times the number of palynofloral taxa described by Nichols from the same beds, despite the huge difference in sample size (Nichols observed ~450 000 playnomorphs and Johnson saw ~30 000 megafossils). This indicates that megafossils sample the flora at a higher taxonomic resolution than palynomorphs (species rather than genera or families). The vegetation of the Hell Creek is dominated by arboreal angiosperms, whereas ferns and conifers are more abundant in the palynoflora than the megaflora. Hotton's statistical analyses are based on a Hell Creek palynoflora composed of about three times as many species as recognized by Nichols, because these authors took somewhat different taxonomic approaches. It is significant that both authors conclude that about one-third of the palynoflora became extinct at the K-T boundary. Johnson, whose fossil data set has higher taxonomic resolution, concludes that ~80% of the Hell Creek flora did not survive the terminal Cretaceous extinction event. These results are not in disagreement, but instead result from sampling a biotic record at different taxonomic levels.

The depth of understanding that comes from combining the strengths of palynology and megafloral paleobotany is impressive. Because pollen and leaves are derived from the same vegetation, interpretations based on one organ can be extrapolated to the other. The high stratigraphic resolution of palynology allows for the effects of the Cannonball transgression (the initiation of lignite deposition) to be separated from the effects of the impact event that deposited iridium and shocked minerals on the landscape. Megafossils lack that stratigraphic resolution, but offer species-level taxonomic resolution, which allows for a more precise assessment of the magnitude of the extinction. In addition, the paleoclimatic abilities of foliar physiognomy allow for the identification of Late Cretaceous climate trends. A dramatic warming, recorded by fossil leaves that first occur ~20 m below the top of the Hell Creek Formation (Johnson and Wilf, 1996), also is recorded in the record of marine foraminifera near Antarctica (Stott and Kennett, 1990).

VERTEBRATE PALEONTOLOGY

Russell and Manabe (this volume) provide a brief overview of the dinosaurian fauna of the Hell Creek Formation. They discuss the much-collected but rarely mentioned monotypic *Edmontosaurus* dinosaur bone beds found in the lower part of the formation in central South Dakota and adjacent North Dakota (Christians, 1992). These bone beds occur above the Fox Hills–Hell Creek formational contact but generally below the Firesteel lignite zone, which marks the contact between the lower and upper Hell Creek Formation in central South Dakota. The presence and nature of these bone beds are reminiscent of monotypic ceratopsian bone beds described by Eberth (1998, written commun.) from the Dinosaur Park Formation of Alberta. He suggests that these deposits were formed by storm surge across a low-relief coastline that provided both the mechanism of death by drowning and the mode of burial.

Pearson et al. (this volume) combine vertebrate microsites and isolated dinosaur occurrences to plot the distribution of 61 vertebrate taxa relative to the K-T boundary in westernmost North Dakota and South Dakota. All common taxa occur throughout the formation and dinosaurs are present in all localities. There is a zone ~2 m thick at the top of the formation in which no bones have been found, and Pearson et al. interpret this to be related to a change in the sedimentological nature of the interval containing the Hell Creek–Fort Union formational contact. This gap has been long recognized (Clemens, this volume) and remains controversial, but Pearson et al. have clarified the issues by providing the first documentation of a large data set precisely located in reference to both the formational contact datum and the K-T boundary.

Hunter and Archibald (this volume) document the mammalian fauna of the Hell Creek Formation in southwestern North Dakota and show it to be a typical Lancian fauna. Holroyd and Hutchison (this volume) compare the turtle fauna of southwestern North Dakota with that of the type Hell Creek in Montana and other Lancian sites elsewhere and document some regional differences in the turtle faunas suggestive of latitudinal gradients.

Hoganson and Murphy document the vertebrate fauna of the marine Breien Member of the Hell Creek Formation and conclude that it more closely resembles the fauna of the underlying Fox Hills Formation than the overlying fauna of the marine Cannonball Member of the Fort Union Formation. Pearson et al. also noted the presence of a number of fish taxa in the Hell Creek Formation in southwestern North Dakota that indicate proximity of brackish or marine water.

Clemens (this volume) provides a detailed review of the recent and historical work in the Hell Creek type area and addresses the role of fossil mammals for understanding the terminal Cretaceous event. He concludes that immigration played a major role in the turnover of mammalian faunas before the K-T boundary. He discusses Paleocene vertebrate sites in the uppermost Hell Creek section in Garfield County, Montana. These observations appear to be in agreement with the work of Nichols and Johnson and Lund et al., who used palynology and magnetostratigraphy, respectively, to argue that the upper contact of the Hell Creek Formation is diachronous.

INVERTEBRATE PALEONTOLOGY

Hartman and Kirkland (this volume) document the previously unpublished invertebrate fauna collected by Charles Frye in the 1960s and interpret possible variations in salinity based primarily on molluscan associations from the Fox Hills Formation through the end of the Cretaceous. This fauna was derived primarily from the Breien Member of the Hell Creek but also includes specimens from higher and lower in the formation. Many of these species are interpreted to have inhabited brackish or marine waters, suggesting that much of the lower Hell Creek in the Missouri River Valley was deposited close to the remnant Cretaceous Western Interior Seaway. Hoganson and Murphy (this volume) present ichnofossil evidence of marine conditions in the Breien Member and also document the existence of a poorly preserved specimen of the zonal ammonite *Jeletzkytes* cf. *J. nebrascensis. Jeletzkytes nebrascensis* represents the youngest zone of the Western Interior ammonite zonation. Examples of this ammonite are known from the Fox Hills Formation and the Elk Butte Member of the Pierre Shale (Kennedy et al., 1998). The poor preservation of the Hell Creek specimen ammonite is unfortunate considering its potential biostratigraphic significance.

PALEOENTOMOLOGY

Labandeira et al. (this volume) apply a novel approach to understanding the insect fauna of the Hell Creek and Fort Union Formations by studying the insect damage found on the fossil leaves described by Johnson (this volume). They document 49 types of insect damage, including foliage feeding, mining, galling, and piercing and sucking. Only 22 types of insect damage cross the K-T boundary extinction event, and of these, 55% were the more generalized feeding types. They interpret this to suggest the extinction of specialist herbivores at the K-T boundary.

AGE OF THE HELL CREEK FORMATION

Age of the upper contact of the Hell Creek Formation

The age and duration of the Hell Creek Formation are longstanding and still partially unanswered questions. The upper contact of the formation was recognized to approximate the K-T boundary by Dorf (1940, 1942) and Brown (1952), although it was not directly correlated to the marine K-T boundary. Ross (1940), Fox and Ross (1942), and Fox and Olsson (1969) described the early Paleocene (Danian) foraminifera of the Cannonball Member of the Fort Union Formation and showed that the terrestrial K-T boundary could be roughly correlated to the marine K-T boundary. More precise correlation followed with the use of palynology to identify the K-T boundary and the discovery of the iridium anomaly at a level very near the top of the Hell Creek Formation in the type area by Alvarez (1983) and Bohor et al. (1984), and in southwestern North Dakota by Johnson et al. (1989) and Nichols et al. (2000). Magnetostratigraphy in the Hell Creek type area (Archibald et al., 1982; Swisher et al., 1993), near Glendive (Lund et al., this volume), Ekalaka (J. Archibald, 1988, written commun.), and Marmarth (Hicks et al., this volume), places the palynological K-T boundary in a zone of reversed polarity interpreted as subchron C29r. Lund et al. (this volume) show two sections where the top of the Hell Creek Formation is located very close to the base of C29r, which suggests to them that the Hell Creek deposition terminated locally before the end of the Cretaceous. Nichols and Johnson (this volume) use palynology to show that the K-T boundary and the formation contact are separated by 0–270 cm in southwestern North Dakota. This result is similar to work near Ekalaka, Montana; Buffalo, South Dakota (Nichols, 1999, written communication); the Hell Creek type area (Hotton, this volume), and central North Dakota (Murphy et al., 1995). Thus the upper contact of the Hell Creek over most of its outcrop area is roughly the age of the K-T boundary plus or minus the time taken to deposit as much as 3 m of sediment. On the basis of the thickness of C29r, 3 m of Hell Creek sediment would likely have accumulated in 30–100 k.y. Thus, over an east-west transect of the Hell Creek Formation, the upper contact is slightly diachronous.

Age of the lower contact of the Hell Creek Formation

Estimates of the age of the lower contact of the Hell Creek Formation are few and poorly delimited. Hicks et al. (this volume) attempted to date a volcanic ash from Doaks Butte near the base of the formation on the South Dakota-North Dakota border, but did not achieve a tight-enough spread of dates to be significant. The age of the youngest dated ammonite below the Hell Creek is the 70.15 Ma *Baculites grandis* zone that occurs in the uppermost Bearpaw Shale in the Fort Peck Reservoir area, and in the uppermost Pierre Shale in the Cedar Creek Anticline. The 69.57 Ma *Baculites clinolobatus* zone underlies the formation in central North Dakota, as do the undated *Hoploscaphites birkelundi, Hoploscaphites nicolletti*, and *Jeletzkytes nebrascensis* zones. Hicks et al. (this volume) and Lund et al. (this volume) provide estimates of the age of the base of the Hell Creek Formation based on extrapolation of sediment accumulation rates: their estimates are 1.36 Ma and 2.5 Ma, respectively. There is a distinct possibility that the base of the formation is significantly diachronous. The oldest ammonite zone in the uppermost portion of the Pierre Shale below the Hell Creek Formation is the *Baculites cuneatus* zone, which occurs near Ekalaka, Montana. At nearly 73 Ma, this would represent the absolute maximum age for the base of the formation.

Basal Hell Creek unconformity

The nature of the basal contact of the Hell Creek Formation is germane to the discussion of the age of its base. In his original description, Brown (1907) discussed the erosional basal contact of the Hell Creek on the underlying Fox Hills Formation. Subsequent work in the Fort Peck Reservoir region identified basal Hell Creek channels containing quartzite cobbles up to 10 cm

(Bauer, 1925; Jensen and Varnes, 1964). The uppermost unit of the Fox Hills Formation in the Fort Peck Reservoir and Cedar Creek Anticline areas is the Colgate Member, a stark white, leached, 10–20-m-thick sandstone with an eroded upper surface. There has been continuing debate over the extent and magnitude of the basal Hell Creek unconformity. Dobbin and Reeside (1929) studied this issue carefully over the entire Rocky Mountain region and concluded that there was not a significant regional unconformity. Belt et al. (1997) combined sedimentological and magnetostratigraphic data to argue that this unconformity was regional and represents a significant period of time between the deposition of the Fox Hills and the Hell Creek Formations. Several observations cause us to regard their hypothesis favorably, as seen in the accompanying Wheeler diagram (Fig. 3). Evidence for an unconformity includes the extrabasinal conglomerate lag at the base of the Hell Creek, the fact that none of the magnetostratigraphic studies have identified subchrons C30r or C31r, and the absence of lignite beds in the base of the Hell Creek Formation. Lignite beds are commonly present in a regression sequence as the beds shoreward of the strand. Such a situation occurs in the Denver Basin, where the Laramie Formation, the unit immediately above the Fox Hills Formation, is rich in coal seams. Figure 3 represents a fairly radical view of the genesis of the Hell Creek Formation. It implies that the formation was deposited in response to the early inception of the Cannonball transgression rather than simply representing the landward component of the Fox Hills regression, as has long been the consensus.

PROXIMITY OF THE WESTERN INTERIOR SEAWAY

Analysis of the easternmost Hell Creek Formation outcrops shows that the Cretaceous Western Interior Seaway, once thought to be absent in Hell Creek time, was probably present

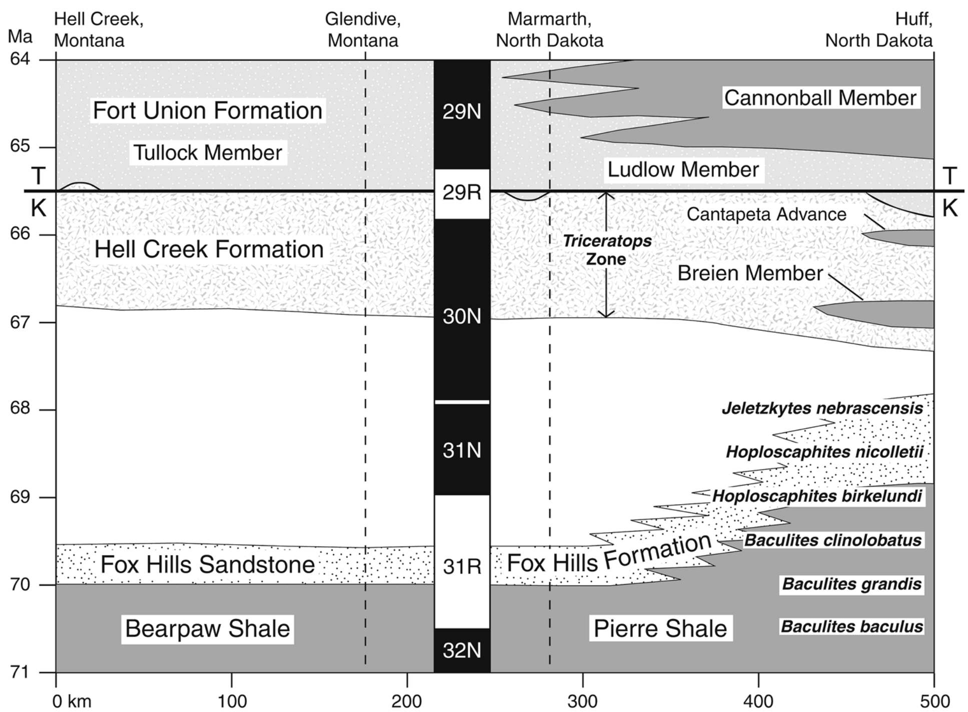

Figure 3. Wheeler diagram based on Figure 2 using Cretaceous-Tertiary (K-T) boundary as datum. In this interpretation, there is large unconformity between base of Hell Creek Formation and top of Fox Hills Formation. This unconformity is based on (1) Hicks et al. (1999) estimate for duration of 1.36 m.y. for Hell Creek Formation near Marmarth; (2) absence of magnetic polarity subchrons C30r, C31n, and C31r in well-sampled base of Hell Creek near Doaks Butte and Sunset Butte, North Dakota; (3) the historically well documented scoured contact of Hell Creek Formation on Fox Hills Formation; and (4) absence of lignite beds in base of Hell Creek Formation, a situation that would be expected if the Hell Creek represented a regressional deposit laterally and temporally equivalent to the Fox Hills Formation. This diagram represents end-member minimum-duration interpretation for Hell Creek Formation. Patterns are only to distinguish units and have no lithologic implications. White space indicates temporal hiatus. Single and partial ammonite specimen identified as *Jeletzkytes* cf. *J. nebrascensis* was found in Breien Member (Hoganson and Murphy, this volume). Highest ammonite zones that have reliable radiometric dates are middle of *Baculites grandis* zone (70.15 ± 0.65 Ma) and top of *Baculites clinolobatus* zone (69.57 ± 0.37 Ma), both from Red Bird, Wyoming (Hicks et al., 1999).

somewhere relatively close to the present eastern erosion-controlled outcrop margin. Evidence of the presence of the seaway exists in the lithologies and ichnofossils described by Murphy et al. (this volume) and Hoganson and Murphy (this volume), the vertebrate fossils described by Pearson et al. (this volume) and Hoganson and Murphy (this volume), and the brackish and marine invertebrate faunas described by Hoganson and Murphy (this volume) and Hartman and Kirkland (this volume). If the monotypic dinosaur bone beds of central South Dakota represent storm-surge–related mass drowning and burials, then they are one more argument for a near-coastal setting for the Hell Creek Formation. Correlation and interpretation of electric logs by Cherven and Jacob (1985) indicated that uppermost Cretaceous marine deposits are present in the subsurface of the Williston Basin, suggesting that the entire thickness of Hell Creek in North Dakota and South Dakota was subject to some marine influence.

In this nontraditional interpretation, the regression of the Cretaceous seaway, represented by the Fox Hills Formation, was followed by a fall in base level that caused sediment bypass and erosion in the area that would later be covered by the Hell Creek Formation. Eventually regression ceased, and the base level stabilized and then began to rise. It was during this time that the deposition of the Hell Creek Formation began. Small-scale transgressions during Hell Creek time resulted in the deposition of the Breien Member and the Cantapeta advance (Murphy et al., this volume). The distal effects of these or similar transgressions were the few lignite beds known in the Hell Creek, most notably the Firesteel lignite in central South Dakota.

The Cannonball transgression began shortly before the K-T boundary. The abundant lignite beds of the Ludlow and Tullock Members of the Fort Union Formation are a testimony to the rise in base level and increase in coastal aggradation caused by a rapidly transgressing Paleocene seaway. That the Hell Creek–Fort Union formational contact, which is defined most often by the inception of peat deposition, is nearly isochronous over a depositional slope of more than 500 km argues for the rapidity of this event and the flatness of the terrain.

K-T BOUNDARY

Data presented in this volume represent the first integrated assessment of a complete terminal Cretaceous terrestrial biota. Never before have plants, vertebrates, and insects been observed together in a well-dated stratigraphic context that contains the physical evidence of the K-T impact event and its associated shift in carbon isotopes. In addition, many of these chapters also assess the biota of the overlying Paleocene beds. The debate concerning the biotic effects of the K-T impact event has been an enduring one. Some workers even question the existence of a major K-T extinction of terrestrial biota (Sarjeant and Currie, 2001). One of the reasons that this controversy persists is that there have been very few integrated studies with adequate sample density to refute the apparent gradualism resulting from small samples. A second reason is that most arguments have relied on individual groups rather than entire biotas. The pattern that emerges in this volume is one of substantial, abrupt, biota-wide devastation at the K-T boundary. Furthermore, high-resolution stratigraphy allows for the effects of the K-T event to be separated from those are attributed to Late Cretaceous climate change and transgression of the Cannonball Seaway.

FUTURE QUESTIONS

This volume has raised and refined a number of questions. Perhaps the most obvious is the unresolved age of the base of the Hell Creek Formation and its implication for the duration of Hell Creek deposition. Does the formation have a duration of 1.36 m.y., as suggested by Hicks et al. (this volume), or does it fill all of the time between the highest dated ammonite and the K-T boundary, a span of 4.6 m.y.? Is there really a major unconformity between the Fox Hills and Hell Creek Formations? The answers to these questions have tremendous implications for our ability to assess the rate of biotic change before the K-T boundary event. Despite the presence of bentonites and the efforts of Hicks et al., there have been no precise radiometric ages derived from the Hell Creek Formation.

The issue of the vertebrate fossil-free gap in the uppermost 2 m of the formation continues to beg an explanation. It may be related to the speed at which the Cannonball Sea transgressed the flat terrain, but the sedimentological details of this formational transition still await insightful analysis. A good start would be the publication of the stratigraphic positions of the huge collections of vertebrate fossils from the Fort Peck Reservoir area that are in the collections at the University of California at Berkeley. More work needs to be done to correlate palynofloral and megafloral taxa, and the megaflora of the Hell Creek type area should be collected and studied. Insights into the facies patterns of the Hell Creek and its relationship to marine strata in the subsurface of the Williston Basin should be sought by interpretation and correlation of electric logs. The possibility that a marine K-T boundary section is beneath the plains of the eastern Williston Basin is tantalizing. Its discovery would be a splendid solution to the ongoing problem of correlating the marine and terrestrial K-T boundary records.

Note added in proof: Recent palynological and paleomagnetic analyses of the Kiowa Core in the Denver Basin (Nichols and Fleming, 2002) document the *Wodehouseia spinata* Assemblage Zone in polarity subchrons C29r and C30n and the underlying *Aquilapollenites striatus* Interval Zone in subchrons C31n and C31r within the Laramie and Fox Hills Formations. Since the base of the Hell Creek section in southwestern North Dakota contains palynomorphs indicative of the *W. spinata* Assemblage Zone and not the older *A. striatus* Interval Zone, there is now further evidence for the Fox Hills–Hell Creek unconformity discussed in this chapter.

REFERENCES CITED

Alvarez, L.W., 1983, Experimental evidence that an oasteroid impact led to the extinction of many species 65 million years ago: National Academy Sciences Proceedings, v. 80, p. 627–642.

Archibald, J.D., Butler, R.F., Lindsay, E.H., Clemens, W.A., and Dingus, L., 1982, Upper Cretaceous–Paleocene biostratigraphy and magnetostratigraphy, Hell Creek and Tullock Formations, northeastern Montana: Geology, v. 10, p. 153–159.

Bauer, C.M., 1925, Quartzite pebbles at the base of the Lance Formation in Montana: American Association of Petroleum Geologists Bulletin, v. 9, p. 344–346.

Belt, E.S., Hicks, J.F., and Murphy, D.A., 1997, A pre-Lancian regional unconformity and its relationship to Hell Creek paleogeography in southeastern Montana: University of Wyoming, Contributions to Geology, v. 31, p. 1–26.

Bohor, B.F., Foord, E.E., Modreski, P.J., and Triplehorn, D., 1984, Mineralogic evidence for an impact event at the Cretaceous-Tertiary boundary: Science, v. 244, p. 867–869.

Brown, B., 1907, The Hell Creek beds of the Upper Cretaceous of Montana: American Museum Natural History Bulletin, v. 23, p. 823–845.

Brown, R.W., 1952, Tertiary strata in eastern Montana and western North and South Dakota: *in* Sonnenberg, F.P., ed., Billings Geological Society Guidebook: Billings, Montana, Billings Geological Society, Third Annual Field Conference, p. 89–92.

Cherven, V.B., and Jacob, A.R., 1985, Evolution of Paleogene depositional systems, Williston Basin in response to global sea level changes, *in* Flores, R.M., and Kaplan, S.S., eds., Cenozoic paleogeography of the west-central United States: Society of Economic Paleontologists and Mineralogists, Rocky Mountain Symposium 3, p. 127–170.

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

Collier, A.J., and Knechtel, M.M., 1939, The coal resources of McCone County, Montana: U.S. Geological Survey Bulletin 905, 77 p.

D'Hondt, S., Herbert, T.D., King, J., and Gibson, C., 1996, Planktic foraminifera, asteroids, and marine production: Death and recovery at the Cretaceous-Tertiary boundary, *in* Ryder, G., Fastovsky, D., and Gartner, S., eds., The Cretaceous-Tertiary event and other catastrophes in Earth history: Geological Society of America Special Paper 307, p. 303–317.

Dobbin, C.E., and Reeside, J.B., Jr., 1929, The contact of the Fox Hills and Lance Formations: U.S. Geological Survey Professional Paper 158B, p. 9–25.

Dorf, E., 1940, Relationship between floras of the type Lance and Fort Union Formations: Geological Society of America Bulletin, v. 51, p. 213–236.

Dorf, E., 1942, Upper Cretaceous floras of the Rocky Mountain region, 2. Flora of the Lance Formation at its type locality, Niobrara County, Wyoming: Carnegie Institution of Washington Publication 508, p. 83–168.

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.

Fox, S.K., Jr., and Ross, R.J., Jr., 1942, Foraminiferal evidence for the Midway (Paleocene) age of the Cannonball Formation in North Dakota: Journal of Paleontology, v. 16, p. 660–673.

Fox, S.K., Jr., and Olsson, R.K., 1969, Danian planktonic foraminifera from the Cannonball Formation in North Dakota: Journal of Paleontology, v. 43, p. 1397–1404.

Hicks, J.F., Obradovich, J.D., and Tauxe, L., 1999, Magnetostratigraphy, isotopic age calibration and intercontinental correlation of the Red Bird section of the Pierre Shale, Niobrara County, Wyoming, USA: Cretaceous Research, v. 20, p. 1–27.

Jensen, F.S., and Varnes, H.D., 1964, Geology of the Fort Peck Area, Garfield, McCone, and Valley Counties, Montana: U.S. Geological Survey Professional Paper 414F, 49 p.

Johnson, K.R., Nichols, D.J., Attrep, M., Jr., and Orth, C.J., 1989, High-resolution leaf-fossil record spanning the Cretaceous/Tertiary boundary: Nature v. 340, p. 708–711.

Johnson, K.R., and Wilf, P., 1996, Paleobotanical temperature curve for the Cretaceous-Tertiary boundary interval and a scenario for the revegetation of North America after the terminal Cretaceous event: Geological Society of America Abstracts with Programs, v. 28, no. 7, p. 225.

Kennedy, W.J., Landman, N.H., Christensen, W.K., Cobban, W.A., and Hancock, J.M., 1998, Marine connections in North America during the late Maastrichtian: Paleogeographic and paleobiogeographic significance of *Jeletzkytes nebrascensis* Zone cephalopod fauna from the Elk Butte Member of the Pierre Shale, SE South Dakota and NE Nebraska: Cretaceous Research, v. 19, p. 745–775.

Murphy, E.C., Nichols, D.J., Hoganson, J.W., and Forsman, N.F., 1995, The Cretaceous/Tertiary boundary in south-central North Dakota: North Dakota Geological Survey Report of Investigations 98, 74 p.

Nichols, D.J., and Fleming, F., 2002, Palynology and palynostratigraphy of Maastrichtian, Paleocene, and Eocene strata in the Denver Basin, Colorado: Rocky Mountain Geology, v. 37, no. 2 (in press).

Nichols, D.J., Murphy, E.C., Johnson, K.R., and Betterton, W.J., 2000, A second K-T boundary locality in North Dakota verified by palynostratigraphy and shocked quartz: Geological Society of America Abstracts with Program v. 32, no. 7, p. 130.

Rigby, J.K., and Rigby, J.K., Jr., 1990, Geology of the Sand Arroyo and Bug Creek Quadrangles, McCone County, Montana: Geology Studies, v. 36, p. 69–134.

Ross, R.J., Jr., 1940, The foraminiferal fauna of the Cannonball Formation in North Dakota and its bearing on the problem of the Mesozoic-Cenozoic boundary [B.S. thesis]: Princeton, New Jersey, Princeton University, 84 p.

Sarjeant, W.A.S., and Currie, P.J., 2001, The "Great Extinction" that never happened: The demise of the dinosaurs considered: Canadian Journal of Earth Sciences, v. 38, p. 239–247.

Smit, J., 1999, The global stratigraphy of the Cretaceous-Tertiary boundary impact ejecta: Annual Review of Earth and Planetary Sciences, v. 27, p. 75–113.

Stott, L.D., and Kennett, J.P., 1990, The paleoceanographic and paleoclimatic signature of the Cretaceous-Paleogene boundary in the Antarctic: Stable isotopic results from ODP LEG 113, *in* Proceedings, Ocean Drilling Program, Leg 113: College Station, Texas, Ocean Drilling Program, p. 829–848.

Swisher, C.C., III, Dingus, L., and Butler, R.F., 1993, $^{40}Ar/^{39}Ar$ dating and magnetostratigraphic correlation of the terrestrial Cretaceous-Paleogene boundary and Puercan Mammal Age, Hell Creek-Tullock Formations, eastern Montana: Canadian Journal of Earth Sciences, v. 30, p. 1981–1996.

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