THE CRETACEOUS/TERTIARY BOUNDARY IN SOUTH-CENTRAL NORTH DAKOTA

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Edward C. Murphy, Douglas J. Nichols, John W. Hoganson, and Nels F. Forsman

REPORT OF INVESTIGATION NO. 98
NORTH DAKOTA GEOLOGICAL SURVEY
J.P. Bluemle, State Geologist
1995

1895 - North Dakota Geological Survey's Centennial Year - 1995

The North Dakota Geological Survey was created by an act of the North Dakota Legislature in 1895, six years after statehood. The Geological Survey was directed to make a

> *... complete account of the mineral kingdom ... including the number, order, dip and magnitude of the several geological strata, their richness in ores, coals, clays, peats, salines and mineral water, marls, cements, building stones and other useful materials, the value of said substances for economic purposes, and their accessibility.*

Such studies continue, but over the years the Geological Survey's mission has grown and is now three-fold: to investigate the geology of North Dakota; to administer regulatory programs and act in an advisory capacity to other state agencies; and to provide public service and information to the people of North Dakota.

The Geological Survey serves as the primary source of geological information in the State. A large amount of geological information can be obtained from NDGS publications; comprehensive collections of cores, samples, and fossils; oil and gas records; coal and subsurface mineral records; and through our affiliate office of the nationwide Earth Science Information Center.

On the cover: Trail to Barren Butte, Sioux County, where section no. 27 was measured. Barren Butte is the isolated butte in the upper left portion of the photograph, view is to the north.

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ABSTRACT

The Cretaceous/Tertiary (K/T) boundary in south-central North Dakota occurs near the lithostratigraphic contact between the Upper Cretaceous (Maastrichtian) Hell Creek and lower Paleocene (Danian) Ludlow Formations. These strata are of continental origin and are composed of alternating beds of poorly lithified sandstone, siltstone, claystone, and mudstone. The formations are distinguished in the field by color, bedding characteristics, and the presence of persistent lignite beds in the Ludlow Formation. The lithostratigraphic contact between the Hell Creek and Ludlow Formations has traditionally been placed at the base of the lowest persistent lignite above dinosaur-bone-bearing strata. However, during this study the contact was placed at the base of the lowest persistent lignite at only one-third of the study sites. Instead, the contact was often placed at the top of the highest occurrence of swelling claystone which often coincided with a break in slope and a color change.

Sections were measured across the Hell Creek/Ludlow lithostratigraphic contact at 32 localities, 76 samples were collected for palynologic analysis from 12 of the stratigraphic sections, and vertebrate fossils were collected above and below the contact. The K/T boundary was identified by abrupt changes in palynomorph assemblages, including the disappearance of species of Cretaceous pollen, suggesting an extinction event. The palynologic data indicate that the Cretaceous/Tertiary boundary generally occurs within 3 meters either side of the lithologic contact between the Hell Creek and Ludlow Formations in this area. Vertebrate fossils are rare, but when present support the placement of the K/T boundary as determined by palynological analysis.

ACKNOWLEDGEMENTS

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INTRODUCTION

The cause or causes of the mass extinction at the end of the Cretaceous Period have long been of interest to geologists. In 1980, Walter and Luis Alvarez discovered an enrichment of platinum metals (primarily iridium) in marine rocks at the Cretaceous/Tertiary boundary in Italy, Denmark, and New Zealand (30, 60, and 120 times background, respectively). Alvarez et al. (1980) suggested that the only plausible explanation for the source of this iridium was extraterrestrial, that is from asteroids or comets. Based upon their findings, they theorized that an asteroid impact triggered the extinction of the dinosaurs and left an iridium enrichment signature. The impact theory sparked a worldwide search for the remains of a Cretaceous/Tertiary boundary fallout layer or, as it is often referred to, the boundary clay. As a result, the last fifteen years have seen the unprecedented microstratigraphic examination of the thin geologic interval containing the Cretaceous/Tertiary boundary throughout the world. This work has involved detailed studies of the stratigraphy, paleontology, and geochemistry of this interval. In addition to the iridium anomaly, the presence of shocked quartz and glass or altered-glass spheres in this interval at some localities has further supported the impact theory. Additional theories supporting or refuting the impact theory abound and the controversy over what caused the mass extinction at the end of the Cretaceous Period is as vital today as ever.

In North Dakota, the Cretaceous/Tertiary boundary occurs near the lithostratigraphic contact between the Upper Cretaceous (Maastrichtian) Hell Creek and lower Paleocene (Danian) Ludlow Formations. These strata are of continental origin and are composed of alternating beds of poorly lithified sandstone, siltstone, claystone, and mudstone (Figure 1). This lithostratigraphic contact is exposed at the surface in portions of Bowman and Slope Counties in the southwestern part of the state and in portions of Morton, Grant, Sioux, Emmons, and Burleigh Counties in south-central North Dakota.

In the early 1980s, a field party consisting of Roger Colton, U.S. Geological Survey, Susan

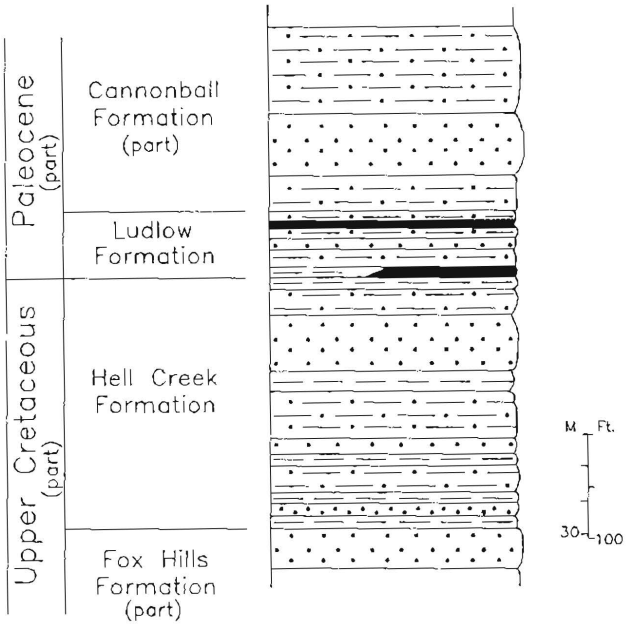


Figure 1. A generalization of part of the stratigraphic column of south-central North Dakota. The legend for the lithologic and paleontologic symbols used in this report is in Appendix A.

Vuke-Foster, Montana Bureau of Mines and Geology, and Ed Murphy examined the Hell Creek/Ludlow Formation contact at Pretty Butte in Slope County, North Dakota. The three picked different stratigraphic contacts, all within a 30- to 40-foot (9-12 m) interval. This example illustrates how difficult it can be to pick this contact at some localities in North Dakota. For some mapping purposes, accuracy within 30 to 40 feet (9-12 m) is acceptable. However, the detailed microstratigraphy needed to precisely locate the Cretaceous/Tertiary boundary requires that both the lithostratigraphic contact and the systemic boundary interval be determined within inches or centimeters.

Purpose

This project was initiated with the following objectives: 1) to determine the lithostratigraphic contact between the Hell Creek (Upper Cretaceous) and Ludlow (lower Paleocene) Formations, 2) to determine the Cretaceous/Tertiary (K/T) boundary based upon palynomorph assemblages, 3) to determine the relationship between the K/T

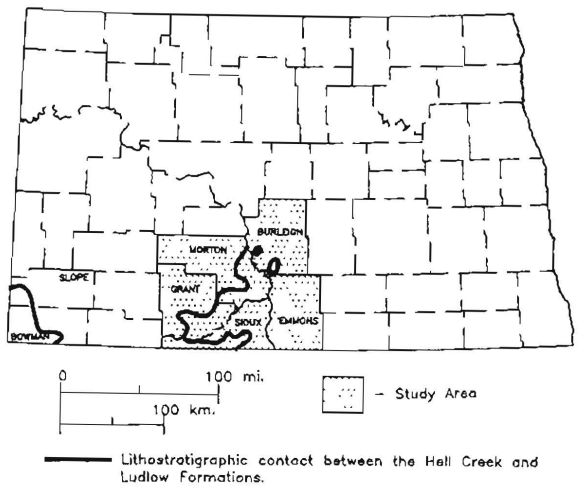


Figure 2. Location of the study area in south-central North Dakota and the extent of the Hell Creek and Ludlow lithostratigraphic contact in North Dakota.

boundary and the Hell Creek/Ludlow lithostratigraphic contact, 4) to determine the relationship between the K/T boundary and the occurrence of vertebrate and other fossils, and 5) to examine the K/T boundary interval for the presence of iridium and shocked minerals.

Study Area

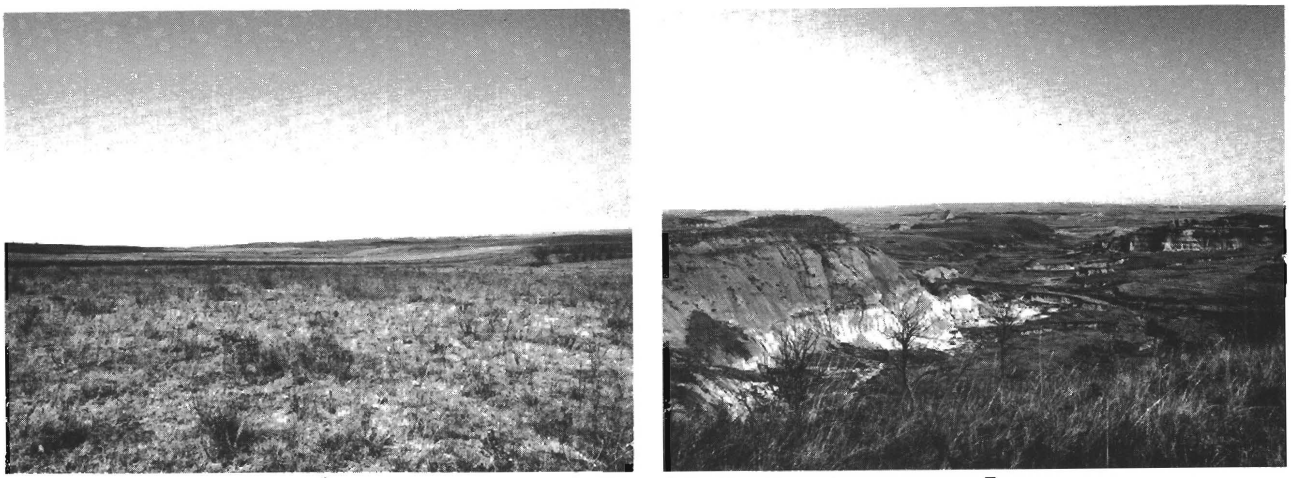
The study area consists of 2,110 square miles (6,100 square km) in portions of Morton, Grant, Sioux, Burleigh, and Emmons Counties, North Dakota (Figure 2). The area consists primarily of rolling prairie, and outcrops are generally limited to the valleys and associated badland topography of the Cedar Creek, Cannonball, and Missouri Rivers (Figure 3).

PREVIOUS WORK

In 1854, the Hayden surveys explored the coal-bearing regions of the Rocky Mountains and the Great Plains, especially along the Yellowstone and Missouri River Valleys. Hayden (1861) termed the strata in this area the Great Lignite Group. Shortly thereafter, Meek and Hayden (1862) substituted the term "Fort Union Lignite Group" for the Great Lignite Group. They made this substitution even though the type area of the Fort Union near the mouth of the Yellowstone River contains only the upper portion of the strata originally included in the Great Lignite Group. By the late 1860s or early 1870s, scientists recognized that the Mesozoic/Cenozoic boundary lies somewhere within the Great Lignite Group because dinosaur bones were present in rocks in the lower part of the group, indicating a Cretaceous age, and fossil plants were present in the upper portion that indicated a Tertiary age. As a result, geologists began separating the Fort Union strata into a lower dinosaur-bearing unit and an upper non-dinosaur-bearing unit. Marsh (1889) proposed the term "Ceratops beds" for the lower dinosaur-bearing strata of the Great Lignite Group. In 1903, Hatcher proposed replacing "Ceratops beds" with "Lance Creek beds", named for dinosaur-bearing strata exposed along Lance Creek, Converse County, Wyoming. Barnum Brown (1907) was first to propose Hell Creek as the name for strata along Hell Creek and East Hell Creek in Garfield County, Montana and later Brown (1914) demonstrated that the Lance and Hell Creek strata were equivalent.

The evolution of stratigraphic nomenclature proceeded uneventfully until 1909, when F. H. Knowlton, a paleobotanist for the U.S. Geological Survey, grouped the dinosaur- and non-dinosaur-bearing rocks together again into the Fort Union Formation. Knowlton's actions resulted from his belief, shared by some of his colleagues, that the strata within the Fort Union (as then defined) could not be separated based on paleofloral content. The confusion brought about by Knowlton's action was compounded by subsequent workers as a result of the lithologic similarity between the lower and upper Fort Union strata and the absence of an unconformity, which many thought should exist at the Cretaceous/Tertiary boundary. As a result of a series of errors made by workers in the field, the Cretaceous/Tertiary boundary was not universally accepted at its present position between the Hell Creek and Ludlow Formations until it was placed there by Roland Brown in 1938.

The complex history of development of stratigraphic nomenclature surrounding the Cretaceous/Tertiary boundary and the difficulty in



A B

Figure 3. Topographic setting of the study area. **A**, Most of the area consists of rolling prairie. **B**, Outcrops of the Hell Creek and Ludlow Formations are generally limited to badlands topography in the valleys of the Cedar Creek, Cannonball, and Missouri Rivers.

defining the boundary in the Great Plains is discussed at length by Brown (1962) in his monograph concerning Paleocene floras of the Rocky Mountains and Great Plains. Frye (1969) and Moore (1976) present similar reviews for North Dakota. The following is a brief review of Hell Creek and/or Ludlow stratigraphic studies previously conducted in North Dakota.

Most of the early work on the stratigraphy of Cretaceous and lower Tertiary rocks in North Dakota was by A. G. Leonard, former North Dakota State Geologist. Leonard (1908) initially grouped the rocks above the marine Cretaceous in southwestern North Dakota into one formation, the Fort Union Formation. He recognized lithologic differences within the Fort Union and divided the formation into three distinct members, a light-colored (yellow and light brown) unit sandwiched between two somber-colored (gray, blue, and brown) units. The lower somber-colored unit includes the present-day Hell Creek and Ludlow Formations. Previously, part of the section exposed along the Little Missouri River had been referred to as the Laramie Formation (Wilder, 1902) but Leonard rejected that usage. Later, Leonard (1911) included his lower dark and somber-colored member in the "Lance Formation."

Lloyd and Hares (1915) proposed the name "Ludlow lignitic member" for a member of the Lance Formation and designated a type section for the member near the town of Ludlow in northwestern South Dakota. They also noted that this member was in part laterally equivalent to their "Cannonball marine member" north and east of the "Ludlow lignitic member" type locality. Hares (1928) extended this terminology to the Little Missouri River area of southwestern North Dakota by dividing the Lance Formation into an upper lignite-bearing "Ludlow member" underlain by *Triceratops*-bearing beds of the "Hell Creek member." Dorf (1940) determined that the flora of the upper part of the Lance, including the Ludlow, was Paleocene rather than Cretaceous in character and placed the Ludlow, Cannonball and other equivalent upper Lance units in the Fort Union. He also raised the Fort Union to group rank with the Ludlow being the basal formation in the group. This usage was adopted by the North Dakota Geological Survey, but some workers prefer to consider the Ludlow to be the basal member of the Fort Union Formation (e.g., Belt et al., 1992). A detailed discussion of the stratigraphy and environments of deposition of the Ludlow was presented by Moore (1976).

Thom and Dobbin (1924) introduced the term Hell Creek to North Dakota, in a cross-section, considering it to be the lower member of the Lance

Formation. Hares (1928) reinforced the use of that terminology in southwestern North Dakota and also considered the Hell Creek to be the lower member of the Lance Formation. The Hell Creek was elevated to formation rank by Brown (1938) and has held that rank in North Dakota since. The occurrence of Cretaceous dinosaur fossils in the formation established its age early on. Frye (1967, 1969) conducted a detailed study of the Hell Creek Formation and divided it into several formal members.

Brown (1962) concluded that the lowest persistent coal bed above the highest dinosaur occurrence is a workable Cretaceous/Tertiary chronostratigraphic boundary in the Great Plains. This criterion was initially recognized by Calvert (1912) working near Glendive, Montana. This same concept for establishing the K/T boundary had essentially been established in North Dakota by Hares (1928) in his study of the stratigraphy along the Little Missouri River when he divided the Lance into the underlying *Triceratops*-bearing beds of the "Hell Creek member" overlain by the lignite-bearing "Ludlow lignitic member." Laird and Mitchell (1942) placed the Hell Creek/Ludlow contact at the top of the highest bentonitic bed in southern Morton County. They also noted that the uppermost bentonitic beds were often overlain by a lignite or a carbonaceous horizon. These criteria were used by Frye (1969) to define the Hell Creek/Ludlow contact in the Little Missouri and Missouri River Valleys. Moore (1976) suggested that the Hell Creek and Ludlow Formations are not only separable by their floral and faunal differences, but also because the beds within the Ludlow Formation are generally more laterally persistent than those in the Hell Creek Formation and lignite beds are fewer, thinner and more discontinuous in the Hell Creek Formation. However, Moore also cautioned that individual lithologies of the two formations are "highly similar, if not identical." This similarity presents a particular problem in some areas of south-central North Dakota.

Lindberg (1944) examined heavy minerals from the Fox Hills, Hell Creek, Ludlow, and Cannonball Formations in Morton and Sioux Counties. He identified heavy mineral zonations within these strata, but no significant distinctions were discovered between the Hell Creek and Ludlow Formations. A marked change in heavy mineral content was, however, noted at the base of the Cannonball Formation. Farris (1984) found a difference in heavy mineral content between Fox Hills and Hell Creek strata in Bowman and Slope Counties of southwestern North Dakota. He warned that the differences in the heavy mineral content of these units may reflect diagenetic processes rather than subtle differences in source areas.

Frye (1967) reported that sandstone in the Ludlow Formation almost invariably contain pelletal glauconite, at times in enough quantity to make greensand in Emmons County. Green-colored sandstone was not observed in the area of the present study. Frye also reported that an absence of dark-colored chert grains in thin sections appears to be a distinctive characteristic of Ludlow siltstone as compared with Hell Creek siltstone, but warned that sweeping conclusions should not be based on his examination of a few thin sections.

Few detailed analyses of fossils from the Hell Creek and Ludlow Formations in North Dakota have been published. In contrast, the Cannonball invertebrate (e.g., Cvancara, 1966; Van Alstine, 1974; Fenner, 1976; Silfer, 1990) and vertebrate (Hoganson and Cvancara, 1989, 1991; Cvancara and Hoganson, 1993) faunas are fairly well known and unequivocally indicate a Paleocene age for the formation. The Hell Creek vertebrate fauna in North Dakota is not well known (e.g., Frye, 1967; Sheehan et al., 1991) but indicates a latest Cretaceous age. Differences between Hell Creek and Ludlow molluscan faunas have also been recognized (Hartman, 1984). Megafloral changes across the Cretaceous/Tertiary boundary in North Dakota have been studied by Johnson et al. (1989), Johnson and Hickey (1990), and Johnson and Nichols (1994) and indicate marked floral differences between the Hell Creek and Ludlow Formations. This floral change is also noted in palynological records (Lerbekmo and Coulter, 1984; Johnson et al., 1989; Nichols, 1990; Nichols and Fleming, 1990). These studies indicate that when fossils are present, they are useful tools in helping to differentiate between the lithologically similar

Hell Creek, Ludlow, and Cannonball Formations.

Lerbekmo and Coulter (1984) placed the Cretaceous/Tertiary boundary 7.6 feet (2.3 m) above the base of the Ludlow Formation as picked by Laird and Mitchell (1942) at a site near Huff, North Dakota. Lerbekmo and Coulter based this placement on fifteen palynological samples and on paleomagnetic analyses. They found that palynomorph extinctions occurred near the middle of a reversed polarity zone which they interpreted to be 29R. A similar palynomorph extinction occurred in this polarity zone at Red Deer, Alberta, and a foraminifera extinction occurred within this zone at the Gubbio section in Italy (Lerbekmo and Coulter, 1984).

In the southwestern corner of North Dakota, at Pyramid Butte, Johnson et al. (1987) determined that the Cretaceous/Tertiary boundary lies within a thin, carbonaceous mudstone overlying the basal coal of the Ludlow Formation, i.e., 35 inches (90 cm) above the base of the Ludlow Formation. They based their placement of the boundary on megafloral changes, palynofloral disappearances, an iridium anomaly, and the presence of shocked mineral grains. An iridium anomaly of 0.72 parts per billion (ppb) was detected in the mudstone as compared to concentrations of 0.35 and 0.55 ppb found slightly above and below the mudstone, respectively. In contrast, background concentrations of 0.025 ppb were found in rocks 31.5 inches (80 cm) either side of this mudstone.

Nichols (1990) concluded that the Cretaceous/Tertiary chronostratigraphic boundary in western North America often does not coincide with lithostratigraphic formation contacts, and that it may occur below, within, or above the basal coal of the Fort Union Group (or equivalent). He also suggested that palynology is a useful tool in establishing the position of the chronostratigraphic boundary within a section.

FIELD METHODS

Measured Sections

Portions of three field seasons were spent studying the Hell Creek/Ludlow stratigraphic interval in south-central North Dakota. Geologic sections were measured at 32 localities (Figure 4). Potential sections for study were chosen by comparing outcrops identified from aerial photographs with existing geologic maps (Clayton, 1980; Carlson, 1982, 1983; Kume and Hansen, 1965; Bluemle, 1984). Outcrops near the mapped contact were field checked and the most complete sections that included the contact were measured. Measured sections in the south-central portion of the state ranged in thickness from 60 to 275 feet (18.3 to 83.8 m), with an average thickness of 143 feet (43.6 m). A total of 4,560 feet (1,389.9 m) of section was measured in the study area.

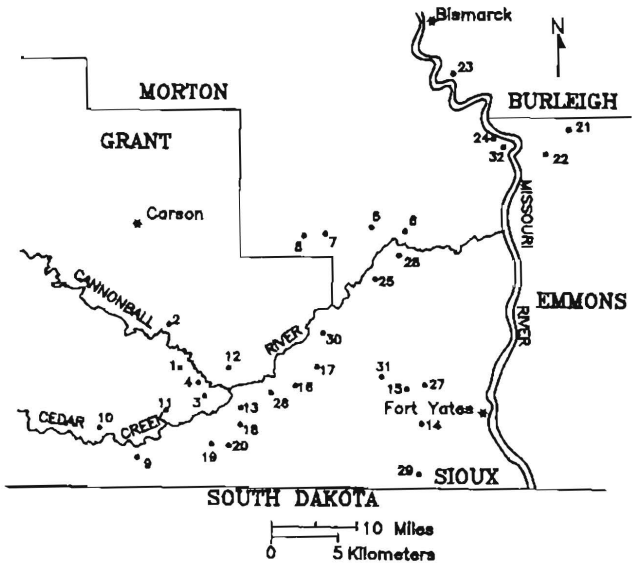


Figure 4. Location of measured geologic sections in south-central North Dakota.

Rock Samples

Samples of carbonaceous claystone, carbonaceous mudstone, and coal were collected from selected intervals at 12 of the 32 sections. Contiguous samples were obtained across a 6.7 foot (2 m) interval that included the K/T boundary at the Miller site (section no. 24). In all cases, individual beds were excavated to a sufficient depth to ensure that an unweathered sample was obtained. Care was also taken to obtain clean, uncontaminated samples. In addition to these hand samples, 3-inch (7.6 cm) Shelby tubes and 2-inch (5.1 cm) split-spoon

samplers were driven through the K/T boundary interval at several of the sites using an 8-pound sledge hammer. Both of these coring methods resulted in close to 100% core recovery, although the driving of the samplers by this method severely fractured the samples. The split-spoon samples were much easier to recover and were transferred intact from the field using pre-cut, split sections of 2-inch (5.1 cm) PVC pipe with capped ends. Samples for palynomorph and iridium analysis were placed in sealed plastic bags and transported to the U.S. Geological Survey Paleontology Laboratory in Denver, Colorado. One set each of Shelby and split-spoon core samples was transported to the Department of Geology and Geological Engineering at the University of North Dakota for shocked mineral analysis. A reference set of core samples is stored at the North Dakota Geological Survey warehouse in Bismarck.

Fossil Prospecting

Measured section and adjacent outcrop areas were searched for both faunal and floral megafossils. Vertebrate, invertebrate, and plant megafossils were sparse in the study area except at the Stumpf and Katus sites. Vertebrate fossils consisted of disarticulated, isolated skeletal elements and were found mostly as float on outcrop surfaces. No articulated skeletons were found. Invertebrate fossils were mostly steinkerns. The stratigraphic position of the fossil occurrences were recorded as the sections were measured. The occurrence of leaf fossils were also noted but only if they were well enough preserved to be identifiable.

LABORATORY METHODS

Palynomorph Identification

Samples of coal and carbonaceous beds were taken for palynologic analysis from 12 of the 32 sections. The total number of samples processed for palynologic analysis was 76. Palynomorphs were recovered from all of the samples.

Samples for palynologic analysis were processed using standard laboratory procedures for coal and clastic rocks (Doher, 1980). Palynomorphs were separated from carbonaceous rock by treatment with hydrochloric and hydrofluoric acids. Organic residues were floated using heavy liquids and then treated with nitric acid. Palynomorph-bearing residues were stained and mounted for microscopic study.

Shocked Mineral Analysis

Sample treatment procedures in the search for mineralogic evidence of impact debris involved disaggregation and liberation of sand and coarse silt-size grains from original mudstone or lignitic units recovered by coring. Because no discrete thin clay layers (boundary clay) were observed within cores, samples from the entire boundary intervals determined by palynological assessment were processed and analyzed. The one-inch-diameter (2.5 cm) cores were separated into two-inch (5.1 cm) vertical sections using cardboard wedges throughout the boundary intervals. Samples from the two-inch (5.1 cm) sections were disaggregated and sieved one at a time to avoid laboratory error. Disaggregation was accomplished by soaking samples in water and magnetic stirring. Carbonaceous samples were soaked in bleach and/or hydrogen peroxide. An ultrasonic water bath was also used to promote the separation of aggregates and to further remove clays. After removing suspended clays by decantation, sand and coarse silt grains were collected by wet sieving and stored in vials. Prior to microscopic examination, the surfaces of the grains were etched by soaking in a solution of hydrofluoric acid.

Iridium Analysis

Contiguous samples across a 39-inch (100 cm) interval containing the Cretaceous/Tertiary boundary at the Miller site (measured section no. 24) were sent to Los Alamos National Laboratory, Los Alamos, New Mexico. A total of 20 samples were analyzed for 45 separate elements, including iridium, under the direction of Moses Attrep, Jr.

Megafossil Identification

Preliminary identification was made of all

megafossils in the field. Following cleaning, these fossils were identified by comparison to known specimens in collections in the North Dakota State Fossil Collection; Geology Museum, South Dakota School of Mines and Technology; and Royal Tyrrell Museum and by consultation with other paleontologists. Fossils recovered during this study are in the North Dakota State Fossil Collection housed in the North Dakota Heritage Center.

STRATIGRAPHY

Hell Creek Formation

The Hell Creek Formation is an Upper Cretaceous (Maastrichtian) clastic wedge that extends from the Rocky Mountains to central North Dakota. This lithostratigraphic unit covers portions of central and eastern Montana, North and South Dakota, and northern Wyoming and is equivalent to the Frenchman Formation in Saskatchewan, Canada. The Hell Creek Formation consists primarily of alternating beds of poorly lithified sandstone, siltstone, claystone, and mudstone, and occasional lignite. It is characterized by somber bluish gray colors and numerous smectitic claystone beds. The Hell Creek is approximately 475 feet (145 m) thick in southwestern North Dakota and thins to less than 200 feet (61 m) in south-central North Dakota (Carlson, 1979). Although primarily nonmarine, a thin brackish tongue, termed the Breien Member, is present in the lower part of the formation in south-central North Dakota (Laird and Mitchell, 1942; Frye, 1967, 1969). The presence of dinosaur bones in the Hell Creek distinguishes it from the overlying non-dinosaur bearing rocks.

Frye (1967, 1969) divided the Hell Creek Formation into eight members, one of which, the Breien Member, had originally been proposed by Laird and Mitchell (1942). He recognized five of these members in south-central North Dakota. Although two or three of the members are generally recognizable in the study area, whether they can be traced across the western half of the state has been questioned by other workers (C.G. Carlson, oral communication, 1994). During this study we noted the common occurrence of bentonite and mudstone beds immediately beneath the Ludlow Formation in south-central North Dakota. These lithologies are characteristic of Frye's (1969) Pretty Butte Member, the uppermost member in the Hell Creek Formation. As noted by Frye (1967, 1969), this member varies considerably in thickness (from a few feet up to 40 feet) across the five-county study area. Frye (1969) named the sand-rich unit beneath the Pretty Butte Member the Huff Member, with its type section located just south of the town of Huff in Morton County. Thick channel-sandstones can be found beneath the Pretty Butte Member throughout southeastern Morton, western Burleigh, and Emmons Counties. Channel sandstones are also prevalent at this stratigraphic position throughout much of Grant and Sioux Counties. Therefore, it is apparent that fluvial systems were dominant in south-central North Dakota near the end of Hell Creek deposition. The utility of Frye's lower members of the Hell Creek was not determined during this study. The prevalence of mudstones and bentonites underlain by channel sandstones is generally characteristic of the upper portion of the Hell Creek Formation throughout the study area.

Ludlow Formation

The Ludlow Formation is a lower Paleocene (Danian) lithostratigraphic unit that overlies the Hell Creek Formation throughout North Dakota. The type section for the Ludlow Formation is in northwestern South Dakota, near the town of Ludlow. The formation extends across western North and South Dakota and appears to be equivalent, at least in part, to the Tullock Member of the Fort Union Formation in eastern Montana. Alternating beds of poorly lithified sandstone, siltstone, claystone, mudstone, and lignite characterize the Ludlow Formation. It is overlain in western North Dakota by the nonmarine Paleocene Slope Formation (formerly Moore's (1976) upper member of the Ludlow) and is overlain by or in some cases interbedded with the marine Paleocene Cannonball Formation in central North Dakota (Clayton et al., 1977; Cvancara, 1976). The Ludlow is the basal formation of the Fort Union Group, which consists of a maximum of 1800 feet (549 m) of clastic sediments (primarily nonmarine) in North Dakota that thin to the east. An exception

within the Fort Union Group is the marine Cannonball Formation, which thins to the west. The Ludlow Formation reaches a maximum thickness in outcrop in North Dakota of 330 feet (100 m) at Pretty Butte, Slope County, and thins to only 7.5 feet (2.3 m) in outcrop in western Emmons County.

The Hell Creek/Ludlow contact in the study area is generally exposed on or near the tops of ridges or buttes. As a result, the thickness of measurable Tertiary sedimentary rocks in this area is generally less than 50 feet (15 m). The top of the Ludlow Formation was seldom visible, either due to its absence or to vegetative cover. In the five sections where the upper contact was observable, the Ludlow Formation was found to vary from 7.5 to 114 feet (2.3 to 35 m) thick, with an average thickness of 45 feet (14 m).

Marine fossils, including shark teeth, characteristic of the Cannonball Formation, were found in some of the covered intervals overlying the measurable Ludlow Formation. Their presence further suggests that the Ludlow Formation is very thin in the areas where the upper contact was not observed in outcrop (generally less than 40 feet [12 m] thick). However, the presence of marine fossils in the soil horizons on the tops of some of these small buttes does not unequivocally indicate the presence of the Cannonball Formation, as they could be lag deposits eroded from Cannonball strata.

Criteria for Differentiating the Contact Between the Hell Creek and Ludlow Formations

The contact between the Hell Creek and Ludlow Formations in south-central North Dakota is exposed in the badlands topography associated with the Missouri and Cannonball Rivers and Cedar Creek. The best exposures are generally found along Cedar Creek in Grant County. In southwestern North Dakota, the contact between the Hell Creek and Ludlow Formations is well exposed along the eastern flank of the Cedar Creek anticline in the Little Missouri badlands both north and southeast of the town of Marmarth, Slope County.

Walt Moore studied the Hell Creek/Ludlow contact in the Marmarth area in the 1970s while he was a professor at the University of North Dakota. Recently Moore stated that his work led him to believe there is no substitute for field experience with these lithostratigraphic units because there is no single stratigraphic or sedimentological criterion that can be used to differentiate between these formations in every outcrop. He found, through extensive fieldwork, that he could pick the contact based on "gut feelings", which belied subtle lithologic changes that were difficult to list as criteria and harder yet to explain to others (W.L. Moore, oral communication, 1994). We concur with Moore that no one criterion exists, but that several stratigraphic criteria can be used in combination to identify the contact between the Hell Creek and Ludlow Formations. The following criteria that were used to identify the contact have varying degrees of importance depending upon the area considered:

1) **Lignite:** The base of the Ludlow Formation is defined as the base of the lowest persistent lignite above dinosaur-bone-bearing strata (Brown, 1962). The basal contact of the Ludlow Formation is therefore, generally placed at the lowest laterally persistent coal bed (Figure 5.1A). Lloyd and Hares (1915) split the upper part of the Lance Formation (the lower part of their Lance is equivalent to the Hell Creek Formation) into the "Ludlow lignitic and Cannonball marine members." They stated that the presence of lignite in the "Ludlow lignitic member" was one of the chief criteria for differentiating it from both the underlying and overlying units.

The upper part of the Hell Creek Formation contains numerous carbonaceous beds but does not commonly contain well-developed lignite beds. Where lignite is present within the Hell Creek, it is not laterally persistent and is often observed only as lenses within a single outcrop (Figure 5.1B). These lenses or pods are generally only a few inches (several centimeters) thick and a few feet (about a meter) wide. However, some may reach about 3 feet (one meter) in thickness (Stumpf site, section no. 32).

Even though persistent lignite is considered to be the main lithologic criterion for differentiation of these units, the base of the Ludlow was placed at

lignite in a minority of our measured sections because other criteria often dictated the contact be placed below the first persistent lignite. The base of the lowest persistent lignite was chosen as the base of the Ludlow Formation in only 11 (35%) of the 31 stratigraphic sections measured in south-central North Dakota.

2) **Color Change**: At several localities, a color change marks the contact between the drab grays of the Hell Creek Formation and the overlying yellows and browns of the Ludlow Formation (Figure 5.2A). In many areas, however, the color change across the contact is so subtle that it is not readily apparent (Figure 5.2B).

The Hell Creek Formation consists of multicolored mudstone (generally shades of purple and gray), bluish gray claystone and thick, gray sandstone. In contrast, the Ludlow Formation generally consists of grayish brown mudstone and yellowish brown sandstone. The Cannonball Formation generally consists of yellow/brown to gray mudstone and yellow/brown to gray sandstone. Consequently, the color change across the contacts of these lithostratigraphic units varies from sharp to subtle. The color change can at times be deceiving. At several of the study sections, a visible color change occurred well into the Ludlow Formation.

3) **Swelling "Popcorn Weathered" Claystone**: The top of the Hell Creek Formation is often placed at the top of the highest occurring swelling "popcorn weathered" claystone (Figure 5.3A). These claystones have traditionally been referred to as bentonites, implying that they formed from the alteration of volcanic glass. We did not attempt to verify the origin of these swelling claystone beds, and therefore it is more appropriate to term them smectitic claystone. Claystone beds in the Ludlow Formation do not generally have the classic "popcorn weathered" surface texture found on most of the Hell Creek claystone beds (Figure 5.3B).

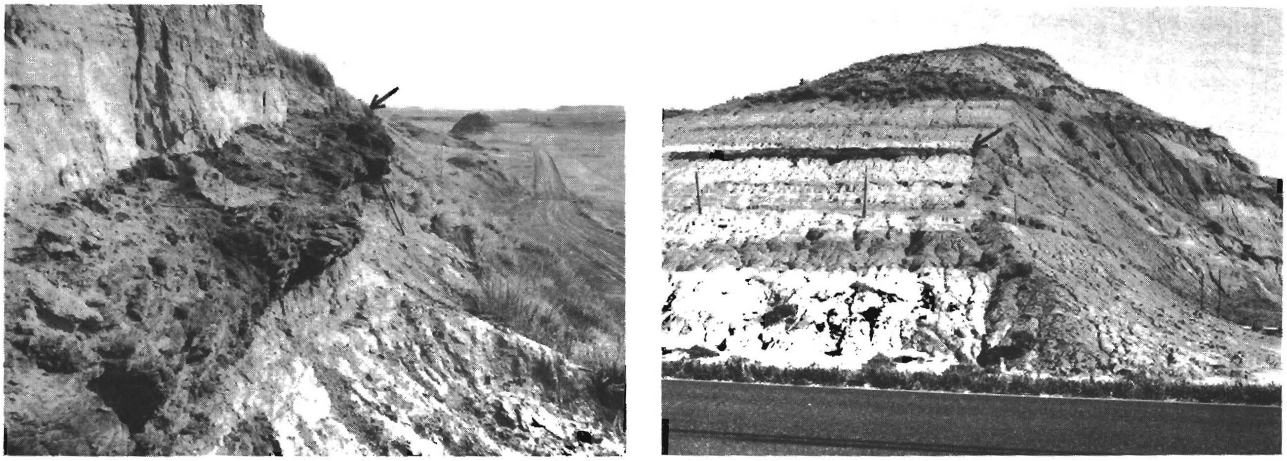
4) **Change in Slope**: The stratigraphic contact between the Hell Creek and Ludlow Formations often occurs at a break or change in slope (Figure 5.4A). Even though the lithologies of the units are similar, the mudstones in the Ludlow are generally less indurated and therefore less resistant to erosion than those of the Hell Creek. As a result, the Hell Creek generally forms steeper slopes and the Ludlow gentler slopes.

5) **Barren vs. Vegetated Surfaces**: The slopes of the Hell Creek Formation are generally barren of vegetation due to the difficulty plants encounter establishing roots in the smectitic claystone and mudstone. In contrast, the slopes of the overlying Ludlow Formation are generally well-to- moderately vegetated (Figure 5.4B). This difference in vegetative cover facilitates mapping of the contact between these formations from a distance, but makes measuring the stratigraphic sections above the contact very difficult.

6) **Observable Bedding**: In areas of good outcrops, the general absence of distinguishable bedding in the Hell Creek Formation often contrasts sharply with the change to observable bedding or layering in the overlying Ludlow Formation. Claystone and mudstone units in the Hell Creek Formation generally have poorly defined bedding, while those in the Ludlow Formation often have distinct bedding planes that are observable due to slight color changes or iron staining in the layers.

7) **Piping**: The greater induration of Hell Creek strata compared with Ludlow strata and the greater abundance of swelling claystones results in pronounced piping in the Hell Creek Formation. Piping is not prevalent in Ludlow strata.

8) **Carbonaceous Mudstone**: Carbonaceous mudstone in the Hell Creek Formation in the study area is characteristically reddish brown in color, typically has a paper-like fabric, contains recognizable coniferous needles, and generally contains visible pieces (up to 0.25 inch [0.6 cm]) of amber. In contrast, carbonaceous mudstone in the Ludlow Formation is typically dark brown to dark grayish brown, contains a higher clay content, and is more likely to contain recognizable deciduous leaves. Amber may also be present in some of the mudstone beds within the Ludlow Formation, although it appears to be much less abundant than in the underlying Hell Creek Formation. This may



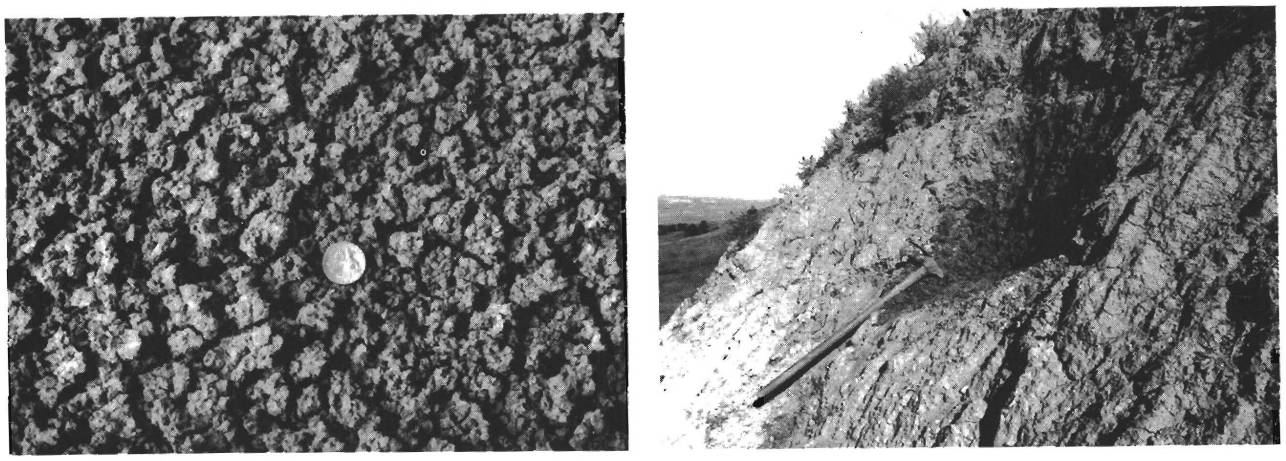
A B

1. The base of the Ludlow Formation may be placed at the base of the lowest persistent lignite. **A**, Lignite (arrow) at the base of the Ludlow Formation (west of section no. 5). The Hell Creek/Ludlow contact was placed at a lignite in only 35% of the study sections. **B**, Lignites (arrow) are rarely present in the Hell Creek Formation but are not persistent (section no. 20). The Hell Creek/Ludlow contact is present at the top of the roadcut.

A B

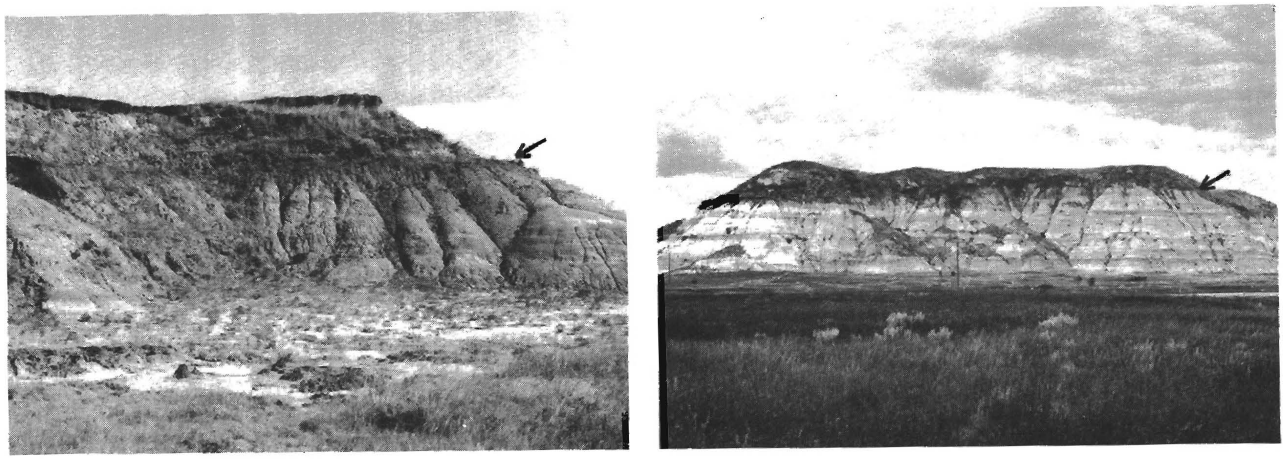
2. The base of the Ludlow Formation often coincides with a change in color from the drab grays of the Hell Creek Formation to the yellows and browns of the overlying Ludlow Formation. **A**, An obvious change in color marks the contact (arrow) at this locality (section no. 9). **B**, There is not always an obvious color change at the lithostratigraphic contact. At this section (no. 20), the contact (arrow) was placed at the base of the lowest persistent lignite.

Figure 5. Criteria that can be used to differentiate between the Hell Creek and Ludlow Formations in the field.



A B

3. The top of the Hell Creek Formation often coincides with the top of the highest occurring swelling "popcorn weathered" claystone. **A**, Typical "popcorn weathered" surface texture of a Hell Creek Formation claystone (section no. 9). **B**, Ludlow claystones and mudstones generally do not exhibit strongly defined "popcorn weathered" surfaces (section no. 22).



A B

4. The base of the Ludlow Formation is generally marked by a change in slope of the outcrop. This often coincides with an increase in vegetation on the Ludlow Formation. **A**, An obvious break in slope at the lithostratigraphic contact (arrow) between the Hell Creek and Ludlow Formations (east of section no. 9). **B**, Vegetation is absent from the surface of the Hell Creek Formation but is prevalent on the Ludlow Formation (section no. 25). Arrow points to contact.

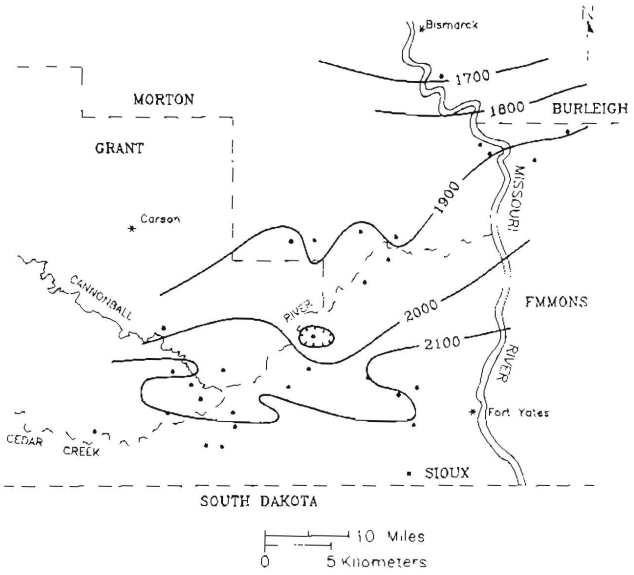


Figure 6. Structural contour map on the Hell Creek/Ludlow contact in the study area.

reflect either a decrease in abundance of conifers that produced this resin or a change in preservation potential.

9) **Channel Sandstone**: The contact between the Hell Creek and Ludlow Formations is especially difficult to determine when it occurs between fluvial channel facies. Channel sandstones in both the Hell Creek and Ludlow Formations are generally moderately to poorly sorted and range in grain size from very fine to medium sand. The channel sandstones in the Hell Creek generally contain 1- to 3-foot (0.3 to 0.9 m) organic-rich foreset beds that are generally gray in color, while those in the Ludlow vary from gray to grayish brown and generally lack the organic-rich bedding. Frye (1967) noted that Hell Creek channel sandstones tend to be gray in Grant and Sioux Counties but are both gray and brown in other parts of the state. This generalization does not always hold true, as golden-colored channel sandstone in the Hell Creek was found in Sioux County (T130N, R85W).

Attitude of the Contact

Laird and Mitchell (1942) traced the Hell Creek/Ludlow contact throughout southern Morton County. They determined that the contact occurred at an elevation of 2000 feet (610 m) along the Grant/Morton County line and decreased in elevation to the north and east to 1800 feet (549 m) along the Missouri River. The contact between Hell Creek and Ludlow strata was found to range from a high of 2182 feet (665 m) at the Schaeffer site (section no. 20) in southwestern Sioux County to a low of 1682 feet (513 m) at the University of Mary site (section no. 23) in Burleigh County (Figure 6) during this study. The stratigraphic contact dips gently to the north-northeast with an average gradient of only 9 feet per mile (1.7 m per kilometer).

CRETACEOUS/TERTIARY BOUNDARY

During the field determination of the lithostratigraphic contact between the Hell Creek and Ludlow Formations in south-central North Dakota no unusual layers suggesting a sudden change in sediment accumulation, i.e., a "boundary clay layer", were identified. Particular attention was paid to determining whether or not a boundary clay layer exists at the Cretaceous/Tertiary chronostratigraphic boundary in North Dakota. No noticeable sudden changes in lithology were noted within the interval spanning the chronostratigraphic boundary. In other areas, such as the Raton Basin in southern Colorado and northern New Mexico, the boundary clay layer is a thin kaolinitic claystone that is generally similar in appearance to a tonstein bed (Pollastro and Pillmore, 1987). The boundary clay is believed to have resulted from the alteration of glass that was ejected during a meteorite impact and spread across a large portion of the Earth. No such "boundary clay layer" was observed in any of the measured stratigraphic sections in south-central North Dakota.

The search for the chronostratigraphic boundary in south-central North Dakota required examination of both megafossils and microfossils. It was decided during the course of this study that if the K/T boundary interval could be narrowed to a meter or less at a study site through the use of palynomorphs, laboratory examination of sediment samples would be undertaken to search for sedimentological evidence of a boundary "event."

Palynomorphs

In the study area, palynomorphs (fossil spores and pollen) are most often found preserved in lignites and carbonaceous mudstones and claystones. The Cretaceous/Tertiary boundary is identified by the disappearance of certain palynomorphs that are restricted to the Cretaceous. Palynomorphs from Upper Cretaceous and lower Tertiary rocks may be separated into four general categories: 1) palynomorphs that occur in both Cretaceous and Tertiary rocks, 2) palynomorphs that occur in both Cretaceous and Tertiary rocks, but differ significantly in abundance in rocks of these ages, 3) palynomorphs that occur only in Cretaceous rocks, and 4) palynomorphs that occur only in Tertiary rocks. Examples of the first three categories are illustrated in Figure 7. It is the disappearance of the third category of palynomorphs from the rock record, that marks the K/T boundary (Figure 7). At some localities, another characteristic feature is the abundance of fern spores within a 6-inch (15 cm) interval above the boundary. This has been referred to as the "fern spike."

The major limiting factor in using palynology to determine the Cretaceous/Tertiary boundary is that the fossil pollen and spores are generally preserved only in lignites or carbonaceous claystones and mudstones, reducing the number of available rocks that can be sampled. However, even with this constraint, we were able to define the stratigraphic interval within which the K/T boundary occurs to within 1 foot (0.3 m) at eight of the twelve sections that were sampled.

Megafossils

Although megafossils were not commonly found during this study, either vertebrate, invertebrate, or plant fossils were recorded at 23 of the 32 measured section localities. Only two sites produced vertebrate fossils in meaningful numbers, the Katus site (section no. 9) and the Stumpf site (section no. 32) (Appendix C and D). Dinosaur remains were discovered at only 5 of the 32 measured section localities. At one of these localities, Standing Rock Sioux Tribe site (section no. 28), the Ludlow Formation is absent, and the highest stratigraphic occurrence of dinosaur remains were found 123 feet (37 m) below the contact between the Hell Creek Formation and Quaternary alluvium. The highest stratigraphic occurrences of dinosaur remains at the McGregor (section no. 10), Katus (section no. 9), Campbell (section no. 3), and Stumpf (section no. 32) sites were 49, 21, 80, and 102 feet (15, 6.5, 24, and 31 m) below the contact between the Hell Creek and Ludlow Formations, respectively (Appendix C). The K/T boundary was palynologically defined, although imprecisely because of the sparsity of carbonaceous rocks near the boundary, at only two of these sites (Katus and Stumpf sites). Therefore, at the Katus site dinosaur remains occur within 33.5 feet (10 m) to 3.5 feet (1.1 m) of the K/T boundary and at the Stumpf site dinosaur remains occur within 102 feet (31 m) to 91 feet (28 m) of the K/T boundary (Appendix C).

Plant fossil fragments are generally common in Hell Creek and Ludlow strata in the study area, but identifiable leaf fossils were noted in only 13 of the 32 measured sections (Appendix C). Six of these measured sections contained leaf fossils within 10 feet (3 m) on either side of the contact between the Hell Creek and Ludlow Formations. No attempt was made to systematically collect or identify the leaf fossils.

Search for Iridium Anomalies

At least nine areas in western North America contain iridium anomalies associated with palynological changes at the Cretaceous/Tertiary boundary (Nichols and Fleming, 1990). The easternmost of these localities is Pyramid Butte, Slope County, North Dakota (Johnson et al., 1989). At Pyramid Butte, an iridium anomaly of 0.72 parts per billion (ppb) was identified in a mudstone 2.6 feet (0.8 m) above the Hell Creek/Ludlow contact. Iridium concentrations of 0.35 and 0.55 ppb were detected slightly above and below the mudstone and background concentrations of 0.025 ppb were recorded in rocks 2.6 feet (0.8 m) either side of the anomaly.

Lerbekmo and Coulter (1984) identified the Cretaceous/Tertiary boundary at a site near Huff, North Dakota (the Miller site, section no. 24 in this

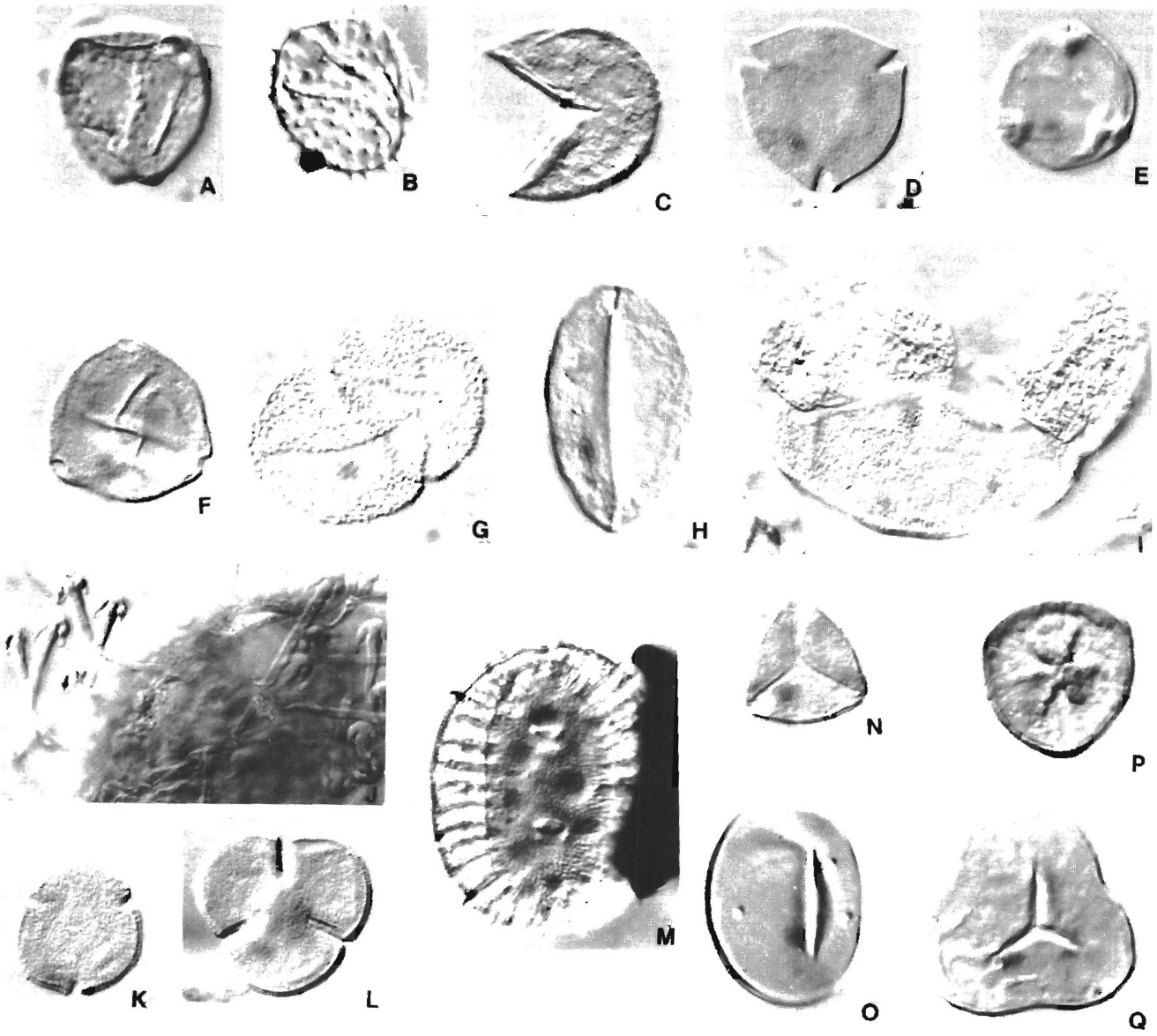
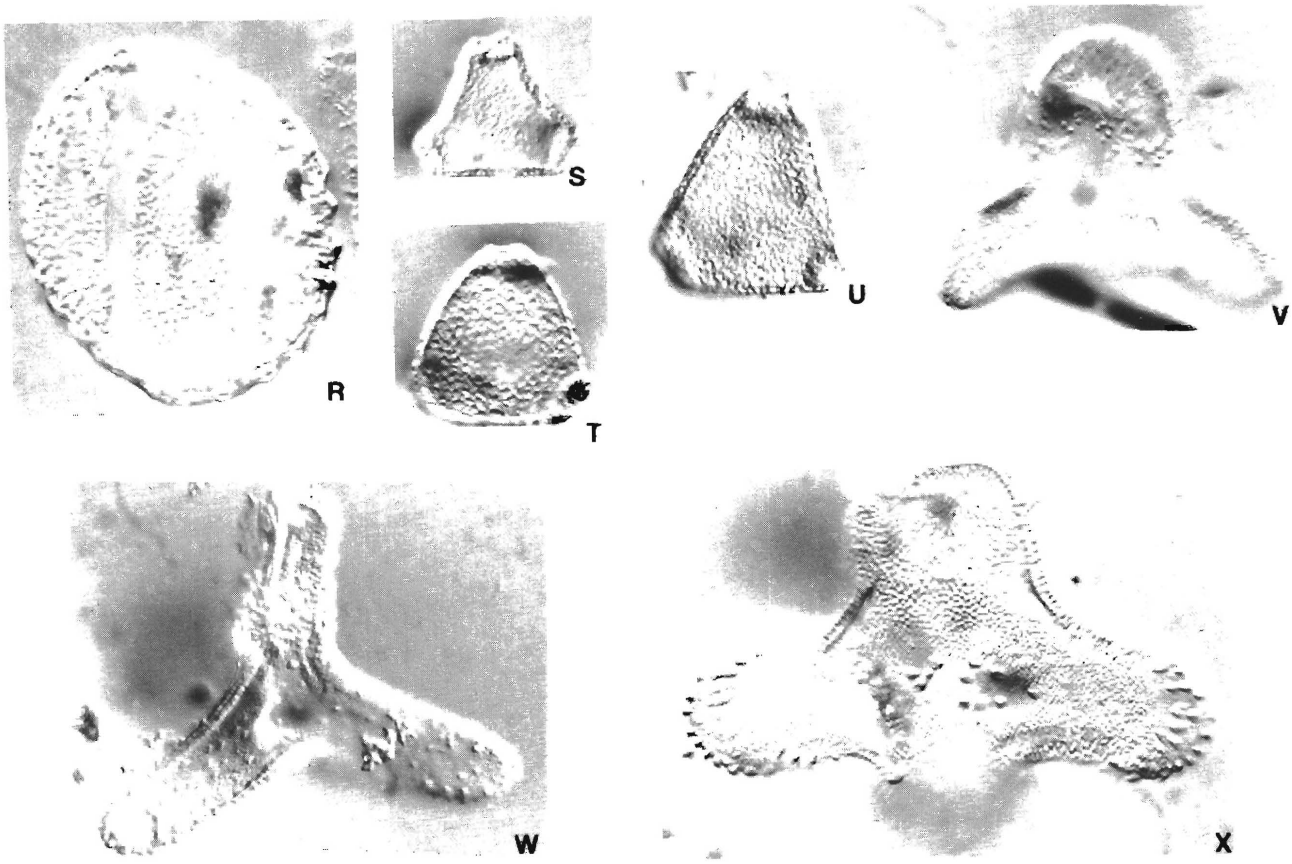


Figure 7. Palynomorphs that occur in Hell Creek and/or Ludlow strata in south-central North Dakota. (A-J) Examples of palynomorphs that occur in both Cretaceous and Tertiary rocks. **A.** *Ulmipollenites krempii*, pollen of a plant related to modern elms. **B.** *Pandaniidites typicus*, pollen of an extinct flowering plant with living relatives. **C.** *Taxodiaceaepollenites hiatus*, pollen of a plant related to modern bald cypress. **D.** *Kurtzipites circularis*, pollen of an extinct flowering plant. **E.** *Kurtzipites trispissatus*, pollen of an extinct flowering plant. **F.** *Triporopollenites* sp., pollen of an extinct flowering plant likely an ancestral member of the birch family. **G.** *Dyadonapites reticulatus*, a "Siamese twin" pair of pollen grains (or dyad) likely from a marsh plant. **H.** *Arecipites* sp., palm pollen. **I.** *Pityosporites* sp., pollen of a plant related to modern pines. **J.** *Azolla cretacea*, megaspore of an aquatic fern. (K-Q) Examples of palynomorphs that occur in both Cretaceous and Tertiary rocks, but differ significantly in abundance in rocks of these ages; their abundance can be evidence of the age of the rocks in which they occur. For example, species illustrated in K-M occur primarily in the Upper Cretaceous and are rare in the lower Tertiary; species illustrated in N-Q are present in the Upper Cretaceous but usually are much more abundant in the lower Tertiary. **K.** *Discoidites parvistriatus*, pollen of an extinct flowering plant. **L.** *Gunnera microreticulata*, pollen of an extinct flowering plant. **M.** *Wodehouseia spinata*, pollen of an extinct flowering plant. **N.** *Syncolporites minimus*, pollen of an extinct flowering plant. **O.** *Laevigatosporites* sp., spore of a species of fern related to certain living ferns. **P.** *Stereisporites* sp., spore of a fossil species of sphagnum moss. **Q.** *Cyathidites diaphana*, spore of a species of fern related to certain living ferns. (R-X) Examples of palynomorphs that are restricted to Cretaceous rocks. **R.** *Liliacidites complexus*, pollen of an extinct flowering plant. **S, T, and U.** *Proteacidites* sp., pollen of extinct flowering plants. **V.** *Aquilapollenites quadrilobus*, pollen of an extinct flowering plant. **W.** *Aquilapollenites collaris*, pollen of an extinct flowering plant. **X.** *Aquilapollenites attenuatus*, pollen of an extinct flowering plant. Magnification is 1000x.



report) based on palynology and paleomagnetic stratigraphy. They apparently did not test for iridium. The Miller site was the only site analyzed for iridium during this study (Mosses Attrep, Jr., written communication, 1992). Background concentrations of .007 to .051 ppb were detected 1.4 feet (0.4 m) below to 2.9 feet (0.9 m) above the K/T boundary at this site. Iridium concentrations were 0.040 and 0.051 ppb, within background levels, at the systemic boundary. However, an iridium concentration of 0.122 ppb was detected in mudstone 2.5 feet (0.8 m) above the K/T boundary at this site.

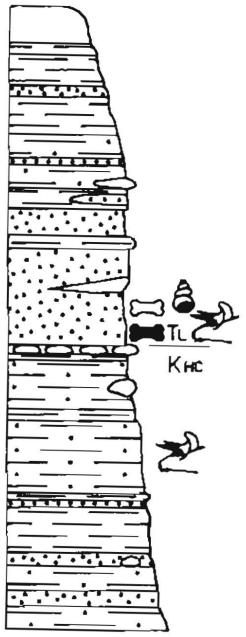
Shocked Minerals

Even though no distinct boundary clay layer was detected, it is possible that shocked mineral grains might still be mixed within sediments composing the boundary interval as determined by palynological assessment. Relatively few sand-size grains were obtained during the sample disaggregation process and no shocked mineral grains were found. The scarcity of grains may have been due to the sampling method, which produced relatively small core samples (1-3 inches, 2.5-7.6 cm) through the interval. A larger sample may be needed to increase the probability of recovering an adequate number of grains for analysis.

RELATIONSHIP BETWEEN THE LITHOSTRATIGRAPHIC CONTACT AND K/T BOUNDARY

The palynomorph analysis of a dozen sections throughout south-central North Dakota enabled a detailed comparison of the relationship between the Hell Creek and Ludlow Formations and the chronostratigraphic boundary in this area. Detailed descriptions of ten of these sections, beginning in the southwestern corner of the study area and proceeding to the northeast, are given in this chapter. Descriptions of measured sections not presented in the text are given in Appendix B.

Section no. 9 — Location: T129N R87W sec. 10 (sw/sw/se) Sioux County
Landowner: Robert Katus — Top of section: 2160 fasl.



Thickness Ft.	Thickness M.	
6	1.8	Covered. Fossil: Bivalvia (unidentified).
		LUDLOW FORMATION
2	0.6	Claystone; black (fresh and weathered), carbonaceous.
4.7	1.4	Mudstone; brown to reddish/brown(fresh), light brown (weathered), sandy, carbonaceous, iron oxide stained.
2	0.6	Sandstone; gray/brown (fresh), gray (weathered), fine grained, organic rich, clayey, poorly cemented.
5.7	1.7	Claystone; gray/dark brown (fresh), light gray to reddish/brown(weathered), silty, iron oxide stained layers, iron oxide concretions.
4	1.2	Mudstone; gray/brown (fresh), gray to light brown (weathered), fines upward, iron oxide stained, selenite, root casts.
0.5	0.2	Sandstone; gray/brown (fresh and weathered), very fine grained, well cemented, contains organic horizons with plant fragments.
4	1.2	Mudstone; brown (fresh), gray (weathered), clayey, iron oxide concretions at base.
1	0.3	Claystone; dark brown/black (fresh and weathered), carbonaceous, contains small concretions.
0.8	0.2	Sandstone; gray/brown (fresh and weathered), very fine grained, clayey, contains plant fragments and lignite lenses.
0.5	0.2	Claystone; brown/black (fresh and weathered), carbonaceous, lignite lenses, selenite.
4.7	1.4	Sandstone; gray/brown (fresh), gray (weathered), very fine grained, organic laminae, organics common at base.
3	0.9	Mudstone; black/brown (fresh and weathered), sandy, carbonaceous, paper shale, interbedded with sandstone lenses.
16	4.9	Sandstone; brown/gray (fresh), light gray/brown (weathered), very fine to fine grained, poorly to moderately cemented, cross-bedded, iron oxide stained, contains laminated carbonaceous lenses from 1 to 3 feet (.3 to 1 m) in thickness, fossiliferous.
		HELL CREEK FORMATION
0.3	0.1	Concretion zone; dark brown/black (fresh and weathered).
1	0.3	Claystone; gray (fresh and weathered), popcorn texture.
9	2.7	Mudstone; gray/brown (fresh), gray (weathered), clayey, plant fragments, root traces, dark gray claystone lenses, contains numerous iron oxide concretions, carbonaceous at top.
2	0.6	Claystone; gray/brown (fresh), reddish brown (weathered), carbonaceous, plant fragments and lignite lenses.
12	3.7	Mudstone; brown/gray (fresh and weathered), plant fragments, contains iron oxide concretions and carbonaceous zones, contains dinosaur bone fragments.
0.5	0.2	Claystone; brown (fresh), dark brown (weathered), carbonaceous.
1	0.3	Sandstone; olive gray (fresh), gray (weathered), fine grained, silty, abundant plant fragments.
8	2.4	Claystone; gray (fresh), light to medium gray (weathered), silty, blocky, contains black carbonaceous lenses.
2	0.6	Sandstone; yellow gray (fresh), gray (weathered), very fine grained, silty, contains iron oxide concretions, laterally discontinuous.
4	1.2	Mudstone; gray/brown (fresh), gray (weathered), contains plant fragments.
2.5	0.8	Sandstone; gray (fresh and weathered), fine grained, silty and clayey, laminated, jarosite, concretions.
4	1.2	Mudstone; gray (fresh and weathered), contains scattered plant fragments, carbonaceous content increases at top.

Figure 8. Measured geologic section no. 9 at the Katus site, Sioux County. Legend and vertical scale for all of the measured sections are in Appendix A.

A B

Figure 9. Photographs of the Katus site (section no. 9). **A,** The section was measured at the prominent point (arrow) in the photo, view is to the southeast. **B,** Photograph of the measured section site. Base of the channel sandstone (arrow) marks the Hell Creek/Ludlow lithostratigraphic contact.

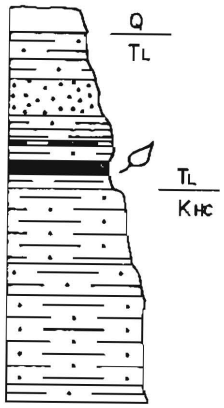
Katus Site (section no. 9)

The Katus geologic section (section no. 9) is located on the west-facing slope of a small hill on the south edge of Cedar Creek valley in section 10 (T129N R87W), Sioux County (Figures 8 and 9). Approximately 46 feet (14 m) of Hell Creek and 55 feet (17 m) of Ludlow strata are exposed at this locality (Figure 8). The Hell Creek/Ludlow contact at this site occurs at the base of a channel sandstone. The lithostratigraphic contact coincides with both a color change and the top of the highest occurring swelling "popcorn weathered" claystone. Where measured, the channel sandstone is dull gray and contains large, cross-bed foresets which have organic-rich lenses at their bases, characteristics often associated with Hell Creek sandstones. Laterally, the channel sandstone becomes golden brown in color, a characteristic of the Ludlow Formation. The Cretaceous/Tertiary boundary interval extends from 12.5 feet (3.8 m) below the lithostratigraphic contact to 17.5 feet (5.3 m) above the contact (Plate 2). The boundary interval is quite thick at this section because there were insufficient carbonaceous beds to allow further delineation.

North of the Ludlow channel sandstone at this site, both Hell Creek and Ludlow strata appear to be dipping to the south whereas beds in these formations south of the channel appear to dip to the northeast. Immediately north of the measured section locality, the channel extends much deeper and is predominantly filled with claystone and siltstone. There is no evident truncation of Hell Creek strata by the fluvial channel.

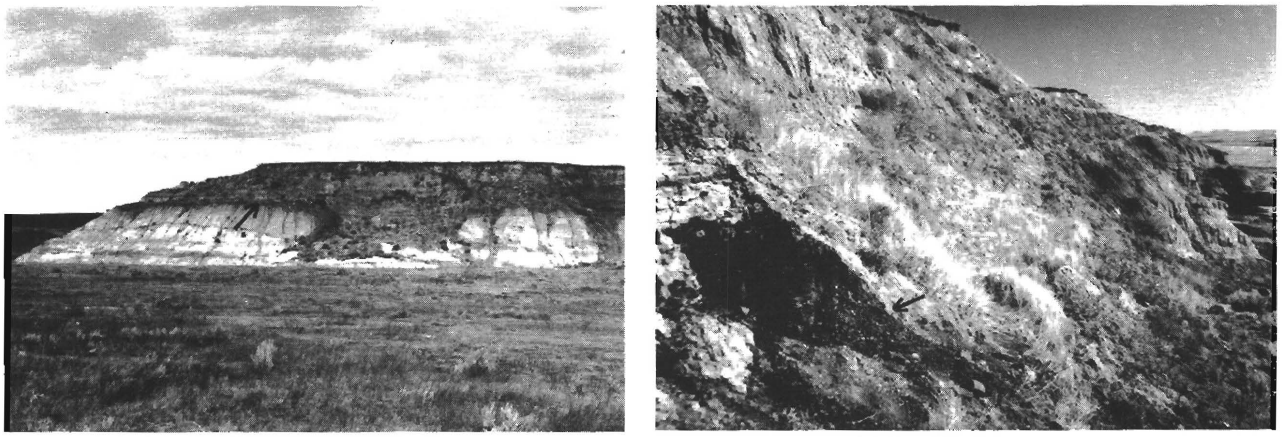
A fragmentary, unidentifiable dinosaur bone was found on the outcrop surface 21 feet (6.5 m) below the contact between the Hell Creek and Ludlow Formations at the Katus site (Figure 8). Unidentifiable dinosaur remains were also observed immediately below the fine-grained portion of the Ludlow Formation channel fill, north of the measured section locality. Vertebrate fossils, including marine and freshwater fish, turtle, champsosaur, crocodile, alligator, dinosaur, and mammal and *Teredo*-bored petrified wood, were recovered throughout the Ludlow Formation channel deposits just above the contact between the Hell Creek and Ludlow Formations (Appendix C). Dinosaur remains found in these channel deposits consist of shed hadrosaur teeth and ossified tendon, both of which are durable and are interpreted to be reworked. Teeth of the shark, *Carcharias taurus*, and *Teredo*-bored petrified wood, found in the channel deposits are both characteristic of the marine Paleocene Cannonball Formation, and are also believed to be reworked. The fossil assemblage of this Ludlow channel is, therefore, interpreted to be a mix of Paleocene and reworked Cretaceous and marine Paleocene taxa. A similar situation, at the Hell Creek/Ludlow contact in Montana, sparked controversy over whether or not dinosaurs existed for a brief time during the Paleocene (Rigby et al., 1987; Eaton et al., 1989; and Lofgen et al., 1990).

Section no. 11 Location: T130N R86W sec. 19 (se/ne/nw), Grant County
Landowner: Sid Brenner Top of section: 2140 fasl.



Thickness Pt.	Thickness M.	
4	1.2	QUATERNARY Loam.
		LUDLOW FORMATION
4	1.2	Mudstone; highly weathered.
3	0.9	Mudstone; yellow/brown (fresh), gray (weathered), sandy, iron oxide stained.
6	1.8	Sandstone; yellow/brown(fresh), gray/brown(weathered), fine grained, poorly sorted, contains concretionary zones, iron oxide stained.
3	0.9	Mudstone; gray/brown fresh and weathered surfaces, iron oxide stained, plant fragments, iron oxide concretions.
1.5	0.5	Claystone; dark brown (fresh), gray (weathered), paper shale, carbonaceous, grades into overlying mudstone.
0.5	0.2	Claystone; reddish brown (fresh), light brown (weathered), silty, carbonaceous, plant fragments, fissile.
2	0.6	Mudstone; gray/brown (fresh), light gray/brown (weathered), contains 2 inch (5.1 cm) carbonaceous clay layer, leaf fossils.
2.5	0.8	Lignite.
2	0.6	Claystone; reddish brown (fresh), light brown (weathered), carbonaceous, oxidized.
		HELL CREEK FORMATION
12.5	3.8	Mudstone; gray/brown to brown (fresh), gray/brown (weathered), clayey, contains 5 inch (12.7 cm) carbonaceous clay lens near base, amber, plant fragments.
5	1.5	Mudstone; gray/brown (fresh), light gray (weathered), sandy, very fine grained, jarosite.
14	4.3	Mudstone; brown (fresh), dark gray (weathered), clayey, organic rich, popcorn texture, contains 3 foot (1 m) thick organic rich horizons.
3	0.9	Mudstone; gray/brown (fresh), gray (weathered), sandy, plant fragments, large roots.

Figure 10. Measured geologic section no. 11 at the Brenner site, Grant County.



A B

Figure 11. Photographs of the Brenner site (section no. 11). **A**, South-facing exposures of a small ridge containing measured section no. 11. Arrow marks the stratigraphic contact between Hell Creek and Ludlow strata. **B**, Sample pit (arrow) excavated into coal and carbonaceous claystone at the base of the Ludlow Formation in section no. 11.

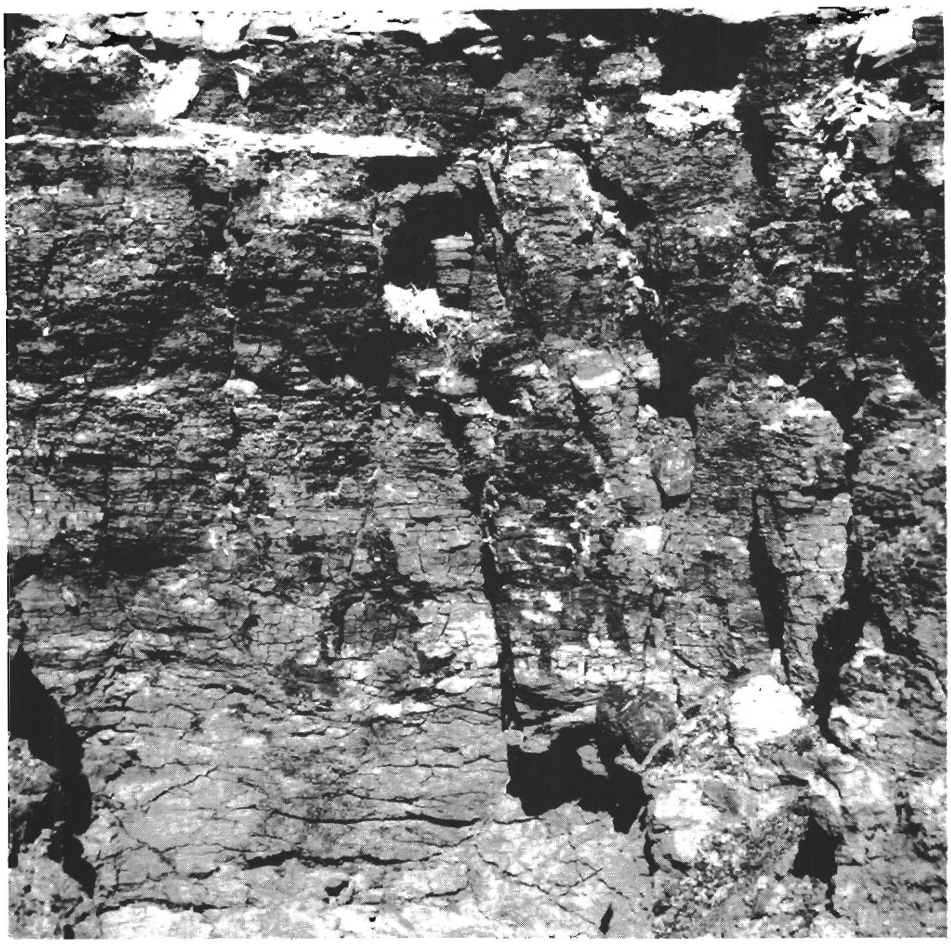


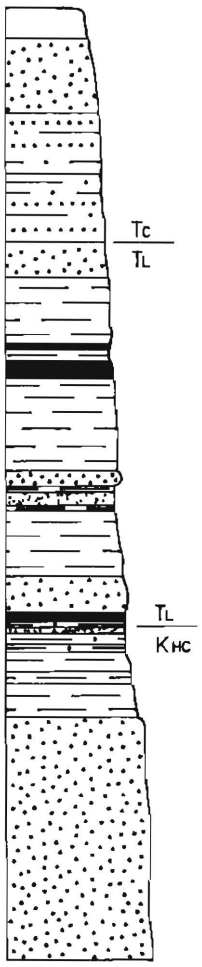
Figure 12. Relationship between the Hell Creek/Ludlow lithostratigraphic contact (0, not shown) and the Cretaceous/Tertiary boundary interval at the Brenner site (section no. 11). Measurements are distances above the contact.

Brenner Site (section no. 11)

The Brenner measured section (section no. 11) is located on the southwest face of a small knoll or ridge in section 19 (T130N R86W), Grant County (Figures 10 and 11). The section contains approximately 40 feet (12 m) of Hell Creek strata overlain by 30 feet (9 m) of Ludlow strata (Figure 10). The Hell Creek/Ludlow contact was placed at the base of a 4.5-foot (1.4 m) thick carbonaceous bed which consists of a 2-foot (0.6 m) thick carbonaceous claystone that grades into an overlying 2.5-foot (0.76 m) thick coal. The contact was not placed at the base of the coal because the contact between coal and underlying carbonaceous claystone was gradational. The lithostratigraphic contact at this site coincides with a slight break in slope and a sharp color change from grays of the Hell Creek to yellow-browns of the Ludlow. Palynomorph data place the Cretaceous/Tertiary boundary within an 11-inch (28 cm) interval of coal spanning the area 6 to 17 inches (15-43 cm) above the base of the coal (Figure 12). The Cretaceous/Tertiary boundary therefore, occurs within an interval 2.5 to 3.4 feet (0.8 to 1.1 m) above the Hell Creek/Ludlow contact at this site.

Identifiable leaf fossils are present near the base of the mudstone that overlies the coal at this section (Appendix C). No vertebrate or invertebrate fossils were observed at this site.

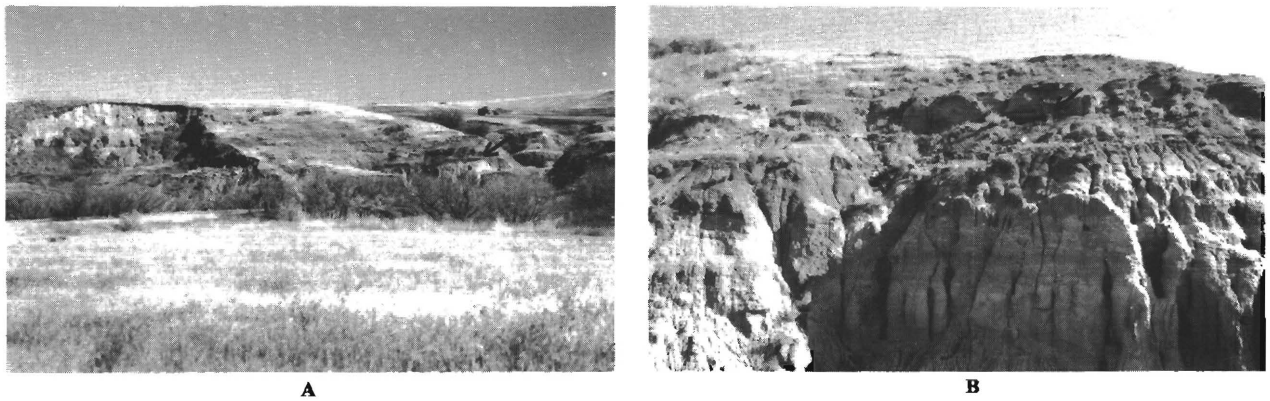
Section no. 2 Location: T132N R86W sec. 29 (ne/nw/sw), Grant County
Landowner: Lloyd and Dan Stewart Top of section: 2100 fasl.



Thickness Ft.	Thickness M.	
5	1.5	CANNONBALL FORMATION Sand; light gray brown (fresh and weathered), silty to clayey.
12	3.7	Sandstone; light gray to buff (fresh and weathered), fine grained, well sorted, poorly cemented.
10	3.1	Sandstone; light gray (fresh and weathered), interbedded with thin clay lenses.
17	5.2	Mudstone; light gray to light yellow/gray (fresh), light gray to tan (weathered), iron oxide stained, the mudstone contains interbedded sand and clay lenses, heavily burrowed.
6	1.8	LUDLOW FORMATION Mudstone; light gray to tan (weathered and fresh), sandy, moderately indurated, rooted (large, 3 inch (7.6 cm) root casts, contains lignite clasts, iron oxide stained, contains 6-8 inch (15-20 cm) paleosol at top of unit.
11	3.4	Claystone; dark gray (fresh) to light gray (weathered), silty, fissile at base, blocky at top, some plant fragments.
0.5	0.2	Lignite.
2	0.6	Claystone; light gray/brown (fresh) to light gray (weathered), silty, plant fragments, jarosite staining.
2.5	0.8	Lignite.
15	4.6	Claystone; medium to dark brown (fresh) to light gray to brown (weathered), silty, carbonaceous, very carbonaceous lenses 3 feet (1 m) from top of unit.
2	0.6	Sandstone; light yellow/orange (fresh) to light gray (weathered), clayey, poorly cemented.
0.5	0.2	Claystone; red to gray (fresh and weathered), appears to have burned, white clay lens.
3	0.9	Siltstone; light gray (fresh and weathered).
0.5	0.2	Claystone; red to gray (fresh and weathered), appears to have burned in areas, contains white clay lenses.
11	3.4	Mudstone; light gray to dark brown (fresh) to light to medium brown (weathered), silty claystone, very carbonaceous at top.
6	1.8	Sandstone; light to medium gray (fresh), light gray (weathered), silty, very fine grained, jarosite.
0.9	0.3	Lignite.
0.3	0.1	Claystone; dark brown to black (fresh and weathered).
0.8	0.3	HELL CREEK FORMATION Siltstone; gray to white (fresh and weathered), clayey, laminated, numerous root traces.
1	0.3	Mudstone; gray (weathered and fresh), silty.
1	0.3	Mudstone; gray to dark gray (weathered and fresh), silty.
1.4	0.4	Claystone; dark to medium brown (fresh) to light gray (weathered), silty, carbonaceous, popcorn texture.
1	0.3	Claystone; dark brown to black (fresh and weathered), carbonaceous.
5	1.5	Claystone; dark to medium brown (fresh) to light gray (weathered), silty, carbonaceous.
40	12.2	Sandstone; light gray to light gray/brown (fresh) to light gray (weathered), very fine grained, contains iron oxide concretionary layers, moderately to poorly cemented, 4 inch (10 cm) iron oxide concretionary layer at base.

Began measuring section on plateau, 10 feet (3 m) above the Cannonball River.

Figure 13. Measured geologic section no. 2 at the Cannonball Stage Stop site, Grant County.



A B

Figure 14. Photographs of the Cannonball Stage Stop site (section no. 2). **A**, South-facing outcrops above the Cannonball River at section no. 2. Arrow points to lithostratigraphic contact between Hell Creek and Ludlow strata. **B**, Arrow points to pit excavated across the Hell Creek/Ludlow contact at section no. 2.

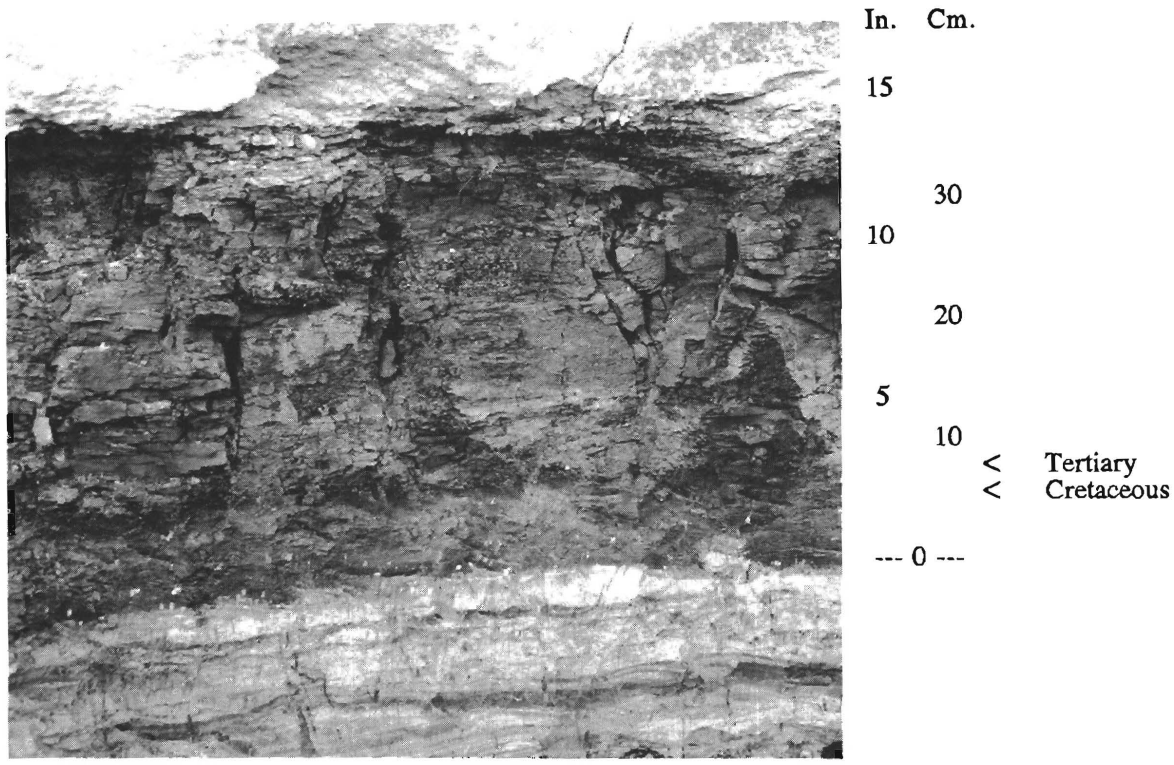
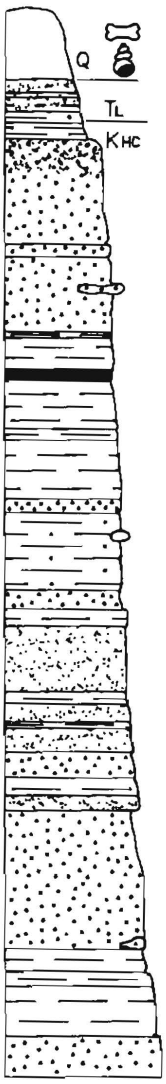


Figure 15. Relationship between the Hell Creek/Ludlow lithostratigraphic contact (at 0) and the Cretaceous/Tertiary boundary interval at Cannonball Stage Stop site (section no. 2). Measurements are distances above the contact.

Cannonball Stage Stop Site (section no. 2)

The Cannonball Stage Stop site (measured section no. 2) is located on a cut above the north bank of the Cannonball River in section 29 (T132N R86W), Grant County (Figures 13 and 14). The site is located 1/4 mile (1/2 kilometer) north of a rest area situated on the historic site of one of the rest stops of the Deadwood to Bismarck stagecoach. The outcrop contains strata of the Hell Creek, Ludlow, and Cannonball Formations. Approximately 50 feet (15 m) of Hell Creek and 62 feet (19 m) of Ludlow strata are exposed at this site (Figure 13). The Hell Creek/Ludlow contact was placed at the base of a thin carbonaceous mudstone that underlies the first continuous lignite. The contact was placed at the base of the carbonaceous mudstone rather than at the base of the overlying lignite because it also corresponded to a slight color change in the strata and a slight change in slope. The Cretaceous/ Tertiary boundary was determined by palynological analysis to fall within a 3-inch thick (8 cm) interval in the top 2 inches (5 cm) of the underclay and the bottom 1 inch (2.5 cm) of coal (Figure 15). The Cretaceous/Tertiary boundary occurs within an interval 1.5 to 4.5 inches (3.8 to 11.4 cm) above the lithostratigraphic contact (Plate 2). No unique layers were observed within either the coal or underclay, but a white to gray, heavily rooted siltstone, believed to be kaolinitic, is present beneath the underclay at this site. Approximately 33 feet (10 m) of Cannonball strata are exposed at the site. The contact between Ludlow and Cannonball strata was placed at a 6- to 8-inch (15-20 cm) thick paleosol underlain by a rooted mudstone and overlain by a burrowed mudstone.

No vertebrate or invertebrate fossils were found at this section. Marine cartilaginous fish fossils, characteristic of the Cannonball Formation, were found at land surface 1/4 mile (0.5 km) east of the measured section.



Section no. 1 — Location: T131N R86W sec. 22 (sw 1/4), Grant County
Landowner: Curt Hepper — Top of section: 2160 fasl.

Thickness Ft.	M.	
		QUATERNARY
9	2.7	Loam and lag gravels. Fossils: *Carcharias taurus* (shark), gastropod (marine).
		LUDLOW FORMATION
8	2.4	Mudstone; gray/brown to tan (weathered and fresh), silty to sandy, iron stained, iron oxide concretionary layer 3 feet (1 m) from base.
0.3	0.1	Coal.
0.5	0.2	Mudstone; light to medium gray (fresh), orange (weathered), silty, silt laminae, highly iron oxide stained.
0.4	0.1	Claystone; dark gray to black (weathered and fresh), silt laminae at base, very carbonaceous.
		HELL CREEK FORMATION
3	0.9	Claystone; medium to dark gray (fresh and weathered), plant fragments, popcorn texture.
17	5.2	Sandstone; light gray to brown (fresh and weathered), very fine grained iron oxide nodules, selenite crystals, fines upward.
1.5	0.5	Sandstone; light gray (fresh) to light brown/gray (weathered), well cemented.
12	3.7	Sandstone; gold to light yellow/gray (fresh), light gray (weathered), fine to very fine grained, poorly cemented, iron oxide stained, contains dark brown to black concretion zone, contains organic pods.
1	0.3	Claystone; light to medium brown (fresh), pink to brown (weathered), carbonaceous.
5	1.5	Claystone; light to dark gray (fresh and weathered), silty, popcorn texture.
1.5	0.5	Lignite to carbonaceous claystone.
8	2.4	Claystone; light gray (fresh and weathered), popcorn texture, silty.
2	0.6	Claystone; light to medium brown (fresh and weathered), carbonaceous and lignitic.
9.5	2.9	Claystone; light gray/green to light brown (fresh and weathered), silty to sandy, popcorn texture.
2	0.6	Sandstone; Light yellow/gray (fresh and weathered), very fine grained, silty, poorly cemented.
12.5	3.8	Claystone; interbedded with mudstone, light to medium gray to light brown (fresh and weathered), sandy and silty, carbonaceous zones, iron oxide concretionary zone at top.
3	0.9	Sandstone; light gray (fresh and weathered), clayey, poorly cemented.
3	0.9	Claystone to siltstone; medium brown (fresh and weathered), sandy, carbonaceous, contains amber and plant fragments.
10.5	3.2	Siltstone; medium gray (fresh) to light gray (weathered), clayey, popcorn texture, contains organic or carbonaceous clay lenses, jarosite and limonite concretions.
2	0.6	Claystone; light to dark gray/brown (fresh), light gray/brown to purplish pink (weathered), clayey to sandy, popcorn texture, plant fragments.
3	0.9	Siltstone; light gray (fresh and weathered).
1	0.3	Claystone; medium to dark brown (fresh and weathered), carbonaceous, plant fragments, silty.
4	1.2	Siltstone; light gray (fresh) to light gray and brown on weathered surfaces, popcorn texture, clayey to sandy.
4	1.2	Sandstone; light gray (fresh) to light gray/brown (weathered), fine grained, and poorly cemented.
3	0.9	Claystone; light gray to brown (fresh and weathered), silty, popcorn texture.
2	0.6	Siltstone; medium brown (fresh), to purple/brown (weathered), clayey, plant fragments, jarosite staining.
23	7.0	Sandstone; light to medium gray (fresh), light to very light gray to white (weathered), poorly cemented, organic lenses, concretions at base, and cross-bedded.
4	1.2	Claystone; olive gray to light brown (fresh and weathered), silty, popcorn texture.
2	0.6	Claystone; dark brown to black (fresh and weathered), lignite lenses, carbonaceous.
8	2.4	Claystone; dark to medium brown (fresh and weathered), popcorn texture, silty.
6.8	2.1	Sandstone; very light gray to white (fresh and weathered), fine grained, poorly cemented, organic horizons, cross-bedded.
6.8	2.1	Siltstone; light olive/gray (fresh and weathered), clayey, organic stringers, popcorn surface, organic rich at top of unit.

Figure 16. Measured geologic section no. 1 at the Rattlesnake Butte site, Grant County.

A B

Figure 17. Photographs of the Rattlesnake Butte site (section no. 1). **A**, Southwest-facing slope at the top of Rattlesnake Butte. Arrow points to pit excavated across the Hell Creek/Ludlow contact. **B**, Close-up of pit containing the contact between the Hell Creek and Ludlow Formations at Rattlesnake Butte.

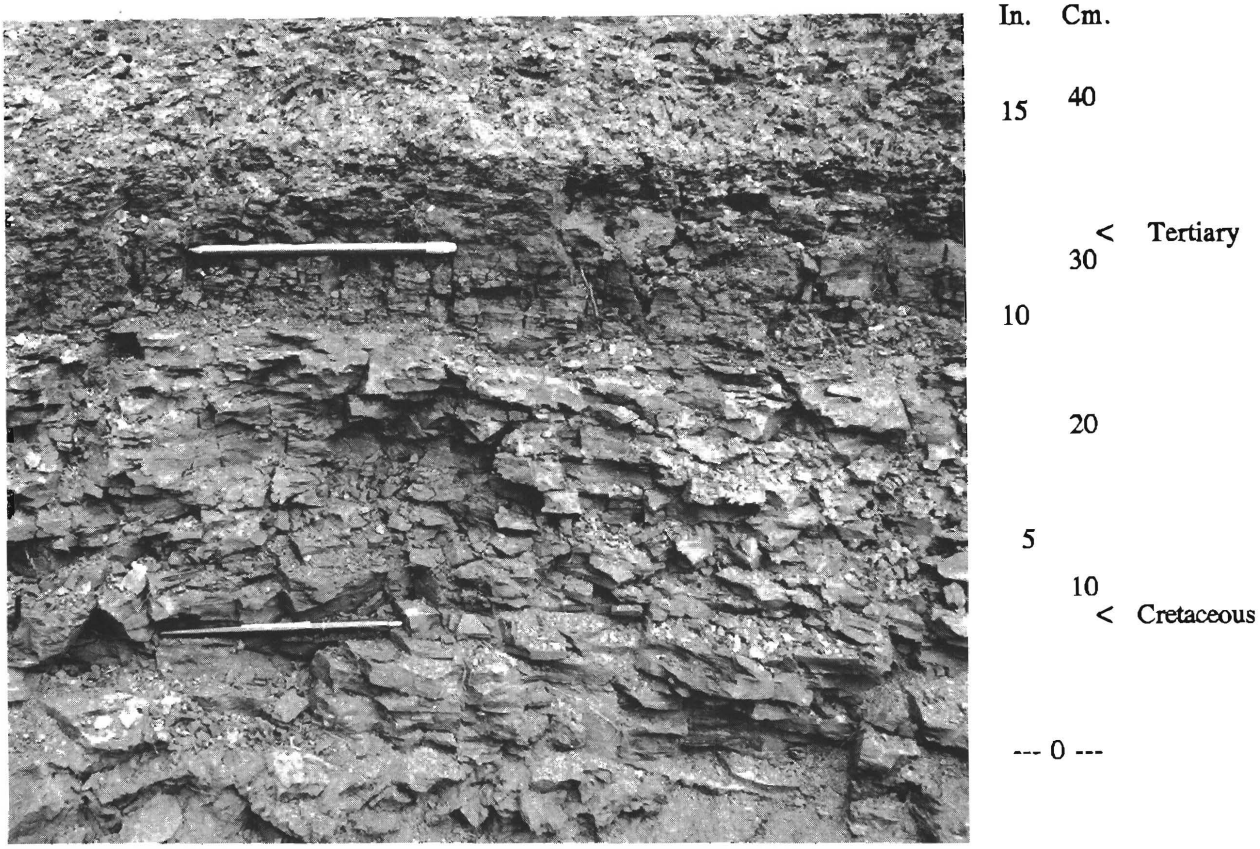


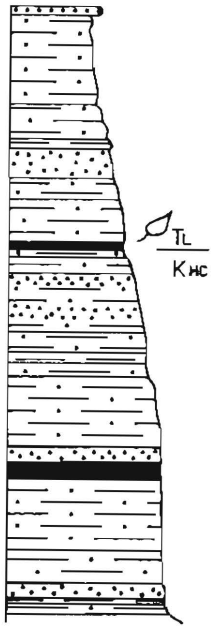
Figure 18. Relationship between the lithostratigraphic contact (at 0) and the Cretaceous/Tertiary boundary interval at the Rattlesnake Butte site (section no. 1). Measurements are distances above the lithostratigraphic contact.

Rattlesnake Butte Site (section no. 1)

Rattlesnake Butte (section no. 1) is a small 10-acre butte situated on the west side of the badlands in the Cannonball River Valley in section 22 (T131N R86W), Grant County (Figures 16 and 17). Strata are well exposed along the steep sides of this butte but access is almost impossible except along the southwest and southeast sides. The butte contains approximately 160 feet (49 m) of Hell Creek strata with only 9 to 10 feet (2.7 to 3 m) of Ludlow exposed at the top (Figure 16). The Hell Creek/Ludlow contact was difficult to pick at this site because of the presence of a 1.5-foot (0.5 m) lignite and an overlying 30-foot (9.1 m) thick channel sandstone in the upper part of the Hell Creek Formation. It is often difficult to distinguish between Hell Creek and Ludlow sandstones in this area. Although the contact was not immediately recognized along the southwest side of the butte where the section was measured, it was more obvious along the southeast side of the butte where there is a break in slope and a slight color change at the contact. The Hell Creek/Ludlow contact was placed at the base of a thin carbonaceous claystone that overlies the highest occurring swelling claystone. It was determined from palynological analysis that the interval containing the K/T boundary in this section ranges from 4 to 12 inches (10-31 cm) above the contact between the Hell Creek and Ludlow Formations (Figure 18, Plate 2).

Marine fish and gastropod fossils were recovered from ant mounds in Quaternary alluvium at the top of the butte (Appendix C). They are interpreted to be lag from the Cannonball Formation.

Section no. 20 — Location: T129N R85W sec. 5 (ne/ne/ne), Sioux County
Landowner: Ross Schaeffer — Top of section: 2220 fasl.



Thickness Ft.	Thickness M.	
14.5	4.4	LUDLOW FORMATION Sandstone; gray (fresh), black (weathered), very fine grained, well cemented.
6	1.8	Mudstone; dark brown (fresh), gray/brown (weathered), sandy, iron oxide concretions, iron oxide staining with interbedded sandstone.
1	0.3	Claystone; medium brown (fresh and weathered), organic.
5	1.5	Sandstone; yellow/brown to gray (fresh), gray (weathered), very fine grained, clayey, concretions, iron oxide stained.
4	1.2	Mudstone; brown (fresh), light brown (weathered), carbonaceous, very dark shale at base.
7	2.1	Mudstone; gray to yellow/brown (fresh), yellow/brown (weathered), sandy, sandy layers, clay rich layers contain leaf fossils, and iron oxide concretions.
0.5	0.2	Lignite.
		HELL CREEK FORMATION
0.5	0.2	Mudstone; red/brown (fresh), light brown (weathered), sandy, carbonaceous, plant fragments.
3	0.9	Mudstone; gray/brown (fresh), gray (weathered), popcorn texture.
9.5	2.9	Interbedded Sandstone and Mudstone; gray/brown (fresh and weathered). Sandstone; fine grained, scattered organics, iron oxide concretions.
3	0.9	Mudstone; medium brown (fresh), light brown (weathered), carbonaceous, plant fragments, amber.
2	0.6	Claystone; dark gray (fresh), light gray (weathered).
2	0.6	Mudstone; red/brown (fresh), medium brown (weathered), carbonaceous, plant fragments, amber.
12	3.7	Mudstone; gray/brown (fresh and weathered), plant fragments, contains two organic rich clay zones.
2	0.6	Sandstone; gray (fresh and weathered), fine grained, moderately indurated, root traces, plant fragments.
2.5	0.8	Lignite; poor to moderate quality.
11.8	3.6	Mudstone; yellow/gray (fresh), gray (weathered), sandy, sand lenses, jarosite, organic content varies, popcorn texture.
5.9	1.8	Mudstone; brown/gray (fresh), dark gray (weathered), organic fragments, popcorn texture, top is carbonaceous.
2	0.6	Sandstone; yellow/brown (fresh), gray/white (weathered), fine grained, clay stringers, jarosite, root traces, fines upward.
1	0.3	Claystone; dark gray to black (fresh), brown (weathered), carbonaceous.
2	0.6	Mudstone; gray/brown (fresh and weathered), sandy, trace of organics, popcorn texture.

Figure 19. Measured geologic section no. 20 at the Schaeffer site, Sioux County.

A **B**

Figure 20. Photographs of the Schaeffer site (section no. 20). **A**, South-facing slope containing measured section no. 20. Arrow points to the contact between Hell Creek and Ludlow strata. **B**, Pit (arrow) excavated across the contact between the Hell Creek and Ludlow Formations at section no. 20.

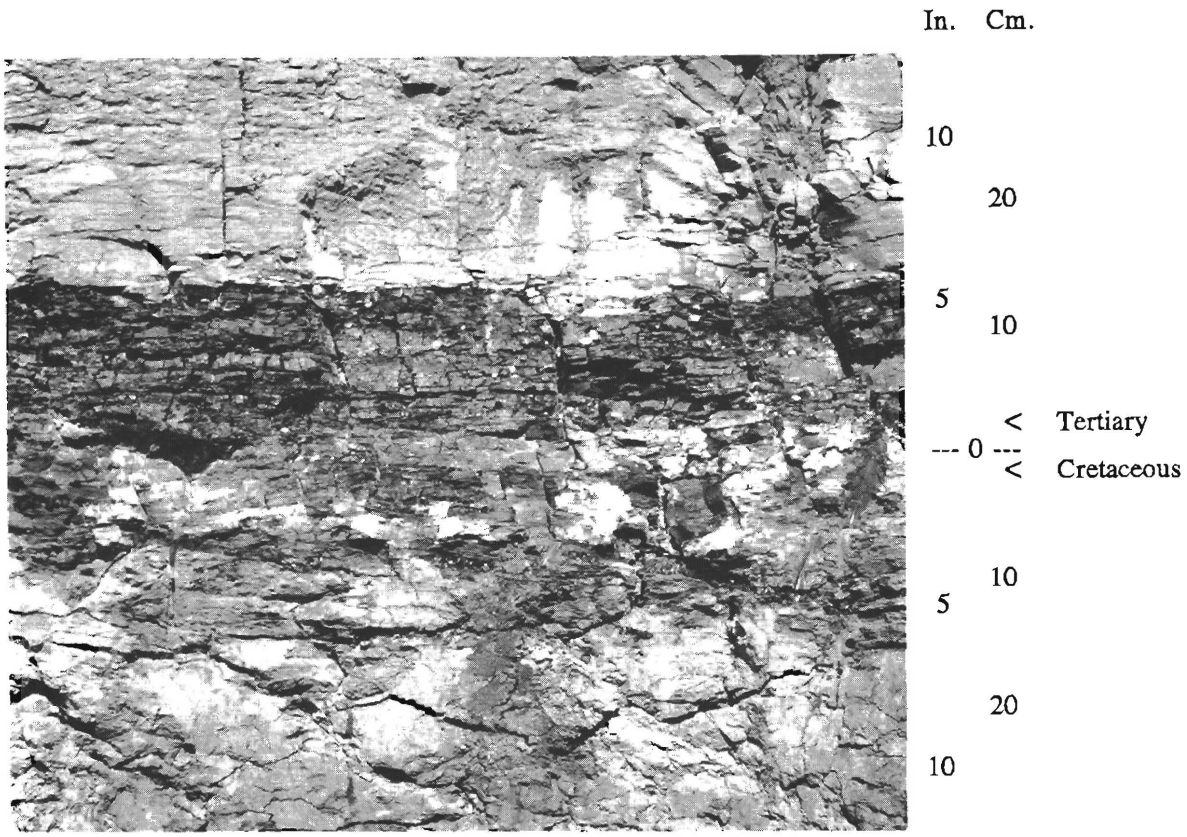


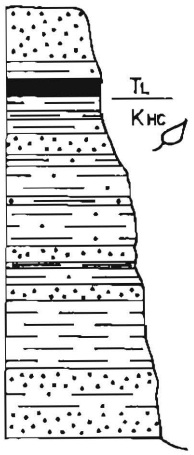
Figure 21. Relationship between the Hell Creek and Ludlow lithostratigraphic contact (at 0) and the Cretaceous/Tertiary boundary interval at the Schaeffer site (section no. 20). Measurements are distances above and below the lithostratigraphic contact.

Schaeffer Site (section no. 20)

The Schaeffer site (section no. 20) is located on the south-facing slope of a hill adjacent to U.S. Highway 31 in section 5 (T129N R85W), Sioux County (Figures 19 and 20). Approximately 60 feet (18 m) of Hell Creek and 39.5 feet (12 m) of Ludlow strata are exposed at this site (Figure 19). The Cannonball Formation is exposed in the uplands east of this locality. The Hell Creek/Ludlow contact was placed at the base of a 6-inch (15 cm) thick lignite that coincided with the top of the highest occurring swelling "popcorn weathered" mudstone and a break in slope (Figure 20B). There was no perceptible color change across the contact at this site. A 2.5-foot (0.8 m) thick coal, that grades laterally to a carbonaceous mudstone, occurs in the upper portion of the Hell Creek Formation at this site. The contact was not placed at the base of this coal because of the presence of swelling "popcorn weathered" mudstones above this bed. Palynomorph analysis of samples from this site determined that the Cretaceous/Tertiary boundary occurs within a 3.5-inch (8.9 cm) thick interval with a Cretaceous palynomorph assemblage present within the top 2 inches (5 cm) of the mudstone below the coal and a Tertiary palynomorph assemblage present in the basal one inch (2.5 cm) of the coal. Therefore, the K/T boundary is within 1 to 2.5 inches (2.5-6.4 cm) of the contact between the Hell Creek and Ludlow Formations at this site (Figure 21, Plate 2).

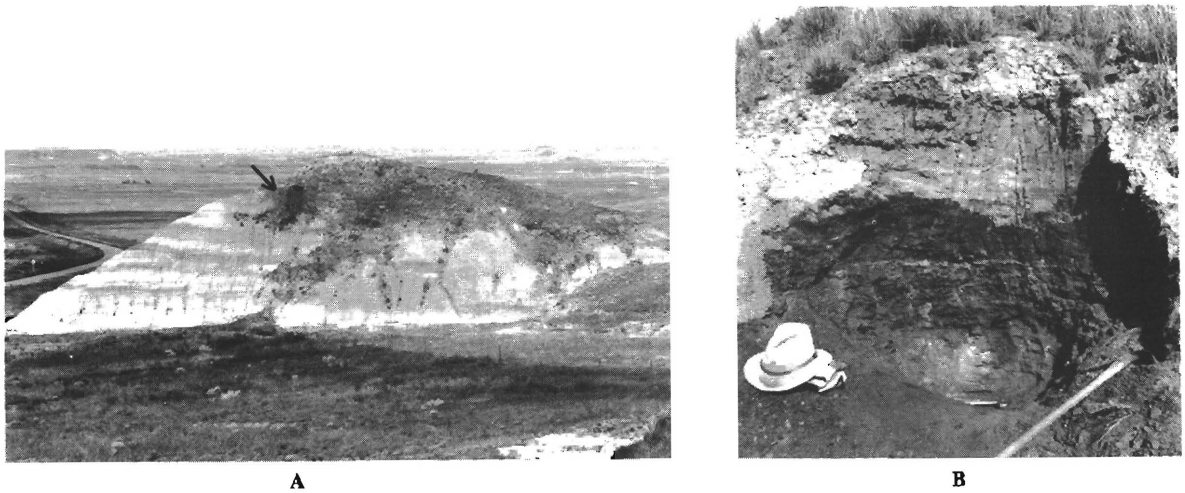
Identifiable leaf fossils were discovered near the base of the Ludlow Formation in the mudstone overlying the basal coal (Appendix C). No vertebrate or invertebrate fossils were found at this locality.

Section no. 18 Location: T130N R85W sec. 23 (se/sw/sw), Sioux County
Landowner: Robert Knispel Top of section: 2140 fasl.



Thickness Ft.	Thickness M.	
		LUDLOW FORMATION
8.8	2.7	Sandstone; yellow/brown (fresh and weathered), very fine to fine grained, coarsens upward, clayey, organic material along bedding planes.
3	0.9	Mudstone; gray/light brown (fresh and weathered), sandy, sand lenses, iron oxide concretions.
2.5	0.8	Lignite.
		HELL CREEK FORMATION
2.5	0.8	Claystone; medium brown (fresh and weathered), carbonaceous, amber, plant fragments.
2	0.6	Claystone; dark brown to dark gray (fresh and weathered), popcorn texture.
2	0.6	Mudstone; gray/brown (fresh and weathered), popcorn texture.
3	0.9	Sandstone; gray (fresh and weathered), very fine grained, clayey, contains leaf fossils, and root traces, jarosite.
2	0.6	Mudstone; medium to dark brown (fresh and weathered), organic rich, carbonaceous.
4.8	1.5	Mudstone; gray/brown (fresh and weathered), silty, popcorn texture.
1.5	0.5	Mudstone; red/brown (fresh), brown (weathered), sandy, organic rich.
6.8	2.1	Mudstone; gray/brown (fresh and weathered), sandy, jarosite, fines upward.
2.5	0.8	Sandstone; gray/brown (fresh and weathered), very fine grained, contains clay lenses, coarsens upward, contains lignite laminae, jarosite, iron oxide staining.
0.5	0.2	Claystone; dark gray (fresh and weathered), carbonaceous, fissile.
3.5	1.2	Mudstone and interbedded claystone; brown to gray/brown (fresh and weathered), organic horizons in the mudstone.
3	0.9	Sandstone; gray (fresh and weathered), very fine grained, poorly indurated, fines upward, iron oxide staining.
11	3.4	Claystone; dark brown (fresh), dark gray/brown (weathered), silty, organic layers, plant fragments, popcorn texture.
11.3	3.4	Interbedded sandstone and mudstone; Sandstone; gray (fresh and weathered), fine grained, jarosite spheres, iron oxide concretions. Mudstone; gray (fresh and weathered), plant fragments and lignite lenses in some mudstone layers, root traces in sandstone.

Figure 22. Measured geologic section no. 18 at the Knispel site, Sioux County.



A B

Figure 23. Photographs of the Knispel site (section no. 18). **A**, East-facing slope of a small hill containing measured section no. 18. Arrow points to the Hell Creek/Ludlow contact. **B**, Pit excavated across the contact between the Hell Creek and Ludlow Formations at section no. 18.

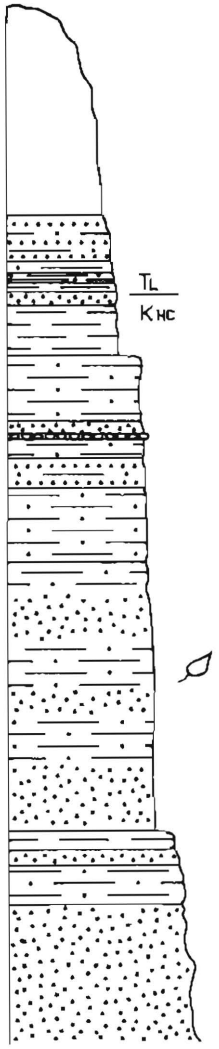
Figure 24. Relationship between the Hell Creek/Ludlow lithostratigraphic contact (at 0) and the Cretaceous/Tertiary boundary interval at the Knispel site (section no. 18). Measurements are distances above and below the lithostratigraphic contact.

Knispel Site (section no. 18)

The Knispel site (section no. 18) is located on the southeast-facing slope of a small hill just north of a county road in section 23 (T130N R85N), Sioux County (Figures 22 and 23). Approximately 56 feet (17 m) of Hell Creek and 14.3 feet (4.3 m) of Ludlow strata are exposed at this site (Figure 22). The Hell Creek/Ludlow contact was placed at the base of a 2.5-foot (0.8 m) thick lignite at this site. This coal has burned to form clinker in the north side of this hill and elsewhere in this area. Several thin, light colored layers are present in the coal but were not identified as tonsteins. The contact between the Hell Creek and Ludlow Formations was placed at the base of the coal and not at the base of the underlying carbonaceous claystone because the general appearance of the claystone, including color and presence of amber, is more characteristic of the Hell Creek Formation. A break in slope at this site coincided with the lithostratigraphic contact. The Cretaceous/Tertiary boundary occurs within a 10-inch (25.4 cm) thick interval that brackets the Hell Creek/Ludlow contact at this locality (Figure 24, Plate 2). This interval extends from 8 inches (20.3 cm) below the top of the carbonaceous claystone that underlies the coal to 2 inches (5.1 cm) above the base of the coal.

Identifiable leaf fossils are present within a Hell Creek sandstone 7 feet (2.1 m) below the lithostratigraphic contact at this site (Appendix C). No vertebrate or invertebrate fossils were noted at this site.

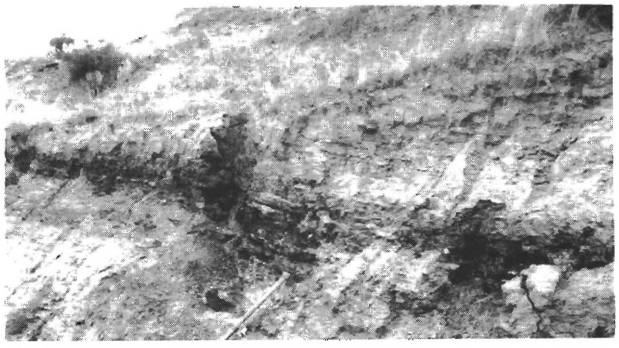
Section no. 24 — Location: T136N R79W sec. 8 (ne/nw/sw), Morton County
Landowner: Bill Miller — Top of Section: 1900 fasl.



Thickness Ft.	Thickness M.	
34	10.4	Covered.
		LUDLOW FORMATION
7.8	2.4	Interbedded Sandstone and Mudstone; [organic rich layer at 7 feet 8 inches(2.4 m)], yellow/brown to gray (fresh and weathered), sandstone is fine grained, iron oxide stained, mudstone is iron oxide stained, iron oxide concretions, organic laminae.
3.4	1.0	Mudstone; black to brown (weathered and fresh), silty, silt lenses at top, lignite lenses throughout, grades laterally into lignite, plant fragments.
		HELL CREEK FORMATION
1.4	0.4	Claystone; gray to brown (fresh and weathered), carbonaceous.
2	0.6	Sandstone; gray (fresh and weathered), very fine grained, jarosite nodules, iron oxide staining, laminae, organic rich.
8.7	2.6	Claystone; black (fresh), light to medium gray (weathered), carbonaceous, plant fragments.
10.3	3.1	Mudstone; gray to red brown, contains selenite, popcorn texture, contains two organic rich lenses, the first is 1 foot (0.3 m) above the base, the second is 2 feet (0.6 m) above the first layer.
2	0.6	Sandstone; gray/brown (fresh and weathered), very fine grained, moderately indurated, silty, jarosite, fines upward,
0.3	0.1	Iron oxide concretion zone.
8	2.4	Mudstone; dark brown at base to gray/brown at top (fresh), medium gray (weathered), sandy, popcorn texture, interbedded sandstone and mudstone, light gray to white sandstone to medium brown mudstone, sandstone layers 1-2 feet (0.3-0.6 m) thick, mudstone 6 inches (15 cm) to 2 feet (0.6 m) thick, sandstone is very fine grained, silty.
11.3	3.4	Mudstone; gray to dark brown (fresh), light gray to medium gray (weathered), sandy in places, popcorn texture.
45.5	13.9	Interbedded sandstone and mudstone; gray/brown to gray (fresh), gray (weathered). Sandstone, fine to medium grained, moderate to poorly cemented, iron oxide chips, contains mudstone clasts. Mudstone; sandy, plant fragments, leaf fossils.
3	0.9	Claystone; olive green at base to dark brown at top (fresh), medium gray (weathered), popcorn surface.
3	0.9	Sandstone; medium brown (fresh), light gray (weathered), very fine grained, no cement.
6.7	2.0	Mudstone; gray/brown (fresh), light gray (weathered), sandy, popcorn, selenite crystals at surface.
23	7.0	Sandstone; light gray (fresh and weathered), very fine to fine grained, moderately indurated, concretionary zones, cross-bedded, organic foresets, clay rich horizons, fines upward, manganese oxide concretions.

Figure 25. Measured geologic section no. 24 at the Miller site, Morton County.

A



B

Figure 26. Photographs of the Miller site (section no. 24). **A**, South-facing slopes of a small hill containing measured section no. 24. Arrow points to cut containing the Hell Creek/Ludlow contact. **B**, The head of the pick marks the contact between the Hell Creek and Ludlow Formations in west-facing roadcut at section 24.

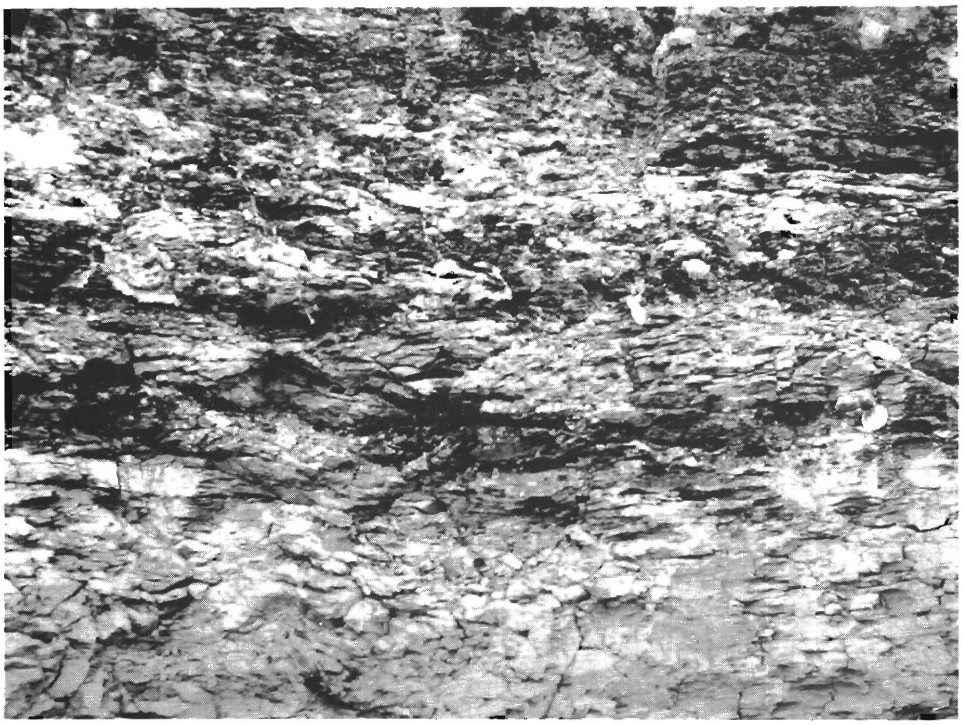


Figure 27. Relationship between the Hell Creek/Ludlow lithostratigraphic contact (at 0) and the Cretaceous/Tertiary boundary interval at the Miller site (section no. 24). Measurements are distances above and below the lithostratigraphic contact.

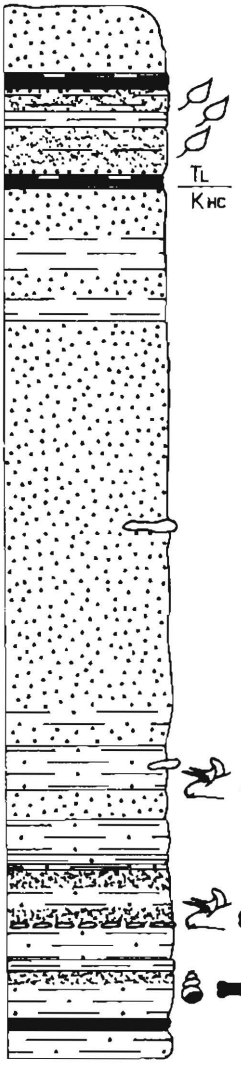
Miller Site (section no. 24)

The Miller site (section no. 24) is located on a small hill situated on the south edge of the Missouri River trench in section 8 (T136N R79W), Morton County (Figures 25 and 26). The lower portion of the section was measured at the southeast face of the hill and the upper portion of the section was measured at a road cut on the west side of the hill. Approximately 120 feet (37 m) of Hell Creek and 20 feet (6 m) of Ludlow strata are exposed at this site (Figure 25). The Hell Creek/Ludlow contact was placed at the base of a carbonaceous mudstone. This mudstone contains sand, silt, and lignite lenses. Both Laird and Mitchell (1942) and Lerbekmo and Coulter (1984) identified the upper portion of this carbonaceous mudstone as a lignite in their sections. Laterally, this mudstone grades into lignite. The underlying claystone is less carbonaceous and contains numerous root traces. The lithostratigraphic contact coincides with a break in slope and the top of the highest occurring swelling "popcorn weathered" claystone.

Thirty palynomorph samples were collected from this site. Twenty-five of these samples were obtained from 4- to-6 inch (10-15 cm) thick intervals at the base of the Ludlow Formation. The Cretaceous/Tertiary boundary occurs within a 4- to-6 inch (10-15 cm) thick interval that straddles the contact between the Hell Creek and Ludlow Formations at this locality (Figure 27, Plate 2). Lerbekmo and Coulter (1984) placed the K/T boundary at this site approximately 10 inches (25 cm) above the position that we chose. They further determined that the K/T boundary interval at this site occurred near the midpoint of polarity zone 29R. Several of the samples we obtained for palynomorph analysis were sent to the Los Alamos Laboratory for iridium analyses, but an iridium anomaly was not detected.

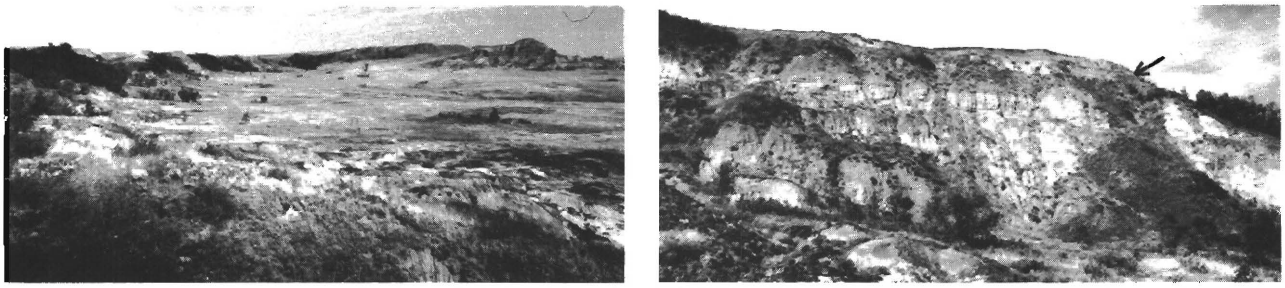
No vertebrate, invertebrate, or plant megafossils were recovered from this site.

Section no. 32 — Location: T136N R79W sec. 28 (nw/sc/se), Morton County
Landowner: John Stumpf — Top of section: 1920 fasl.



Thickness Ft.	Thickness M.	
		LUDLOW FORMATION
11	3.35	Sandstone; yellow/orange to buff (fresh and weathered), silty, very fine grained and poorly cemented.
2.2	0.7	Carbonaceous Layer.
4.0	1.2	Siltstone and Claystone; interbedded, light gray to medium gray (fresh and weathered), iron oxide concretionary layer, fracture fills, contains leaf fossils.
2.8	0.8	Claystone; dark to medium gray (fresh and weathered), interbedded with silt zones, leaf fossils, iron oxide stained top 4 inches (10 cm), organic rich horizons, changes to dark gray/brown (fresh and weathered) at top of unit.
8.3	2.5	Siltstone; gray/brown (fresh and weathered), contains abundant leaf fossils, contains jarosite, and contains very fine sand and clayey zones.
0.7	0.2	Claystone; dark gray/brown (fresh and weathered), carbonaceous clay.
1.3	0.4	Coal.
		HELL CREEK FORMATION
22.5	6.9	Sandstone and Claystone; light gray sand, dark gray claystone (weathered and fresh), layers range in thickness from 4 inches (10 cm) up to 2 feet (0.6 m), iron oxide stained, interbedded.
71.0	21.6	Sandstone; gray to yellow/gray (weathered and fresh), very fine to fine grained, quartz, moderately to poorly cemented, cross-bedded, contains carbonaceous zones, mudstone lenses near base.
7.8	2.4	Mudstone; light gray to gray (weathered and fresh), silty, popcorn texture, FeO concretions 2 feet (0.6 m) below top, contains sequoia cones.
5	1.5	Sandstone; gray to gray/brown (weathered and fresh), very fine grained, FeO staining, FeO concretionary layers.
6	1.8	Mudstone; gray/brown to gray (weathered and fresh), silty, carbonaceous at base and top, popcorn texture, plant fragments.
2	0.6	Mudstone; light gray to gray (weathered and fresh), silty, plant fragments, popcorn texture.
1	0.3	Mudstone; brown (fresh), light gray/brown (weathered), carbonaceous, plant fragments.
14.8	4.5	Mudstone; gray to gray/brown (weathered and fresh), interbedded siltstone and claystone, thin laminae, coarsens upwards to sandstone lenses, carbonaceous mudstone lenses, FeO stained, thin FeO concretions, plant fragments, vertebrate fossils near base.
2	0.6	Claystone; gray (weathered and fresh), fissile.
8	2.4	Mudstone; orange/brown (weathered and fresh), sandy, thin sand lenses, FeO concretions, FeO stained, coarsens upward to sandstone.
1	0.3	Mudstone; dark brown (weathered and fresh), carbonaceous, plant fragments to coal lenses.
1.9	0.6	Coal.
>3	>1	Mudstone; dark brown (fresh) medium brown (weathered), silty, carbonaceous, plant fragments.

Figure 28. Measured geologic section no. 32 at the Stumpf site, Morton County.



A B

Figure 29. Photographs of the Stumpf site (section no. 32). **A**, View to the north along the west edge of the Missouri River trench from section no. 32. **B**, East-facing slope containing measured section no. 32. Arrow points to the Hell Creek/Ludlow contact at the Stumpf site.

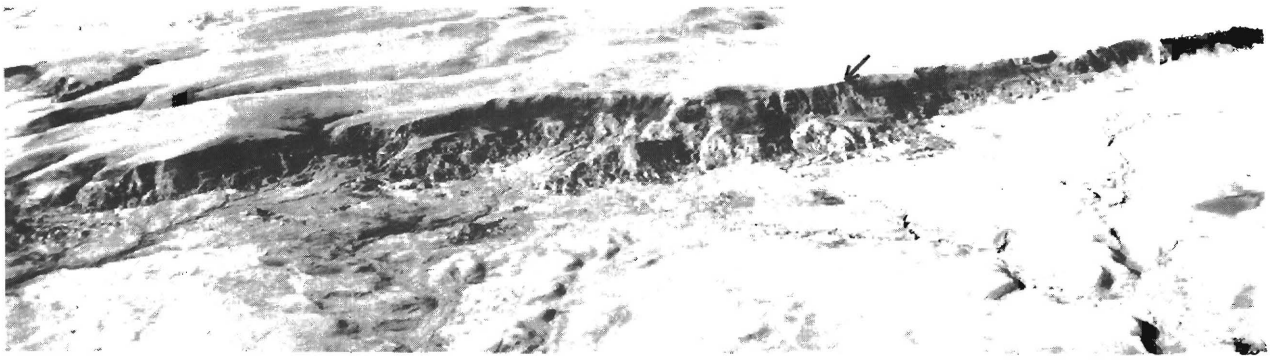


Figure 30. Aerial photograph of the west edge of the Missouri River trench containing the Stumpf site. View is to the west-northwest. Arrow points to section no. 32.

Stumpf Site (section no. 32)

The Stumpf site (section no. 32) is located in badlands terrain on the west edge of the Missouri River trench in section 28 (T136N R79W), Morton County, just a few miles south of the Miller site (section no. 24) (Figures 28-30). Approximately 143 feet (44 m) of Hell Creek and 30 feet (9 m) of Ludlow strata are exposed at this site (Figure 28). The Hell Creek/Ludlow contact was placed at the base of a 15-inch (38 cm) thick coal. This contact coincides with a slight color change. It was determined by palynomorph analysis that the Cretaceous/Tertiary boundary falls within an 11-foot (3.4 m) interval. Samples of the basal Ludlow coal contained a Tertiary palynomorph assemblage and samples from carbonaceous lenses within the underlying Hell Creek mudstone contained a Cretaceous palynomorph assemblage. There were no other carbonaceous beds within this interval to sample for additional palynomorphs. The temporal boundary is likely coincident with, or up to 11 feet (3.4 m) below the contact between the Hell Creek and Ludlow Formations at this site (Plate 2). A two-foot (0.6 m) thick coal is present near the base of the exposed Hell Creek Formation. This coal appears to be of very good quality but, in the absence of outcrops, could not be traced laterally.

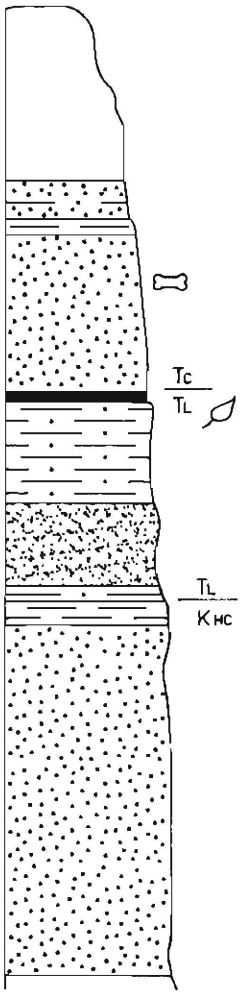
The Stumpf site is by far the most prolific fossil producing site of the localities studied in south-central North Dakota. Hoganson et al. (1994) identified at least 34 taxa of vertebrates, 9 taxa of invertebrates and plant megafossils from the Hell Creek Formation at this site (Appendix C and D). There are four main fossil producing levels at the Stumpf site. Diverse assemblages of vertebrate fossils have been recovered from fluvial deposits of the Hell Creek Formation at positions 102 feet (31 m) and 136 feet (41 m) below the contact of the Hell Creek and Ludlow Formations. These assemblages consist of several species of fish, amphibians, reptiles (including turtles, crocodiles, alligators, champosaurs, and several dinosaur taxa), and mammals, including *Meniscoessus robustus*, all of which are typical of latest Cretaceous northern Western Interior of North America terrestrial faunas (Appendix C and D).

The marine Breien Member of the Hell Creek Formation is exposed 140 feet (42 m) below the Hell Creek/Ludlow contact at the Stumpf site, just below the lowest dinosaur fossil-bearing bed. Marine vertebrate, invertebrate, and trace fossils were recovered from the Breien Member at this site (Appendix C and D). The relationship of the Breien fauna to the Hell Creek terrestrial fauna at this site, and to other Cretaceous and Paleocene marine faunas in south-central North Dakota, is being studied by Hoganson.

Identifiable leaf fossils were noted at three levels in the interval 6 to 14 feet (1.8 to 4.3 m) above the contact between the Hell Creek and Ludlow Formations and at two levels, 102 feet (31 m) and 136 feet (41 m) below the contact at the Stumpf site. Leaf fossils were not collected.

In September, 1994 the Stumpf site was added to North Dakota's Registry of Natural Areas because it is one of North Dakota's most important paleontological sites.

Section no. 23 — Location: T137N R80W sec. 3 (sw/ne/ne), Burleigh County
Landowner: University of Mary — Top of section: 1780 fasl.



Thickness Ft.	Thickness M.	
29	8.8	Covered.
		CANNONBALL FORMATION
6	1.8	Interbedded sandstone and mudstone; gray to gray/brown (fresh and weathered), very fine sand.
2.5	0.8	Claystone; dark brown (fresh), light brown (weathered), carbonaceous.
26	7.9	Sandstone; gray/brown (fresh and weathered), fine to medium grained, moderately cemented, concretions, organic laminae, cross-bedded, iron oxide concretions. Fossils: *Carcharias taurus* (shark), alligator.
		LUDLOW FORMATION
1.5	0.5	Lignite.
17	5.2	Mudstone; dark gray (fresh), light gray (weathered), sandy in places, numerous plant fragments, leaf fossils, carbonaceous zone at 6 feet (1.8 m), iron oxide stained.
13.4	4.1	Sandstone; gray (fresh and weathered), very fine grained, silty, poorly cemented, silt increases upward, jarosite.
3	0.9	Mudstone; light to dark brown (fresh), light brown (weathered), carbonaceous, amber, plant fragments.
		HELL CREEK FORMATION
4	1.2	Claystone; dark to dark brown (fresh), medium gray (weathered), blocky to fissile, popcorn texture.
59	17.9	Sandstone; gray (fresh and weathered), very fine grained, clayey, moderately consolidated, contains organic rich laminae and lenses, iron oxide concretions, popcorn texture on mudstone, contains clay.

Figure 31. Measured geologic section no. 23 at the University of Mary site, Burleigh County.

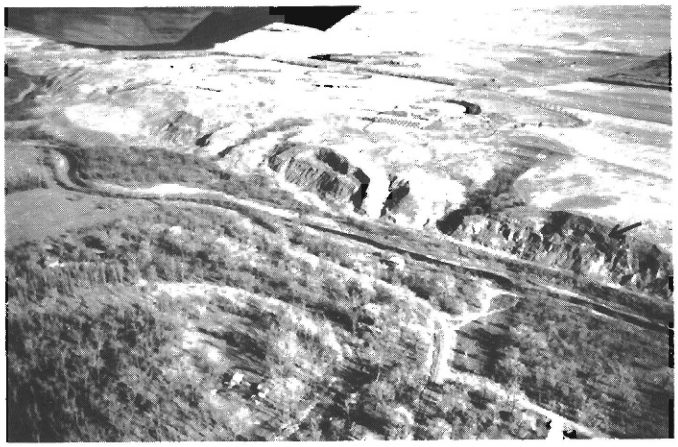
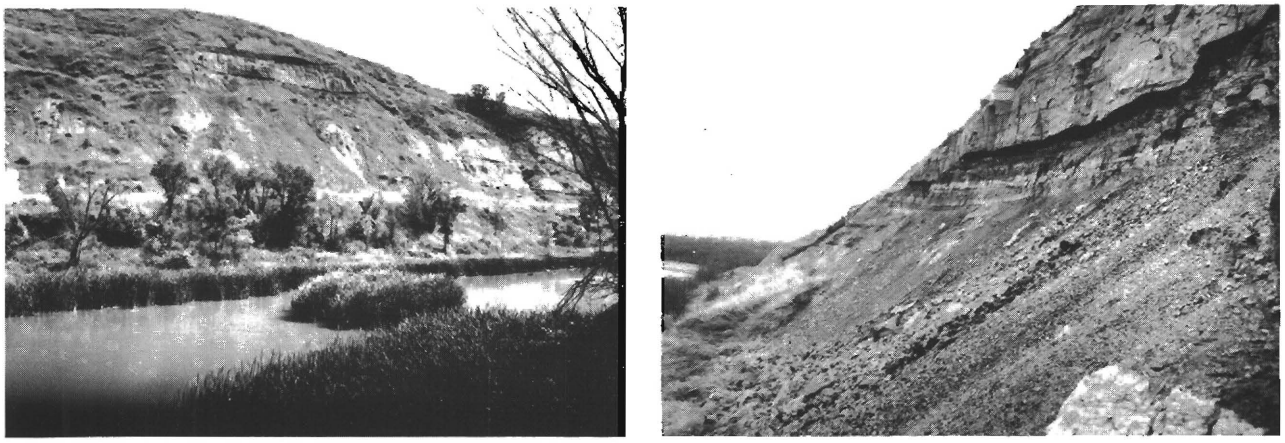


Figure 32. Aerial photograph of the east edge of the Missouri River trench. Arrow points to the University of Mary site (section no. 23).



A B

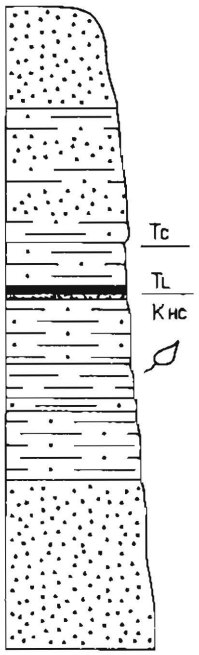
Figure 33. Photographs of the University of Mary site (section no. 23). **A**, West-facing slope beneath the Assumption Priory containing measured section no. 23. **B**, The base of the Cannonball Formation was placed at the top of the thin lignite in this photo.

University of Mary Site (section no. 23)

The University of Mary site (section no. 23) occurs along the west-facing slope of a cut overlooking Apple Creek, just to the southwest of the Annunciation Priory in section 3 (T137N R80W), Burleigh County (Figures 31-33). Approximately 63 feet (19 m) of Hell Creek, 35 feet (11 m) of Ludlow, and 34.5 feet (10.5 m) of Cannonball strata are exposed at this locality (Figure 31). The Hell Creek/Ludlow contact was placed at the base of a carbonaceous mudstone. This contact coincides with the top of the highest observable swelling "popcorn weathered" claystone and with a break in slope. The palynologically defined Cretaceous/Tertiary boundary occurs in the basal 5.5 feet (1.7 m) of the mudstone underlying the coal at this locality. Therefore, the K/T boundary occurs 16.5 to 22.3 feet (5-6.8 m) above the Hell Creek/ Ludlow contact at this site (Plate 2). This section is one of the few sites where the contact between the Hell Creek and Ludlow Formations and the temporal boundary did not closely coincide. It is possible that the Hell Creek/Ludlow contact was not picked correctly at this site and that the true lithostratigraphic contact is 16 feet (4.9 m) stratigraphically higher, i.e., between the sandstone and overlying mudstone. However, despite numerous visits to this site, no field evidence was found to justify changing the position of the contact. As previously noted, it is often difficult to differentiate between Hell Creek and Ludlow sandstones. The highest occurrence of swelling claystone and the break in slope were the determining factors in placing the contact below, rather than above, the sandstone at this locality.

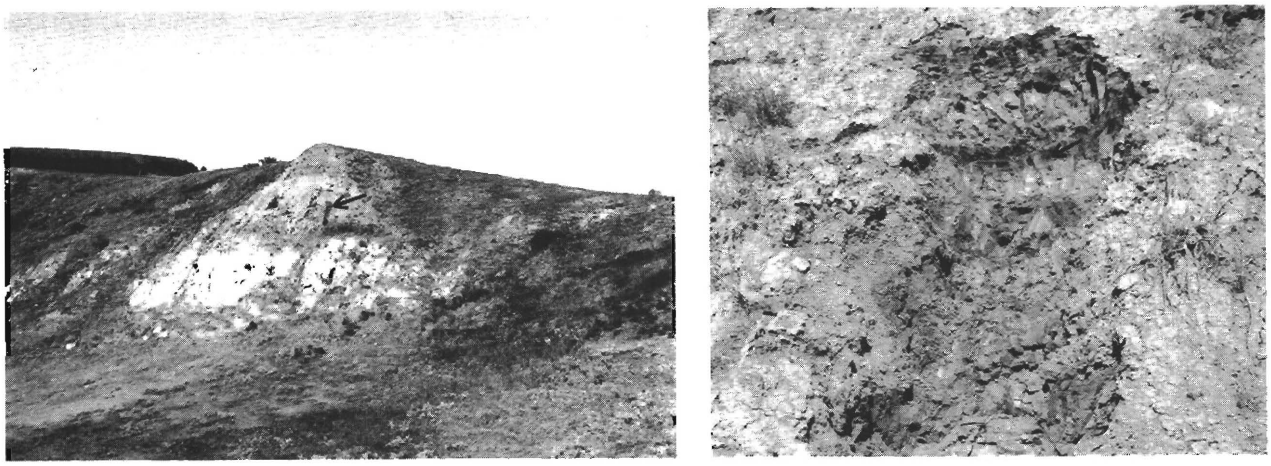
Marine fish fossils, characteristic of the Cannonball Formation, were recovered from the Cannonball Formation at this site (Appendix C). No fossils were found in the Hell Creek or Ludlow Formations.

Section no. 22 Location: T136N R78W sec. 28 (ne/ne/se), Emmons County
Landowner: Ken Snyder Top of section: 2000 fasl.



Thickness Ft.	Thickness M.	
		CANNONBALL FORMATION
17	5.2	Sandstone; gray/brown (fresh and weathered), very fine to fine grained, cross-bedded, poorly cemented, contains clay and organic rich lenses, and concretions.
22	6.7	Mudstone; gray to gray/yellow/brown (fresh and weathered), interbedded sand lenses, very fine grained, iron oxide stained.
		LUDLOW FORMATION
7	2.1	Mudstone; gray to dark brown (fresh), gray (weathered), two (1.5 foot (0.5 m) thick) carbonaceous zones, [one at 2 feet (0.6 m) and one at 5 feet (1.5 m)], numerous root traces.
0.5	0.2	Lignite.
		HELL CREEK FORMATION
1	0.3	Siltstone; light gray (fresh and weathered), clayey, numerous root traces.
11	3.4	Mudstone; brown to black (fresh), light gray (weathered), carbonaceous, contains lignitized wood, clay content increases upward, leaf fossils.
5.8	1.8	Claystone; gray to dark gray (fresh and weathered), blocky.
2	0.6	Mudstone; dark brown (fresh), light brown (weathered), carbonaceous, carbonized wood, amber.
11	3.4	Mudstone; gray (fresh and weathered), sandy, iron oxide staining, jarosite, dark gray clay stringers.
28.5	8.7	Sandstone; gray to gray/brown (fresh and weathered), very fine to fine grained, cross-bedded, moderate to poorly cemented log concretions, organic laminae, 2 foot (0.6 m) thick organic rich foresets near the middle of the unit, interbedded with popcorn weathered mudstone in places, organic rich at the base, iron oxide concretions.

Figure 34. Measured geologic section no. 22 at the Snyder site, Emmons County.



A B

Figure 35. Photographs of the Snyder site (section no. 22). **A**, West-facing slope of a ridge containing measured section no. 22. Arrow points to the contact between the Hell Creek and Ludlow Formations. **B**, Test pit excavated across the Hell Creek/Ludlow contact (arrow) at section no. 22.

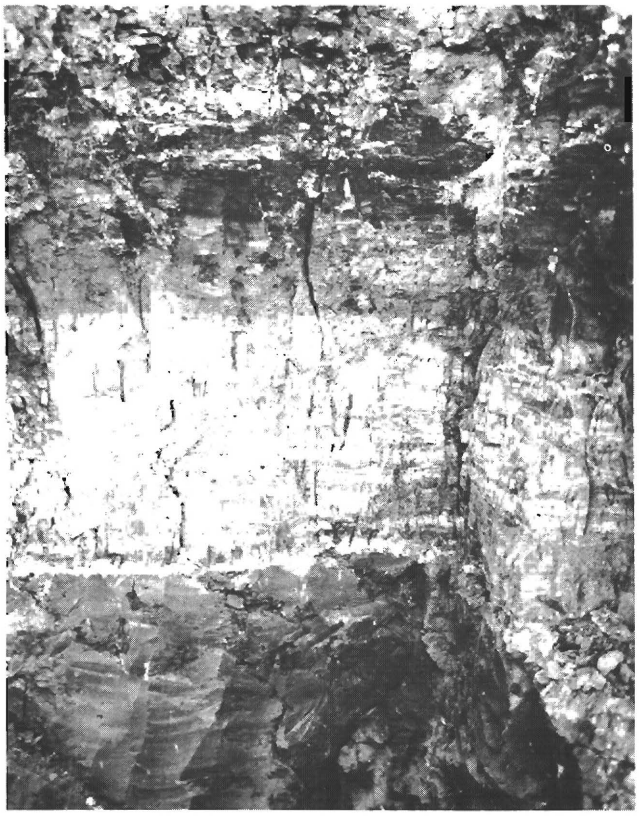


Figure 36. Relationship between the Hell Creek/Ludlow lithostratigraphic contact (at 0) and the Cretaceous/Tertiary boundary interval at the Snyder site (section no. 22). Measurements are distances above and below the lithostratigraphic contact.

Snyder Site (section no. 22)

The Snyder section (section no. 22) is located on a west-facing slope at the east edge of the Missouri River trench in section 28 (T136N R78W), Emmons County (Figures 34 and 35). This section is the easternmost locality that we tested for palynomorphs. Approximately 60 feet (18 m) of Hell Creek, 7.5 feet (2.3 m) of Ludlow, and 39 feet (12 m) of Cannonball strata are exposed at this site (Figure 34). The Hell Creek/Ludlow contact was placed at the base of a 0.5-foot (0.2 m) thick lignite. The contact was placed 11.2 feet (3.4 m) above a slight break in slope corresponding to the highest occurrence of well-exposed swelling claystones and a slight color change, because the intervening mudstone is more characteristic (e.g., contains amber, reddish brown paper claystone, conifer needles, etc.) of typical Hell Creek strata. The Cretaceous/Tertiary boundary occurs within a 12-inch (30 cm) thick interval of siltstone underlying the contact between the Hell Creek and Ludlow Formations (Figure 36, Plate 2).

Identifiable leaf fossils were observed in mudstone 10 feet (3 m) below the top of the Hell Creek Formation (Appendix C). Marine vertebrate (cartilaginous fish) fossils characteristic of the Cannonball Formation were recovered from the basal Cannonball sandstone. No vertebrate or invertebrate fossils were found in the Hell Creek or Ludlow Formations at this site.

SUMMARY

Stratigraphy

The much accepted practice of placing the contact between the Hell Creek and Ludlow Formations at the base of "the lowest persistent bed of lignite" established by Calvert (1912) and followed by subsequent workers is only one of several stratigraphic criteria that can be used to identify this contact in south-central North Dakota. During the course of this study, we placed this stratigraphic contact at the base of a lignite at only 35 percent of the 31 sections. We determined that no single criterion is definitive in identifying the Hell Creek/Ludlow contact throughout south-central North Dakota. The following criteria - the stratigraphically lowest persistent lignite or carbonaceous mudstone, the stratigraphically highest swelling clay, change in slope, color change, and increase in observable bedding - were used in combination to successfully trace this stratigraphic contact in the study area.

Paleontology

Palynologic data indicate that the K/T boundary and the contact between the Hell Creek and Ludlow Formations are essentially coincident at many of the sites, but may be as much as 10 to 20 feet (3-6 m) apart at some of the others. We succeeded in narrowing the stratigraphic interval containing the Cretaceous/Tertiary boundary to within a foot (0.3 m) at eight of the study sites (section nos. 1, 2, 11, 17, 18, 20, 22, and 24) (Table 1). This is consistent with the results of other studies that focused on the relationship between the Cretaceous/Tertiary boundary and the contact between the Hell Creek and Ludlow (or Tullock) Formations in the upper Great Plains (Johnson et al., 1987; Nichols and Fleming, 1990; Swisher et al., 1993). In areas where the Hell Creek/Ludlow contact was difficult to identify (e.g., section nos. 5 and 23), the K/T boundary and contact may be closer than indicated.

Vertebrate fossils were generally sparse at the measured section sites but, where present, support the placement of the K/T boundary as determined by palynological analysis (Appendix C and D). Dinosaur remains were recovered at only 5 of the 32 sites and no articulated dinosaur fossils were found. Dinosaur remains at four of these sites, section nos. 10, 9, 3, and 32, were found 45, 23, 40, and 100 feet (14, 7, 12, and 31 m), respectively, below the base of the Ludlow Formation. The Cretaceous/Tertiary boundary was identified at two of these dinosaur fossil-bearing sites: Katus and Stumpf (nos. 9 and 32). Dinosaur fossils were found 6 to 36 feet (2-11 m) below the K/T boundary at the Katus site and 101 to 111 feet (31-34 m) below the K/T boundary at the Stumpf site. The K/T boundary interval thickness was great at both of these sites due to a lack of carbonaceous beds that could be sampled for palynomorphs. Identifiable leaf fossils were noted at 13 of the stratigraphic sections (Appendix C, Plate 1). Six of these sections contained identifiable leaf fossils within 10 feet (3 m) on either side of the Hell Creek/Ludlow contact. Leaf fossils were not collected during this study.

Boundary Clay, Shocked Minerals, and Iridium

Field observations made at 32 sites in south-central North Dakota indicate that an identifiable boundary clay layer is not present in this area. The work of Johnson et al. (1987, 1989) indicates that an identifiable boundary clay is also not present in southwestern North Dakota. In contrast, a K/T boundary clay layer is commonly recognized in the Raton Basin of New Mexico and Colorado (Pollastro and Pillmore, 1987), the Powder River Basin in Wyoming (Bohor et al., 1987; Nichols and Fleming, 1990; Nichols et al., 1992), the western edge of the Williston Basin in Montana (Bohor et al., 1984), and in the Canadian Provinces of Alberta and Saskatchewan (Nichols et al., 1986; Nichols, 1990; Sweet and Braman, 1992). The absence of a boundary clay layer in North Dakota makes it impossible to accurately identify the K/T boundary in the field without palynological analyses.

Only the Miller site (section no. 24) was tested for iridium. The results of this test did not indicate an iridium anomaly at the palynologically determined K/T boundary although one was detected 2.5 feet above (0.8 m) it. No shocked minerals

Table 1. Relationship of the K/T boundary and the contact between the Hell Creek and Ludlow Formations at measured sections in the study area.

MEASURED SECTION	BOUNDARY LITHOLOGY	BOUNDARY INTERVAL	RELATIONSHIP OF BOUNDARY TO CONTACT
1 -- Rattlesnake Butte	coal/underclay	8 inches (25.4 cm)	4 - 12 inches (10.2 - 30.5 cm) above
2 -- Cannonball Stage Stop	coal/underclay	3 inches (7.6 cm)	1.5 - 4.5 inches (3.8 - 11.4 cm) above
5 -- Fleck	mudstone/siltstone	9 feet (2.7 m)	2 - 11 feet (0.6 -3.4 m) above
9 -- Katus	sandstone/mudstone	30 feet (9.1 m)	12.5 feet (3.8 m) above to 17.5 feet (5.3 m) below
11 -- Brenner	coal	11 inches (27.9 cm)	2.5 - 3.4 feet (0.76 -1.04 m) above
17 -- Standing Rock Sioux	coal/mudstone	1 foot (0.3 m)	9 inches (22.9 cm) above to 3 inches (7.6 cm) below
18 -- Knispel	coal/underclay	10 inches (25.4 cm)	2 inches (5.1 cm) above to 8 inches (20.4 cm) below
20 -- Schaeffer	coal/underclay	3.5 inches (8.9 cm)	1 inch (2.5 cm) above to 2.5 inches (6.4 cm) below
22 -- Snyder	siltstone	1 foot (0.3 m)	0 - 12 inches (0 - 30.5 cm) below
23 -- University of Mary	mudstone	5.5 feet (1.7 m)	16.5 to 22.3 feet (5 to 6.8 m) above
24 -- Miller	mudstone	4-6 inches (10-15 cm)	3 inches (7.6 cm) above to 3 inches (7.6 cm) below
32 -- Stumpf	mudstone	11 feet (3.35 m)	0-11 feet (0-3.4 m) below

were identified in the sediment cores obtained from the K/T boundary intervals at six of the study sites (section nos. 1, 2, 11, 18, 20, and 24). Very few sand-size grains were extracted from the Cretaceous/Tertiary boundary interval in these cores. It is possible that the sampling procedure missed areas that contained ejecta grains because cores are only one inch (2.5 cm) in diameter. The absence of shocked grains may therefore, be the result of sampling bias that could be corrected by taking a larger sample of the boundary interval.

Cretaceous/Tertiary Event

We were able to identify the Cretaceous/ Tertiary boundary at several localities in south-central North Dakota by application of palynological criteria that have been used in other parts of the western region of North America. Our results corroborate numerous other studies done throughout the Western Interior of North America, that a significant reduction or extinction of plant taxa, that had thrived during the Cretaceous, took place at this point in geologic time. The general sparsity of dinosaur remains observed in the Hell Creek Formation at the sites studied does not allow us to speculate on whether the demise of dinosaurs at the end of the Cretaceous was sudden or gradual.

The absence of boundary clay, iridium anomalies, and shocked minerals at the K/T boundary sites does not necessarily provide evidence against the theory of extraterrestrial impact at the end of the Cretaceous. In the Western Interior of North America, shocked minerals and an iridium anomaly generally occur in an exceedingly thin layer at the top of the K/T boundary clay (Izett, 1990). Without the boundary clay as a guide, it is extremely difficult to adequately sample for this layer. Therefore, our inability to find shocked minerals and an iridium anomaly or a visible boundary clay at the boundary should not necessarily be used as evidence against a major impact event. Johnson et al. (1989) interpreted the absence of a boundary clay at their Pyramid Butte site in southwestern North Dakota to be the result of a local unconformity. However, that is not a viable explanation for the absence of a boundary clay in at least six of our study sites where the K/T boundary occurs in a coal or between a coal and an underlying carbonaceous mudstone, where unconformities would not be expected and where one would expect impact ejecta to be preserved. Therefore, other explanations for the absence of a boundary clay must be considered. Although mixing of the ejecta glass with detrital material may have contributed to the absence of a recognizable boundary clay at some of the sites, it does not serve as an adequate explanation for all six of the previously mentioned sites, because mixing (excluding bioturbation) is not generally common in swamp or lacustrine settings. If the impact theory is correct, the absence of a boundary clay in south-central North Dakota may indicate a greater distance from the impact site, compared to other sites in the Western Interior of North America. It is also possible that wind currents and precipitation caused an uneven distribution of ejecta over the Earth's surface resulting in selective deposition of boundary clay sediments.

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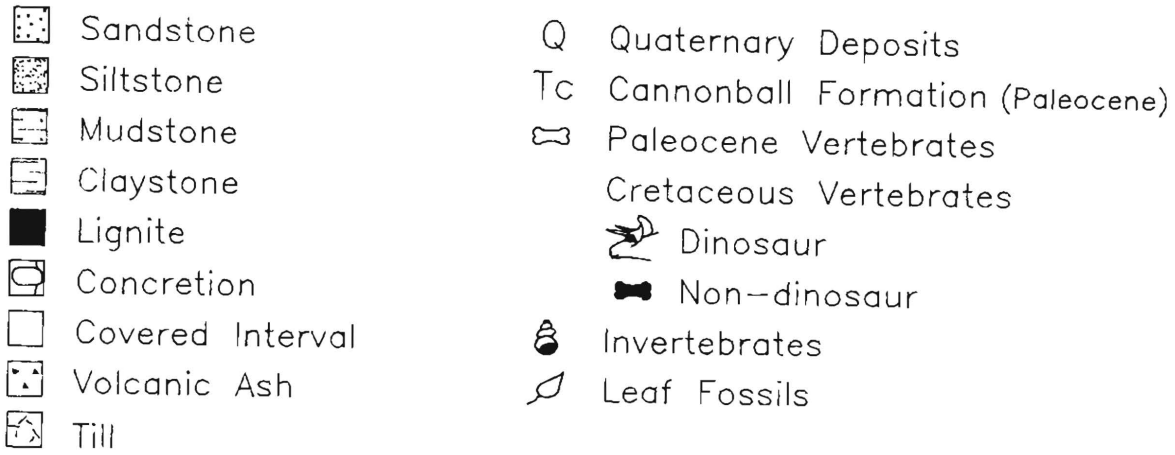
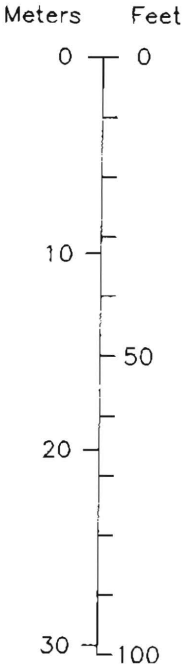
APPENDIX A
Explanation of Symbols Used on Stratigraphic Columns

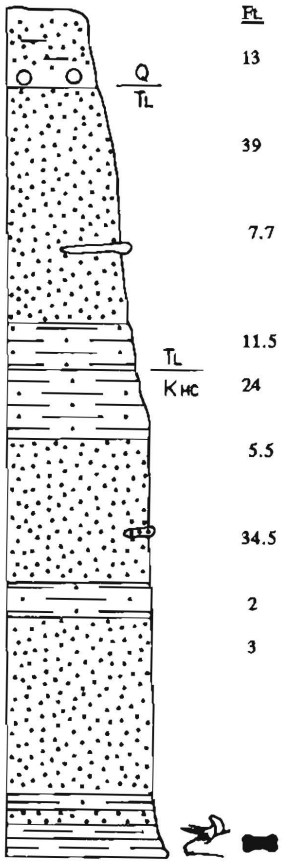


Vertical scale for all measured sections in text.



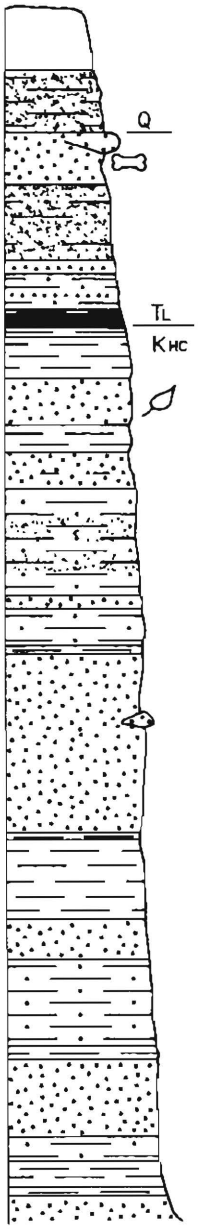
APPENDIX B
Additional Measured Sections

Section no. 3 — Location: T131N R86W sec. 35 (c n1/2), Grant County
Landowner: Campbell Brothers — Top of section: 2145 fasl.



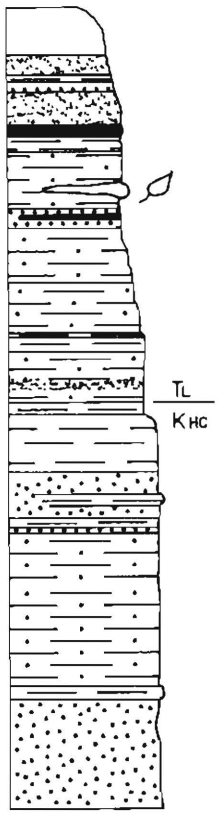
Thickness Ft.	Thickness M.	
		QUATERNARY
13	3.9	Loam; gray/brown (fresh and weathered) gravel at base.
		LUDLOW FORMATION
39	11.9	Sandstone; light yellow/green/gray (fresh), light gray to orange (weathered), fine to very fine grained, poorly lithified, limonite concretions and spheres, organic lenses, iron oxide stained, iron oxide concretionary layer at 11 feet (3.4 m).
7.7	2.4	Mudstone; light gray to light brown (fresh), light brown (weathered), silty clay, carbonaceous, plant fragments, amber.
		HELL CREEK FORMATION
11.5	3.5	Mudstone; light gray to light brown (fresh), light gray (weathered), silty clay to clayey silt, popcorn texture.
24	7.3	Sandstone; yellow brown (fresh) to light gray (weathered), fine grained, clean, poorly cemented, weakly lithified, contains organic lenses, concretionary zones, fines upward, cross-bedded.
5.5	1.7	Claystone; light to medium brown (fresh), light gray (weathered), popcorn texture, very carbonaceous in the upper half, very dark brown claystone with lignite fragments, contains iron oxide stained zones, contains amber.
34.5	10.5	Sandstone; green/gray (fresh) to light gray (weathered), fine grained, very well lithified, well sorted, cross-bedded, contains 1/2 to 2 foot (0.2-.6 m) thick carbonaceous clay zones with plant fragments.
2	0.6	Claystone; light gray to light brown (fresh), light gray (weathered), silty, plant fragments, blocky.
3	0.9	Claystone; medium to dark brown (fresh), light gray to black (weathered), silty, carbonaceous, contains carbonized wood near the top, jarosite. Fossils: unidentified dinosaur bones found at base of section.

Section no. 4 — Location: T130N R86W sec. 1 (ne/nc/ne), Grant County
Landowner: Campbell Brothers — Top of section: 2130 fasL



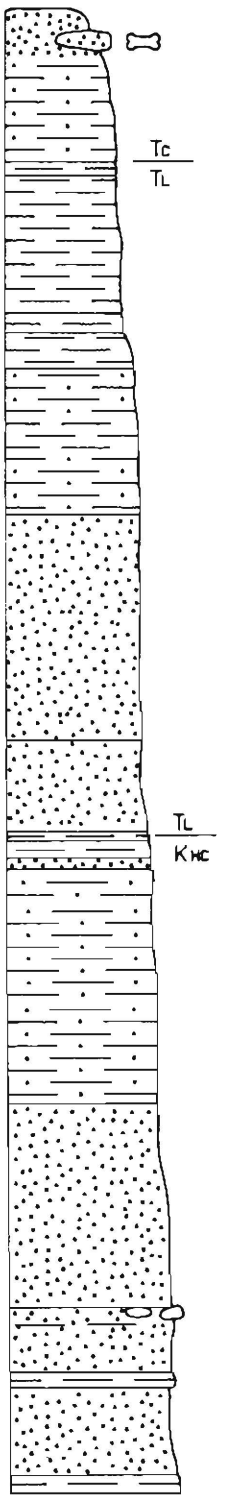
Thickness Ft.	Thickness M.	
10	3.0	QUATERNARY Covered interval.
10	3.0	Loam.
		LUDLOW FORMATION
8	2.4	Sandstone; light yellow/gray (fresh), light gray (weathered), fine grained, poorly cemented, cross-bedded, iron oxide stained, contains concretions at the top. Fossils: lepisosteid (gar) scale.
13	3.9	Mudstone; light gray/brown (fresh), yellow/brown (weathered), interbedded with silt and silty clay, iron oxide stained, fissile, pyrite sphericules, iron oxide concretionary layers.
2	0.6	Sandstone; gray to brown (fresh), purple to brown (weathered), fine grained, contains numerous organic lenses.
6	1.8	Mudstone; light gray/brown (fresh), light gray (weathered), interbedded sandstone, silt and clay, contains carbonaceous clay bed in middle of unit.
0.2	0.1	Claystone; dark brown (fresh), light brown (weathered), carbonaceous, contains plant fragments.
2	0.6	Mudstone; dark gray/black fresh and weathered surfaces.
1	0.3	Mudstone; medium to dark red/brown fresh and weathered surfaces.
		HELL CREEK FORMATION
7	2.1	Claystone; medium to dark brown (fresh), medium gray (weathered), carbonaceous, contains plant fragments, popcorn texture, dark brown to black fissile at the top.
7.7	2.4	Sandstone; gray/brown (fresh), light gray (weathered), very fine to fine grained, organic lenses, poorly cemented, clayey, contains leaf fossils.
4	1.2	Claystone; dark brown (fresh), light brown (weathered), silty, iron oxide concretions at the base.
5	1.5	Sandstone; dark gray to light gray/orange (fresh), light gray (weathered), very fine to fine grained, silt/clay (organic rich) stringers.
17	5.2	Mudstone; light gray to medium brown (fresh), light gray to dark gray/black (weathered), silty clay to clay silt, contains carbonaceous horizons, abundant plant fragments, popcorn texture.
2	0.6	Sandstone; light yellow/gray (fresh), light gray (weathered), iron oxide stained, very fine to fine grained.
6	1.8	Mudstone; light to medium gray (fresh), light gray (weathered), silty claystone, contains plant fragments.
1	0.3	Organic horizon; carbonaceous clay, light to dark brown to red/brown (fresh), black (weathered).
30	9.1	Sandstone; light gray to green (fresh), light yellow/gray (weathered), fine grained, poorly cemented, contains organic lenses and concretionary zones, contains manganese oxide concretions, 1-2 foot (0.3-0.6 m) -thick organic horizon at base.
13	3.9	Claystone; light gray to dark brown (fresh), light to medium gray (weathered), silty, carbonaceous in places, popcorn texture.
7	2.1	Sandstone; light gray/brown (fresh), light gray (weathered), fine grained, poorly cemented, well sorted.
14	4.3	Mudstone; light to medium gray/brown (fresh), light gray (weathered), clayey silt to silty clay, contains plant fragments, carbonaceous zones, popcorn texture at top.
2	0.6	Organic horizons.
13	3.9	Sandstone; light green/gray (fresh), light gray (weathered), very fine to fine grained, cross-bedded, poorly cemented, iron oxide staining, fines upward to clayey sandstone, contains organic lenses.
4	1.2	Mudstone; dark brown (fresh), light to medium gray (weathered), carbonaceous.
4	1.2	Claystone; dark gray (fresh), light to medium gray (weathered), silty, popcorn texture.
2	0.6	Organic horizon; dark brown (fresh), light black (weathered), silty/granular, jarosite.
8.7	2.7	Sandstone; medium gray to brown (fresh), light gray (weathered), silty, poorly cemented, iron oxide staining.

Section no. 5 Location: T134N R82W sec. 11 (se/nw/sw), Morton County
Landowner: Clarence Fleck Top of section: 1990 fasl.



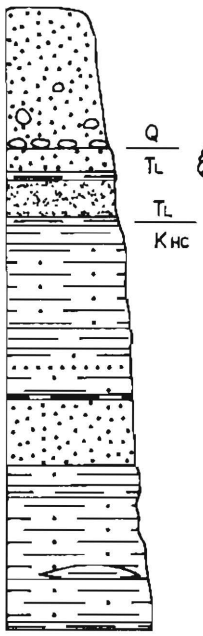
Thickness Ft.	Thickness M.	
8	2.4	Covered.
		LUDLOW FORMATION
3	0.9	Siltstone; light yellow/gray (fresh and weathered).
1	0.3	Claystone; medium brown (fresh and weathered), carbonaceous.
8	2.4	Siltstone; light to medium gray (fresh), light yellow/gray (weathered), iron oxide stained, iron oxide chips, coarsens to sandstone at top.
4	1.2	Claystone; dark brown to black (fresh and weathered), carbonaceous, grads to lignite at the top of unit, contains plant fragments and amber.
9	2.7	Mudstone; light to medium gray (fresh), light gray/brown (weathered), selenite crystals, iron oxide stained, iron oxide chips and concretions, contains leaf fossils.
3	0.9	Sandstone; light gray (fresh and weathered), very fine grained, contains interbedded carbonaceous claystone at the top, contains jarosite.
9	2.7	Mudstone; medium brown (fresh), light gray (weathered), plant fragments, iron oxide chips (the base of the unit is at the 2nd major break in slope).
8	2.4	Mudstone; light gray/brown (fresh and weathered), contains silt zones, contains iron oxide concretions, contains selenite and jarosite.
3	0.9	Claystone; medium to dark brown (fresh and weathered), carbonaceous, black paper shale at the top.
9	2.7	Mudstone; light to medium gray/brown (fresh and weathered), silty, laminated, contains 1 foot (0.3 m)-thick silt lens, contains 2 inch (5 cm) thick lignite stringer.
		HELL CREEK FORMATION
2	0.6	Mudstone; light to medium brown (fresh and weathered), carbonaceous, contains amber.
9	2.7	Claystone; gray/brown (fresh and weathered), silty, popcorn texture, contains plant fragments (the top of the unit is the 1st major break in the slope).
8	2.4	Sandstone; light gray (fresh and weathered), very fine grained, contains 1 foot (0.3 m)-thick carbonaceous clay bed in middle of the unit, contains numerous claystone lenses.
1.5	0.5	Claystone; medium brown/black (fresh), light brown (weathered), carbonaceous.
0.3	0.1	Sandstone; light gray (fresh and weathered), very fine grained, poorly cemented.
25.7	7.8	Mudstone; light to medium brown (fresh), light gray (weathered), sandy, contains numerous plant fragments, roots.
2.5	0.8	Claystone; dark brown/black (fresh and weathered), contains amber, carbonaceous.
18	5.5	Sandstone; gray/light brown (fresh and weathered), fine to medium grained, cross-bedded, organic laminae, fines upward.

Section no. 6 — Location: T134N R81W sec. 16 (se/ne/sw), Morton County
Landowner: State — Top of section: 2000 fasl.



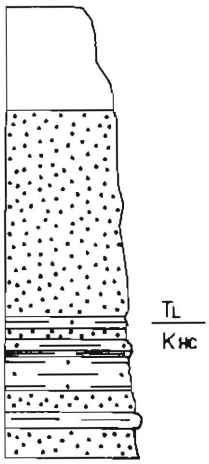
Thickness Ft.	Thickness M.	
		CANNONBALL FORMATION
25	7.6	Mudstone; gray/brown (fresh and weathered), contains very well cemented sandstone lenses which thicken upward, shark teeth in sandstone.
		LUDLOW FORMATION
2	0.6	Claystone; medium to dark brown (fresh and weathered), carbonaceous.
23	7.0	Claystone; light gray to brown (fresh and weathered), silty, some silt lenses, iron oxide chips.
3	0.9	Claystone; light gray to brown (fresh and weathered), carbonaceous, lignite stringers, (staked).
2	0.6	Claystone; medium to dark brown/black (fresh and weathered).
6	1.8	Claystone; medium gray (fresh and weathered), silty, popcorn texture.
24	7.3	Mudstone; light to medium gray (fresh and weathered), contains 1 to 2 foot (0.3-0.6 m)-thick carbonaceous clay lenses near center of the unit.
38	11.6	Sandstone; light gray/green (fresh and weathered), very fine to fine grained, silty, cross-bedded.
15	4.6	Sandstone; light reddish/brown (fresh and weathered), very fine to fine grained, poorly cemented, iron oxide stained, silty.
1	0.3	Claystone; black (fresh and weathered), carbonaceous to lignitic (staked).
		HELL CREEK FORMATION
3	0.9	Mudstone; light to medium brown (fresh and weathered).
2	0.6	Sandstone; light gray (fresh and weathered), very fine grained, silty, poorly cemented, iron oxide stained.
39	11.9	Mudstone; dark to medium brown (fresh), light gray/brown (weathered), contains carbonaceous zones, contains 2 to 3 foot (0.6 0.9 m)-thick sandstone lenses near top of unit, popcorn texture.
34	10.4	Sandstone; light gray (fresh and weathered), fine to medium grained, poorly sorted, poorly cemented, cross-bedded (trough), organic rich lenses, micaceous.
11	3.4	Sandstone; light gray (fresh and weathered), fine grained, poorly cemented, contains numerous clay lenses at top of the unit, contains iron oxide concretions at top of the unit.
2	0.6	Claystone; medium brown (fresh and weathered).
15	4.6	Sandstone; light gray (fresh and weathered), fine grained, poorly cemented, some clay lenses, clay content increases upward.
3	0.9	Claystone; medium to dark brown (fresh and weathered), carbonaceous, lignitic lenses, contains plant fragments.

Section no. 7 | Location: T134N R83W sec. 24 (sw/nw/nw), Morton County
Landowner: Joe Keller | Top of section: 1920 fasl.



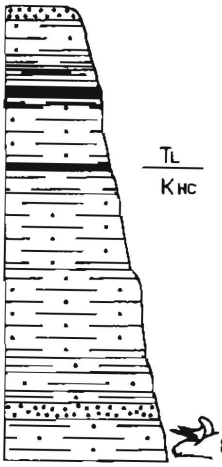
Thickness Ft.	Thickness M.	
		QUATERNARY
23	7.0	Covered; mostly sand and gravel (Pleistocene outwash).
		LUDLOW FORMATION
4	1.2	Sandstone; yellowish to reddish brown (fresh), light gray/yellow (weathered), very fine grained, clayey, iron oxide stained, fossiliferous.
1	0.03	Claystone; reddish brown to dark gray (fresh), light gray (weathered), carbonaceous.
6	1.8	Siltstone; light gray to yellow/brown (fresh), light gray (weathered), clayey, iron oxide concretionary layers, also contains clay rich layers.
1.5	0.5	Claystone; reddish brown (fresh), light gray (weathered), carbonaceous.
		HELL CREEK FORMATION
3	0.9	Claystone; medium to dark gray (fresh), light gray (weathered), blocky to fissile.
14	4.3	Mudstone; reddish brown to medium gray (fresh), light gray (weathered), contains plant fragments, iron oxide staining.
3	0.9	Claystone; medium reddish/brown (fresh), medium gray (weathered), carbonaceous, contains lignite lenses.
8	2.4	Mudstone; light to medium gray/brown (fresh and weathered), contains 2 foot (0.6 m)-thick sand lens, plant fragments, jarosite.
0.5	0.2	Claystone; dark gray/black (fresh), light gray to medium gray (weathered), carbonaceous, shaley.
11	3.4	Sandstone; light gray/brown (fresh), light gray (weathered), fine to medium grained, poorly sorted, poorly to moderately cemented, contains organic rich lenses, fines upward.
3	0.9	Claystone; dark gray-gray (fresh), light to medium gray (weathered), popcorn texture.
2	0.6	Claystone; light reddish-brown/black (fresh and weathered), carbonaceous.
13.3	4.0	Mudstone; light gray/brown (fresh), light gray (weathered), silty, 1 foot (0.3)-thick carbonaceous lens at base, unit fines upward.
7.8	2.4	Mudstone; gray/brown (fresh), light to medium gray (weathered), contains prominent dark gray layer.
0.5	0.2	Claystone; light to medium brown (fresh and weathered), carbonaceous, contains lignite lenses.

Section no. 8 — Location: T134N R83W sec. 16 (sc/nw/sw), Morton County
Landowner: State — Top of Section: 1980 fasl.



Thickness Ft.	Thickness M.	
17	5.2	Covered.
		LUDLOW FORMATION
34	10.4	Sandstone; yellow/brown (fresh), light gray/brown (weathered), very fine to fine grained, clayey, poorly indurated, contains organic rich lenses, cross-bedded, concretions, iron oxide concretions, interbedded with claystone.
		HELL CREEK FORMATION
2	0.6	Mudstone; gray to brown (fresh), gray to gray/brown (weathered), sandy, carbonaceous at top.
1.5	0.5	Sandstone; light gray to gray (fresh), light gray (weathered), clayey, iron oxide stained.
2	0.6	Mudstone; dark gray to gray (fresh), light gray (weathered), contains plant fragments, dark organic rich zones.
0.5	0.2	Claystone; dark gray (fresh), light gray (weathered), carbonaceous.
5.5	1.7	Mudstone; gray (fresh), light gray (weathered), plant fragments, popcorn texture.
3.5	1.1	Sandstone; buff (fresh), light gray (weathered), very fine grained, poorly cemented, cross-bedded at top, contains organic lenses, jarosite nodules.
2.5	0.8	Claystone; dark brown to black (fresh), medium brown (weathered), carbonaceous, lignite pods.
5	1.5	Sandstone; gray/brown (fresh), light gray (weathered), very fine grained, silty, fines upward, contains clay lenses.

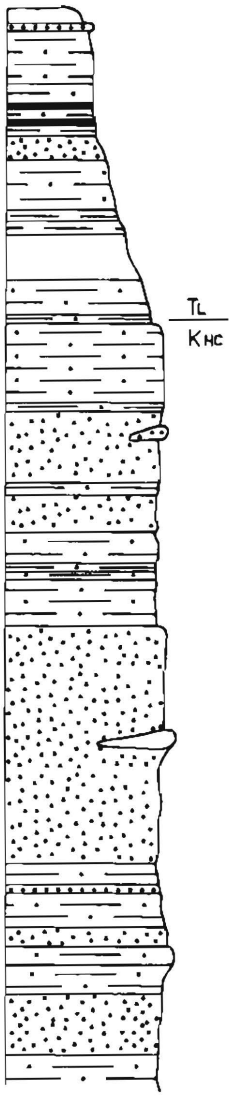
Section no. 10 — Location: T130N R88W sec. 35 (nenwse), Grant County
Landowner: Jim McGregor — Top of section: 2200 fasl.



Thickness Ft.	Thickness M.	
		LUDLOW FORMATION
2	0.6	Sandstone; gray (fresh), gray/yellow (weathered), silty, very fine grained, poorly cemented.
5.7	1.7	Mudstone; yellow/gray (fresh and weathered), iron oxide stained, iron oxide concretions, plant fragments, iron oxide concretionary layer at the top.
1.5	0.5	Claystone; gray/brown (fresh), yellow/brown (weathered), blocky, plant fragments, carbonaceous.
3.7	1.1	Claystone; dark brown (fresh), gray/brown (weathered), carbonaceous, contains 3 to 4 thin lignite beds.
2	0.6	Lignite.
1	0.3	Claystone; reddish brown (fresh), gray/brown (weathered), carbonaceous.
10	3.1	Covered.
0.5	0.2	Lignite.
		HELL CREEK FORMATION
4	1.2	Claystone; dark brown to black (fresh), light gray (weathered), blocky, contains plant fragments.
13	3.9	Mudstone; gray/brown(fresh), gray (weathered), sandy, contains amber, clay rich horizons, jarosite, contains plant fragments.
15	4.6	Mudstone; reddish brown (fresh), light gray/brown (weathered), sandy horizons, iron oxide stained, contains lignite fragments, plant fragments, amber, iron oxide concretions.
2.5	0.8	Mudstone; purple/brown (fresh), purple/gray (weathered), clayey, iron oxide stained, plant fragments.
3	0.9	Mudstone; gray/brown(fresh), light gray/brown(weathered), clayey, iron oxide concretions, plant fragments, selenite, popcorn textured.
2	0.6	Mudstone; gray/brown (fresh), light gray/gray (weathered), silty, plant fragments.
3	0.9	Sandstone; yellow/brown (fresh), gray (weathered), clayey, very fine grained, popcorn texture.
7	2.1	Mudstone; olive gray/brown (fresh), olive/gray (weathered), sandy at base, iron oxide concretions, plant fragments in sandy lenses.

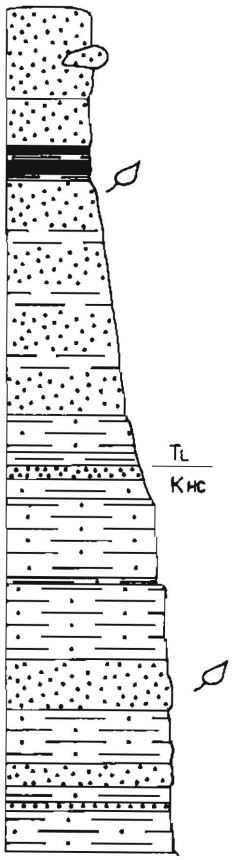
Note: Numerous dinosaur, turtle and crocodile bone fragments were noted in a clay rich mudstone adjacent to the mudstone at the base of the measured section.

Section no. 12 Location: T131N R85W sec. 20 (neseaw), Grant County
Landowner: Duane Voight Top of section: 2120 fasl.



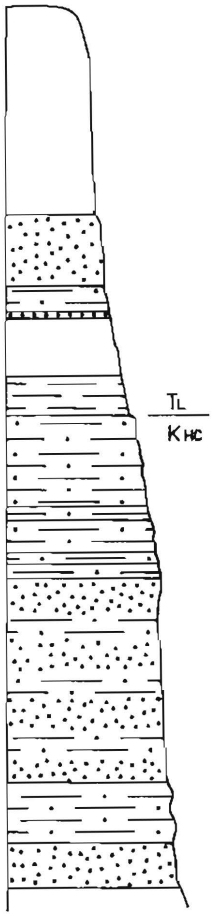
Thickness Ft.	Thickness M.	
2	0.6	Covered.
		LUDLOW FORMATION
1	0.3	Sandstone; gray/brown (fresh and weathered), very fine grained, moderately cemented, forms a ledge at top of the slope.
8.8	2.7	Mudstone; reddish/brown to orange (fresh), yellow/gray (weathered), sandy intervals, iron oxide stained, iron oxide concretions, plant fragments, sandy at top of the unit.
5.8	1.8	Mudstone; gray/brown (fresh), light gray (weathered), contains a thin 4 inch (10 cm)-thick lignite layer in the middle of the unit and a black, blocky carbonaceous clay at the top.
2.5	0.8	Claystone; reddish brown (fresh), light brown (weathered), plant fragments, upper 1 foot (0.3 m) contains lignite.
3.8	1.1	Sandstone; gray/brown (fresh), light gray/brown (weathered), very fine grained, micaceous, small iron oxide concretions, micaceous.
8	2.4	Claystone; gray/brown (fresh), light brown (weathered), sandy lenses, iron oxide stained, fissile.
2	0.6	Claystone; black (fresh), gray (weathered), silty, very organic rich, carbonaceous, fissile.
2	0.6	Claystone; olive/gray (fresh), gray/brown (weathered), silty, contains plant fragments, blocky.
7.3	2.2	Colluvium.
5.8	1.8	Mudstone; gray/brown to black (fresh and weathered), contains thin (less than 1 foot (0.3 m)-thick) lignite beds, carbonaceous claystone, contains plant fragments.
1	0.3	Mudstone; brown (fresh), light gray/brown (weathered), plant fragments, contains 2 inch (5 cm) thick white siltstone.
		HELL CREEK FORMATION
13.3	4.0	Mudstone; gray/brown (fresh), gray (weathered), blocky, plant fragments, amber, iron oxide concretions, popcorn texture.
0.8	0.2	Mudstone; reddish brown (fresh), gray/brown (weathered), carbonaceous, plant fragments, lignite stringers, amber abundant.
12.3	3.7	Sandstone; gray/brown (fresh and weathered), fine grained, fines upward, clayey at top, organic rich horizons, log concretions, iron oxide concretions.
2	0.6	Mudstone; gray/brown (fresh and weathered), popcorn texture, plant fragments.
6	1.8	Sandstone; gray/brown (fresh and weathered), fine to medium grained, organic rich lenses, cross-bedded.
4.8	1.4	Mudstone; gray/brown (fresh), gray/brown (weathered), plant fragments, roots, popcorn texture.
2	0.6	Mudstone; gray/brown (fresh), gray (weathered), plant fragments, roots and stems.
1	0.3	Mudstone; dark brown to black (fresh and weathered), carbonaceous, amber, plant fragments.
7.8	2.4	Mudstone; gray/brown (fresh and weathered), popcorn texture, contains carbonaceous claystone.
39.4	12.0	Sandstone; gray/brown (fresh and weathered), fine to medium grained, variable clay content throughout, organic lenses, contains prominent concretionary ledges, cross-bedded, iron oxide concretions.
4	1.2	Mudstone; gray/brown (fresh and weathered), sandy, roots, plant fragments, iron oxide concretions.
1	0.3	Sandstone; gray/brown (fresh), gray (weathered), clayey, very fine grained, poorly cemented.
6	1.8	Mudstone; gray/brown (fresh and weathered), plant fragments, roots, popcorn texture.
3	0.9	Sandstone; gray/brown (fresh and weathered), clayey, very fine grained, organic rich, plant fragments.
3	0.9	Mudstone; reddish brown (fresh), gray brown to brown (weathered), very organic rich, ledge former, 6 inches (15 cm) to 1 foot (0.3 m) of lignite at top of the unit.
5	1.5	Mudstone; reddish brown to brown (fresh), gray/brown to dark gray (weathered), sandy at base, fines upward, organic rich at top.
10	3.1	Sandstone; gray/brown (fresh and weathered), medium to coarse grained, poorly sorted, organic rich lenses, cross-bedded.
5	1.5	Mudstone; gray/brown (fresh), light gray (weathered), iron oxide stained.

Section no. 13 Location: T130N R85W sec. 14 (ne/ne/se), Grant County
Landowner: Merril Ten Broek Top of section: 2140 fasl.



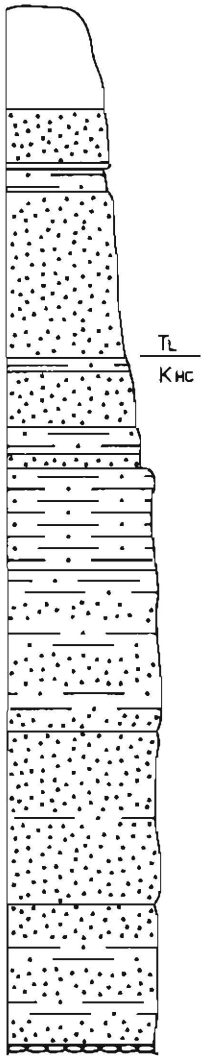
Thickness Ft.	Thickness M.	
		LUDLOW FORMATION
15	4.6	Sandstone; yellow to brown (fresh and weathered), very fine to fine grained, poorly indurated, sandstone concretions.
8	2.4	Sandstone; gray to brown (fresh), yellow to brown (weathered), very fine grained, contains dark gray clay lenses, iron oxide chips.
0.8	0.2	Lignite; highly weathered - leonardite.
1	0.3	Claystone; gray to red/brown (fresh and weathered), carbonaceous.
2	0.6	Lignite.
1	0.3	Claystone; gray to red/brown (fresh and weathered), carbonaceous, contains leaf fossils.
39	11.9	Sandstone; gray to brown (fresh), gray (weathered), very fine to fine grained, poorly lithified, contains interbedded dark gray clay lenses approximately 2 inches (5 cm) thick, and jarosite.
5.8	1.8	Mudstone; red to brown (fresh), gray (weathered), sandy, contains dark gray to black, paper shale layers, coarsens upward.
3	0.9	Claystone; dark gray to black (fresh), brown (weathered), fissile, carbonaceous.
		HELL CREEK FORMATION
2	0.6	Sandstone; brown (fresh), gray (weathered), very fine to fine grained, jarosite, plant fragments, clayey, fines upward, popcorn texture.
3	0.9	Mudstone; brown (fresh), gray (weathered), plant fragments, popcorn texture.
3	0.9	Sandstone; light brown (fresh), gray (weathered), very fine grained, jarosite, iron oxide concretions.
2	0.6	Mudstone; dark brown (fresh), light brown (weathered), fissile, popcorn texture.
13.8	4.2	Mudstone; gray to medium brown (fresh), gray (weathered), plant fragments, roots, fines upward, more carbonaceous near the top of the unit.
1	0.3	Mudstone; brown to dark brown (fresh), brown (weathered), contains plant fragments and is carbonaceous.
12	3.7	Mudstone; gray to brown on (fresh and weathered), sandy, plant fragments, popcorn texture.
8.8	2.7	Sandstone; brown (fresh), gray (weathered), very fine to fine grained, organic layers, leaf fossils, amber, coalified layers, cross-bedded, interbedded claystone.
8.8	2.7	Mudstone; brown (fresh), gray to brown (weathered), sandy, plant fragments, jarosite staining, popcorn texture, contains organic rich zones, iron oxide concretions.
4	1.2	Sandstone; gray to brown (fresh and weathered), fine to coarse grained, poorly sorted, contains large plant fragments.
3	0.9	Mudstone; gray to brown (fresh), gray (weathered), sandy and contains iron oxide concretions.
1	0.3	Sandstone; gray (fresh and weathered), very fine grained, poorly indurated, jarosite.
7.8	2.4	Mudstone; brown (fresh), gray to brown (weathered), carbonaceous, numerous plant fragments, some lignite lenses, very carbonaceous at the top of the unit.

Section no. 14 Location: T130N R81W sec. 14 (sw/se), Sioux County
Landowner: Warren Lund Top of section: 2200 fasl.



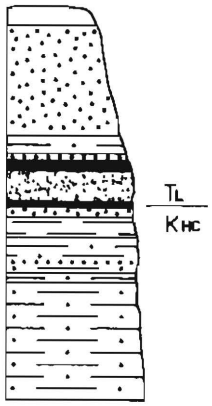
Thickness Ft.	Thickness M.	
34	10.4	Covered.
		LUDLOW FORMATION
11.3	3.4	Sandstone; yellow to brown (fresh and weathered), fine to medium grained, cross-bedded, organic lenses.
4.8	1.5	Mudstone; brown (fresh), light brown (weathered), carbonaceous.
1	0.3	Sandstone; gray to yellow/brown (fresh), gray (weathered), very fine to fine grained, poorly indurated, iron oxide stained.
9.5	2.9	Covered.
6.8	2.1	Claystone; dark brown (fresh), light brown (weathered), blocky, plant fragments.
		HELL CREEK FORMATION
15	4.6	Mudstone; orange/brown to medium brown (fresh), dark gray (weathered), carbonaceous at base, root traces, fissile, popcorn texture.
2	0.6	Mudstone; gray to brown (fresh), gray (weathered), sandy, contains plant fragments.
5.8	1.8	Mudstone; orange to brown (fresh), dark gray (weathered), carbonaceous, plant fragments, popcorn texture.
2	0.6	Mudstone; brown (fresh), gray to brown (weathered), sandy, plant fragments, popcorn texture.
2	0.6	Mudstone; brown to black (fresh), dark gray to brown (weathered), carbonaceous, plant fragments, thin lignite lenses.
35	10.7	Interbedded sandstone and mudstone; gray to brown (fresh), gray to brown (weathered), medium grained, poorly sorted, organic lenses in sandstone, cross-bedded, mudstone contains plant fragments.
9.3	2.8	Mudstone; medium brown to gray brown (fresh), medium gray (weathered), sandy in places, plant fragments, root traces, popcorn texture, fissile.
7.8	2.4	Sandstone; gray to brown (fresh), gray (weathered), fine grained, poorly sorted, cross-bedded, root traces, fines upward.

Section no. 15 — Location: T131N R81W sec. 32 (sw/sw/se), Sioux County
Landowner: Valentine Jochim — Top of section: 2100 fasl.



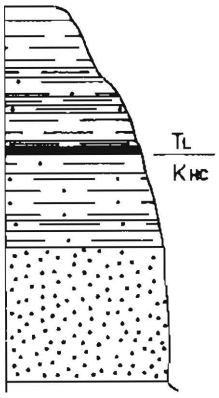
Thickness Ft.	Thickness M.	
17	5.2	Covered.
		LUDLOW FORMATION
8.8	2.7	Sandstone; light green to brown (fresh), light gray (weathered), fine to medium grained, poorly indurated, glauconitic.
0.5	0.2	Iron oxide concretionary layer.
4	1.2	Mudstone; medium brown (fresh), gray (weathered), sandy, iron oxide staining.
28	8.5	Sandstone; gray to yellow/brown (fresh), gray to gray/brown (weathered), iron oxide chips, very fine to fine grained, silty, cross-bedded, iron oxide concretions.
		HELL CREEK FORMATION
2.5	0.8	Mudstone; brown to black (fresh), dark gray (weathered), carbonaceous, lignite fragments, plant fragments, amber.
8.8	2.7	Sandstone; gray to brown (fresh), gray (weathered), fine to medium grained, organic horizons, plant fragments, cross-bedded.
4.5	1.4	Mudstone; dark brown to brown (fresh), dark gray to gray/brown (weathered), sandy at the top, carbonaceous, blocky, some fissile layers, contains plant fragments.
2.5	0.8	Sandstone; gray to brown on fresh and weathered surfaces, fine grained, root traces, jarosite.
17	5.2	Mudstone; gray to brown (fresh), dark gray to gray (weathered), interbedded carbonaceous rich mudstones and sandy mudstone 4 feet (1.2 m) in thickness, popcorn texture, mudstones become carbonaceous near the top of the unit.
80	24.4	Interbedded sandstone and mudstone; Sandstone; gray (fresh and weathered), fine grained, poorly sorted, cross-bedded, contains organic rich lenses. Mudstone; gray/brown to brown (fresh), gray to buff (weathered), sandy, organic content varies, thickness varies from 1 inch to 4 feet (2.5 cm to 1.2 m), popcorn texture, root traces, fluted sandstone in the middle of the unit.
0.5	0.2	Iron oxide concretionary layer.

Section no. 16 — Location: T131N R84W sec. 25 (nw/se/se), Sioux County
Landowner: Standing Rock Sioux Tribe — Top of section: 2100 fasl.



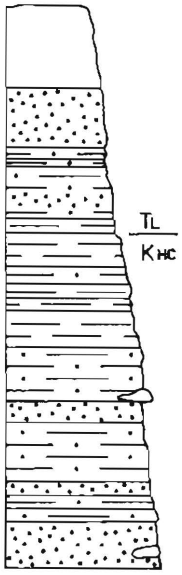
Thickness Ft.	Thickness M.	
		LUDLOW FORMATION
18	5.5	Sandstone; yellow/brown (fresh and weathered), fine grained, iron oxide stained, iron oxide concretions, clayey.
3	0.9	Mudstone; olive/gray to brown (fresh), gray/brown (weathered), sandy, iron oxide concretions, interbedded with dark gray organic rich clay.
1	0.3	Sandstone; gray/brown (fresh), brown (weathered), very fine grained, clayey, iron oxide stained.
1.5	0.5	Lignite.
7.8	2.4	Siltstone; gray (fresh and weathered), laminated with dark gray clay and very fine sand layers, iron oxide concretions.
0.2	0.1	Lignite; surrounded by carbonaceous claystone.
		HELL CREEK FORMATION
2	0.6	Sandstone; light gray (fresh and weathered), very fine grained, silty, laminated, contains organic rich horizons, jarosite and iron oxide concretions.
3.8	1.1	Claystone; brown (fresh), light/dark gray (weathered), blocky, fissile, popcorn texture.
5.8	1.8	Interbedded sandstone and mudstone; Sandstone; gray (fresh and weathered), clayey, very fine grained, plant fragments. Mudstone; gray/brown (fresh), dark gray (weathered), plant fragments, popcorn texture.
1	0.3	Mudstone; brown (fresh), gray (weathered), carbonaceous, plant fragments.
20	6.1	Mudstone; gray/brown (fresh), gray (weathered), sandy, iron oxide concretions (chips) interbedded sand lenses, popcorn texture.

Section no. 17 Location:T131N R83W sec. 17 (ne/nw/sw), Sioux County
Landowner: Standing Rock Sioux Tribe Top of section: 2060 fasl.



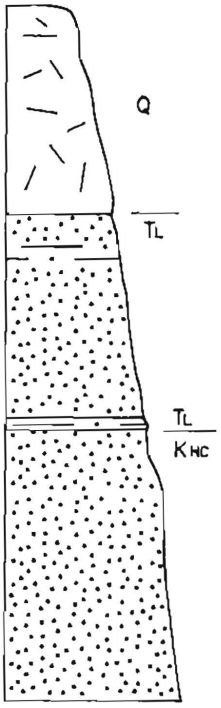
Thickness Ft.	Thickness M.	
		LUDLOW FORMATION
8.3	2.5	Claystone; gray/brown (fresh and weathered), silty, iron oxide stained, iron oxide chips.
1	0.3	Claystone; dark brown (fresh), dark gray (weathered), carbonaceous, paper texture.
4	1.2	Mudstone; gray (fresh), gray/brown (weathered), sandy, blocky, plant fragments, iron oxide stained.
2	0.6	Claystone; dark gray to black (fresh and weathered), carbonaceous.
5	1.5	Claystone; medium brown (fresh and weathered), plant fragments, contains lignite.
3	0.9	Mudstone; dark brown to black (weathered and fresh), contains 6 inch (15 cm) coal at base.
		HELL CREEK FORMATION
2	0.6	Claystone; light gray to olive gray (fresh and weathered), silty, plant fragments, popcorn texture.
7.8	2.4	Mudstone; dark gray to black (fresh and weathered), red brown carbonaceous clay at base, contains sand and clay partings, fissile, fossil wood.
2	0.6	Mudstone; olive gray (fresh and weathered), plant fragments, popcorn texture.
3	0.9	Mudstone; red brown (fresh), dark brown (weathered), carbonaceous, plant fragments.
2	0.6	Mudstone; gray to gray/brown (fresh and weathered), popcorn texture.
23	7.0	Sandstone; gray/brown (fresh and weathered), fine grained, cross-bedded, moderately indurated, contains organic rich lenses, clay lenses, iron oxide concretions, jarosite, and fines upward.

Section no. 19 Location: T129N R85W sec. 6 (ne/sw/nw), Sioux County
Landowner: Ross Schaeffer Top of section: 2200 fasl.



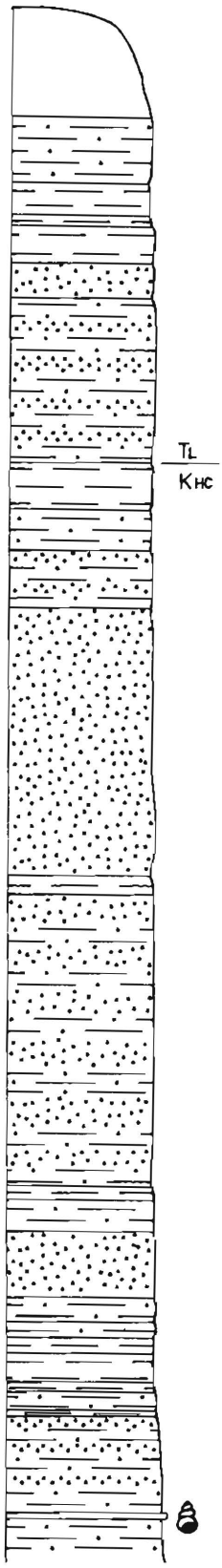
Thickness Ft.	Thickness M.	
13	3.9	Covered.
		LUDLOW FORMATION
10	3.1	Sandstone; yellow/gray (fresh), gray/brown (weathered), fine grained, clayey, iron oxide chips.
2	0.6	Mudstone; yellow/brown (fresh and weathered), plant fragments, iron oxide staining.
1	0.3	Mudstone; dark brown (fresh and weathered), carbonaceous.
7.8	2.4	Interbedded sandstone and mudstone; yellow/brown to light brown (fresh and weathered), very fine grained sand, iron oxide chips, plant fragments.
2	0.6	Claystone; dark gray, dark brown to black (fresh and weathered), paper texture.
		HELL CREEK FORMATION
5.8	1.8	Claystone; dark gray/brown (fresh and weathered), plant fragments, popcorn texture.
3	0.9	Mudstone; yellow/brown to gray/brown (fresh), gray/brown (weathered), carbonaceous, amber, plant fragments.
2	0.6	Claystone; dark gray to dark brown (fresh and weathered), popcorn texture.
1.5	0.5	Claystone; dark brown (fresh and weathered), carbonaceous, some lignite horizons.
6	1.8	Claystone; dark gray to dark brown (fresh), dark brown to black (weathered), fissile, popcorn texture.
8.8	2.7	Mudstone; gray/yellow to brown (fresh and weathered), sandy, plant fragments, sand layers, jarosite.
3	0.9	Sandstone; gray/yellow to brown (fresh and weathered), fine grained, poor to moderately indurated, organic laminae, iron oxide concretions, jarosite, grades into mudstone.
9.5	2.9	Mudstone; gray/brown (fresh and weathered), contains two carbonaceous clay layers, popcorn texture, plant fragments.
2.5	0.8	Sandstone; olive/gray (fresh), gray (weathered), fine grained, organics along bedding planes, root traces, some iron oxide staining, moderately lithified.
2	0.6	Mudstone; medium brown to dark brown (fresh and weathered), carbonaceous, plant fragments.
2	0.6	Mudstone; gray/brown (fresh and weathered), organic horizons.
7.3	2.2	Sandstone; olive/gray (fresh), gray (weathered), fine grained, poorly indurated, cross-bedded, organic laminae, log concretions, iron oxide concretions, fines upward.

Section no. 21 Location: T136N R78W sec.12 (sw/ne/sw), Emmons County
Landowner: John Berger and Ken Horner Top of section: 1960 fasl.



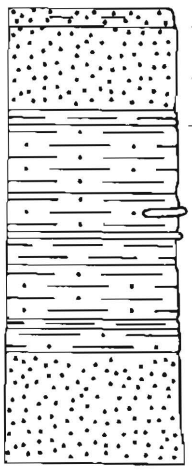
Thickness Ft.	M.	
34	10.4	QUATERNARY Drift.
		LUDLOW FORMATION
34	10.4	Sandstone; gray to yellow/brown (fresh and weathered), very fine to fine grained, cross-bedded, organic laminae, iron oxide stained, iron oxide concretions, interbedded with gray to yellow/brown claystone near the top of the unit.
1.5	0.5	Mudstone; dark brown (fresh), light brown (weathered), carbonaceous.
		HELL CREEK FORMATION
45	13.7	Sandstone; light to medium gray (fresh and weathered), fine grained, clayey/silty lenses, organic laminae, concretions, popcorn texture on clay lenses, fines upward.

Section no. 25 Location: T133N R82W sec. 23 (sesenw), Sioux County
Landowner: Standing Rock Sioux Tribe Top of section:2000 fasl



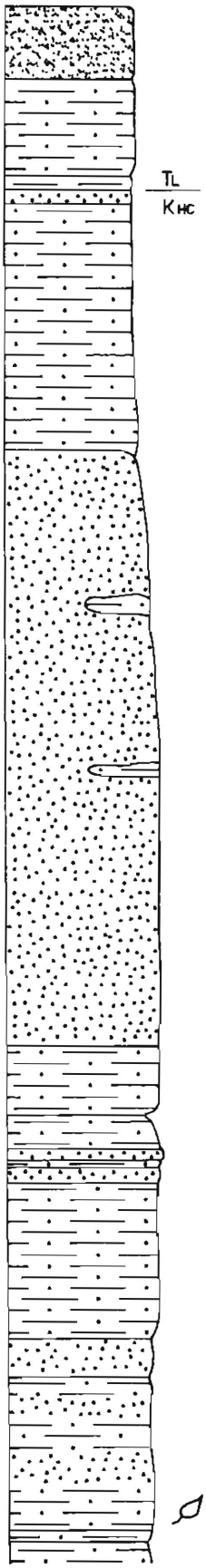
Thickness Ft.	Thickness M.	
19	5.8	Covered.
		LUDLOW FORMATION
12	3.7	Mudstone; gray/brown to yellow/brown (weathered and fresh), silty.
6	1.8	Claystone; gray to dark gray (weathered and fresh), carbonaceous at top.
2	0.6	Claystone; medium to dark brown (weathered and fresh), carbonaceous.
6	1.8	Claystone; medium brown (weathered and fresh), slightly carbonaceous.
6	1.8	Sandstone; yellow/brown (fresh) and gray (weathered), very fine grained, poorly cemented.
28	8.5	Mudstone; yellow/brown to gray/brown (weathered and fresh), silty, finely laminated in places, very fine sand lens.
		HELL CREEK FORMATION
8	2.4	Claystone; gray to dark brown (weathered and fresh), carbonaceous at top.
16	4.9	Mudstone; gray to dark brown (weathered and fresh), silty, finely laminated claystone and silt, clay zones, contain plant fragments.
47	14.3	Sandstone; gray (weathered and fresh), medium to fine grained, silty, cross-bedded, poorly cemented, iron stained lenses, contains thin mudstone lenses and organic-rich lenses at base.
4	1.2	Claystone; brown to black (weathered and fresh), carbonaceous.
51	15.5	Mudstone; gray to brown (weathered and fresh), silty to sandy, contains interbedded sandstone lenses from 6 inches up to 3 feet thick (15 cm-0.9 m) , carbonaceous, FeO concretion layers, plant fragments.
2	0.6	Claystone; brown to black (weathered and fresh), carbonaceous, contains amber.
6	1.8	Mudstone; gray to tan (weathered and fresh), silty, contains plant fragments.
11	3.4	Sandstone; gray (weathered and fresh), fine grained, contains plant fragments, grades upward into mudstone.
4	1.2	Mudstone; gray to brown (weathered and fresh), sandy to clean claystone, carbonaceous at top and base, selenite at top.
2	0.6	Mudstone; gray/white (weathered and fresh), sandy.
2	0.6	Claystone; dark brown to black (weathered and fresh), carbonaceous.
5	1.5	Claystone; gray/brown (weathered and fresh), popcorn texture, smectitic.
1	0.3	Claystone; brown (weathered and fresh), carbonaceous.
3	0.9	Mudstone; gray/brown (weathered and fresh), contains very fine sand lenses, brown claystone layers, iron stained.
0.5	0.2	Mudstone; brown to gray/brown (weathered and fresh), silty to clean claystone, carbonaceous.
17	5.2	Mudstone; gray to gray brown (weathered and fresh), iron stained, brown clay layers, contains very fine sand lenses.
1	0.3	Ironstone Concretion Layer; contains clams, *Toredo*- bored fossil wood.
5	1.5	Mudstone; gray/brown (weathered and fresh), sandy, iron stained, brown clay layers.

Section no. 26 — Location: T130N R84W sec. 8 (nwnene), Sioux County
Landowner: Standing Rock Sioux Tribe — Top of section: 2120 fasl



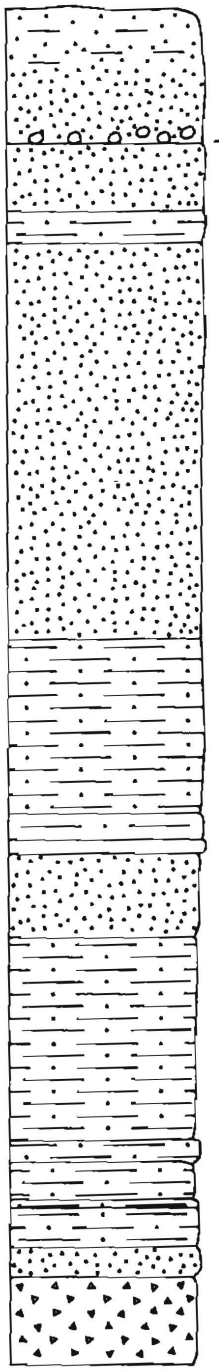
Thickness Ft.	Thickness M.	
		QUATERNARY
3	0.9	Loess.
		LUDLOW FORMATION
14	4.3	Sandstone; yellow/brown to gray (weathered and fresh), very fine to fine grained, poorly cemented, abundant leaf fossils.
2	0.6	Claystone; green to black (fresh), gray (weathered), carbonaceous at top, plant fragments.
		HELL CREEK FORMATION
11	3.4	Mudstone; pink/brown(fresh), gray (weathered), carbonaceous, plant fragments, Fe staining, popcorn texture.
6	1.8	Mudstone; light gray/brown (weathered and fresh), silty, Fe staining, Fe concretion layer, popcorn texture.
0.5	0.2	Ironstone Concretion Layer.
4	1.2	Claystone; light brown (fresh), gray (weathered), fissile.
9	2.7	Mudstone; light brown (fresh), gray (weathered), sandy to silty, iron concretion at base, popcorn texture.
1	0.3	Claystone; dark brown to black (weathered and fresh), silty, popcorn texture.
3	0.9	Mudstone; gray to brown (weathered and fresh), silty, popcorn.
14	4.3	Sandstone; gray/brown(weathered and fresh), fine grained, poorly sorted, cross-bedded, contains carbonaceous mudstone lenses, moderately cemented.

Section no. 27 Location: T131N R81W sec. 22 (scswnw), Sioux County
Landowner: Standing Rock Sioux Tribe Top of section: 2190 fasl



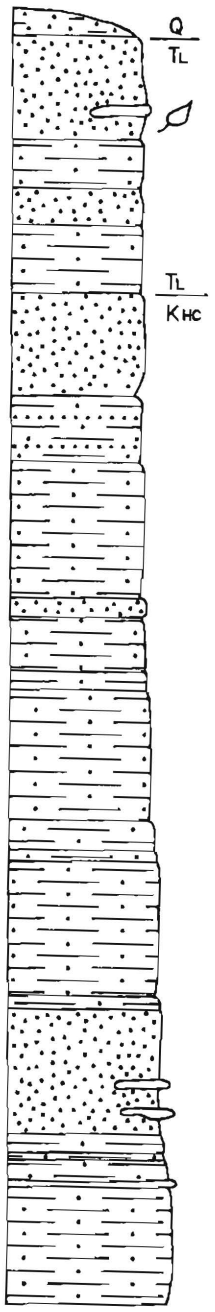
Thickness Ft.	Thickness M.	
		LUDLOW FORMATION
13	3.9	Siltstone; yellow/brown (weathered and fresh), clayey.
17	5.2	Mudstone; yellow/brown to brown (weathered and fresh), silty, iron staining.
3	0.9	Claystone; gray to brown (weathered and fresh), carbonaceous at top, iron layer near middle of unit.
		HELL CREEK FORMATION
3	0.9	Sandstone; yellow/gray (fresh), gray (weathered), very fine grained, silty, poorly cemented, Fe staining.
45	13.7	Mudstone; gray/brown (weathered and fresh), silty to sandy, plant fragments, popcorn texture, carbonaceous and iron concretions at top.
109	33.2	Sandstone; yellow/brown (fresh), gray (weathered), very fine to fine grained, poorly cemented, cross-bedded, contains organic rich horizons near middle of unit.
13.5	4.1	Mudstone; gray to brown (weathered and fresh), sandy to silty, plant fragments, popcorn texture, carbonaceous at top, sandy at base.
6	1.8	Mudstone; light brown to gray/brown (weathered and fresh), silty to clayey, carbonaceous, popcorn texture.
2	0.6	Sandstone; gray (weathered and fresh), very fine to fine grained, poorly cemented.
1.5	0.5	Mudstone; black to brown (weathered and fresh), carbonaceous.
3	0.9	Sandstone; gray (weathered and fresh), very fine grained, poorly cemented, some iron concretions, carbonaceous at top.
29	8.8	Mudstone; gray/brown (weathered and fresh), silty to sandy, popcorn texture, contains 5 thin carbonaceous zones.
7	2.1	Sandstone; gray (weathered and fresh), very fine to fine grained, poorly cemented, spherical iron concretions.
28	8.5	Mudstone; gray to brown (weathered and fresh), sandy, contains medium grained sand lenses, popcorn texture, iron stained, plant fragments, contains leaf fossils.
2	0.6	Claystone; black to brown (weathered and fresh), carbonaceous, plant fragments.
4	1.2	Mudstone; gray to brown/gray (weathered and fresh), sandy, popcorn texture, plant fragments.

Section no. 28 Location: T134N R81W sec. 31 (seswnw), Sioux County
Landowner: Standing Rock Sioux Tribe Top of Section: 1920 fasl



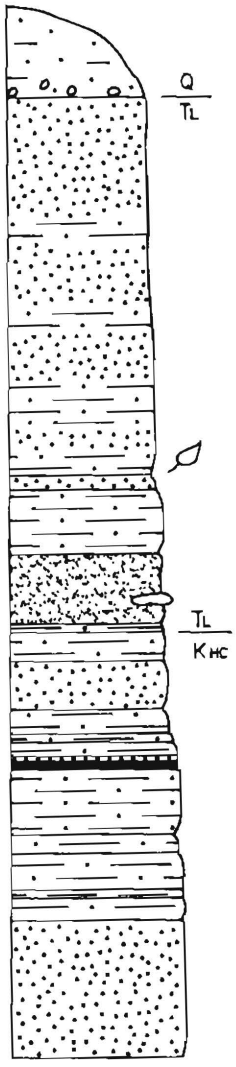
Thickness Ft.	Thickness M.	
		QUATERNARY
22	6.7	Alluvium; gray/brown (weathered and fresh), gravel at base-fining upward, gravel consists of ironstone, silcrete, igneous rocks, fossil wood, top 10 feet (0.3 m) primarily silt.
		HELL CREEK FORMATION
12	3.7	Sandstone; gray/brown to gray (weathered and fresh), fine grained, poorly cemented, some small iron concretions.
5	1.5	Mudstone; brown (fresh), gray/brown (weathered), silty to clayey, plant fragments.
65.5	19.9	Sandstone; gray (weathered and fresh), fine grained, poorly cemented, iron staining, cross-bedded.
28.5	8.7	Mudstone; gray to gray/brown (weathered and fresh), sandy, popcorn texture, carbonaceous layers, plant fragments.
4	1.2	Mudstone; gray/brown to dark brown, silty, popcorn texture, carbonaceous to very carbonaceous, plant fragments.
1	0.3	Ironstone Concretion Layer.
14	4.3	Sandstone; gray (weathered and fresh), fine to medium grained, cross-bedded, poorly cemented, carbonaceous--organic lenses.
34	10.4	Mudstone; gray/brown (weathered and fresh), silty, iron concretions, plant fragments.
3	0.9	Mudstone; dark brown to black, carbonaceous, plant fragments, contains amber.
6	1.8	Mudstone; gray/brown (weathered and fresh), silty, iron concretions, plant fragments.
1	0.3	Mudstone; brown (weathered and fresh), carbonaceous.
6	1.8	Mudstone; gray/brown to brown (weathered and fresh), silty, popcorn texture, iron concretions, carbonaceous, plant fragments.
5	1.5	Sandstone; gray to gray/brown (weathered and fresh), fine grained, poorly to moderately cemented.
15	4.6	Breien Tuff; gray to dazzling white (weathered and fresh), silty to sandy, gray bentonitic claystone at top, plant fragments.

Section no. 29 Location:T129N R81W sec. 16 (nwnene), Sioux County
Landowner: Standing Rock Sioux Tribe Top of section: 2160 fasl



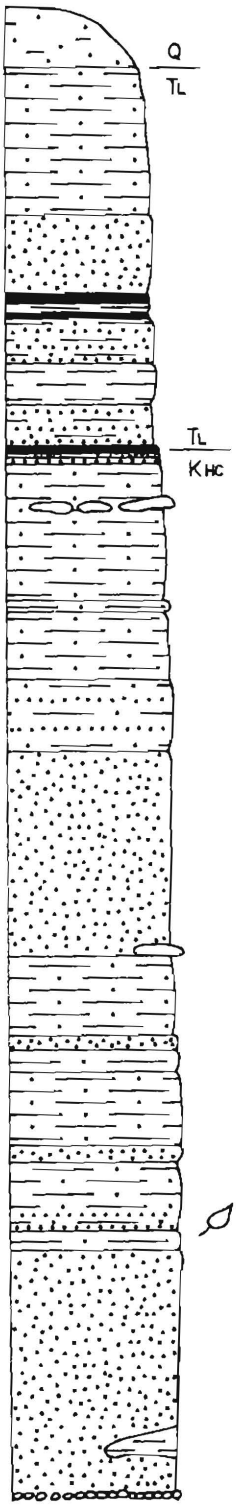
Thickness Ft	Thickness M.	
		QUATERNARY
5	1.5	Loam.
		LUDLOW FORMATION
17	5.2	Sandstone, light gray to gray/brown (weathered and fresh), very fine grained, poorly cemented, contains iron concretions near base with wood molds, root casts, leaf fossils.
8	2.4	Mudstone, light gray/brown (weathered), light to dark brown (fresh), contains clay beds, silty horizons, organic-rich horizons, Fe staining, plant fragments.
6	1.8	Sandstone, light gray/brown(weathered and fresh), very fine grained, silty, poorly cemented, iron concretions.
11	3.4	Mudstone, gray/brown (weathered and fresh), silty, slight popcorn texture, plant fragments, iron staining, silt laminae, iron concretions.
		HELL CREEK FORMATION
17	5.2	Sandstone, yellow/gray (weathered and fresh), fine grained.
11	3.4	Sandstone and Mudstone, interbedded, sandstone is yellow/gray (weathered and fresh), fine grained, iron concretions, iron staining; mudstone is brown/gray (weathered and fresh), popcorn texture, plant fragments, carbonaceous.
23	7.0	Mudstone, gray/brown (weathered and fresh), sandy to silty, plant fragments, carbonaceous rich horizons, iron concretions near top.
3	0.9	Sandstone, yellow/gray (weathered and fresh), very fine grained, silty, poorly cemented.
9	2.7	Mudstone, gray/brown (weathered and fresh), silty, popcorn texture, plant fragments.
3	0.9	Mudstone, brown (weathered and fresh), silty to clayey, carbonaceous.
22	6.7	Mudstone, gray/brown (weathered and fresh), silty, carbonaceous, plant fragments.
5	1.5	Mudstone, gray to gray/brown (weathered and fresh), sandy, iron staining, silty at base.
1.5	0.5	Mudstone, brown/black (weathered and fresh), carbonaceous.
34	10.4	Mudstone, gray/brown (weathered and fresh), silty with sandy intervals, popcorn texture, carbonaceous rich layers, plant fragments, iron staining.
2	0.6	Mudstone, brown/black (weathered and fresh), carbonaceous.
21	6.4	Sandstone, gray (weathered and fresh), fine to medium grained, moderately to poorly cemented, contains organic rich lenses, iron concretions, contains wood molds and plant fragments.
3	0.9	Mudstone, gray/brown (weathered and fresh), sandy, plant fragments, popcorn texture.
1	0.3	Mudstone, brown (weathered and fresh), silty, carbonaceous.
3	0.9	Mudstone, gray/brown (weathered and fresh), silty, plant fragments, popcorn texture.
0.5	0.2	Iron Concretion Layer.
20	6.1	Mudstone, gray/brown (weathered and fresh), silty to sandy, plant fragments, carbonaceous zones, iron staining, popcorn texture.

Section no. 30 Location: T132N R83W sec. 20 (nwswse), Sioux County
Landowner: Standing Rock Sioux Tribe Top of section: 1970 fasl



Thickness Ft.	Thickness M.	
15	4.6	QUATERNARY Alluvium; sand and gravel at base fining upward to brown silt and clay.
63	19.2	LUDLOW FORMATION Sandstone; green/gray (weathered and fresh), fine grained, poorly cemented, contains interbedded mudstone (especially at base) that is gray/brown (weathered and fresh), carbonaceous, with numerous leaf fossils at base.
2	0.6	Sandstone; orange/brown (weathered and fresh), fine grained, poorly cemented, small spherical concretions, abundant selenite.
11	3.4	Mudstone; gray/brown (weathered and fresh), silty, plant fragments.
11	3.4	Siltstone; gray (weathered and fresh), thinly laminated, contains organic rich horizons, iron concretions.
1	0.3	Mudstone; brown/black (weathered and fresh), very carbonaceous, contains coal lenses and some amber.
5	1.5	HELL CREEK FORMATION Mudstone; light gray/brown (weathered and fresh), silty, popcorn texture.
8	2.4	Sandstone; gray (weathered and fresh), very fine to fine grained, moderately cemented, mudstone lenses, ironstone concretions.
4	1.2	Mudstone; gray to gray/brown (weathered and fresh), silty, plant fragments.
1.5	0.5	Mudstone; brown to black (weathered and fresh), coal lenses, very carbonaceous, contains amber.
2	0.6	Mudstone; gray/brown (weathered and fresh), silty.
1	0.3	Siltstone; gray (weathered and fresh), iron stained, iron concretions, root casts, some selenite.
1	0.3	Coal.
11	3.4	Mudstone; gray (weathered), gray/brown (fresh) silty, popcorn, contains lenses of silt.
3	0.9	Mudstone; gray (weathered), red brown to brown (fresh), carbonaceous, silty.
6	1.8	Mudstone; gray/brown (weathered and fresh), sandy, popcorn texture.
1	0.3	Claystone; black (weathered and fresh), very carbonaceous.
4	1.2	Mudstone; gray/brown (weathered and fresh), silty, popcorn texture.
23	7.0	Sandstone, gray (weathered and fresh), very fine to fine grained, poorly to moderately cemented, contains organic lenses.

Section no. 31 Location: T131N R82W sec. 14 (nwnw), Sioux County
Landowner: Standing Rock Sioux Tribe Top of section: 2180 fasl



Thickness Ft.	Thickness M.	
		QUATERNARY
10	3.0	Loam.
		LUDLOW FORMATION
24	7.3	Mudstone; light brown to dark brown (weathered and fresh), sandy, sand lenses, iron stained, abundant selenite.
13	3.9	Sandstone; light gray (weathered and fresh), fine grained, poorly cemented, iron stained, iron concretions, organic lenses at base.
1	0.3	Coal.
2	0.6	Claystone; brown to dark brown (weathered and fresh), very carbonaceous.
0.5	0.2	Coal.
8	2.4	Mudstone; gray/brown (weathered and fresh), contains interbedded sandstone and mudstone, sandstone is very fine to fine grained, poorly cemented, iron stained, mudstone is silty, organic rich, contains plant fragments.
6.8	2.1	Claystone; black to dark gray/brown (weathered and fresh) contains coal lenses, carbonaceous.
7	2.1	Mudstone; gray/brown (weathered and fresh), contains interbedded sandstone and mudstone, sandstone is very fine to fine grained, poorly cemented, iron stained, mudstone is silty, organic rich, contains plant fragments.
0.5	0.2	Coal and carbonaceous claystone.
		HELL CREEK FORMATION
1	0.3	Siltstone; gray (weathered and fresh), contains clay laminae, rooted, plant fragments.
1	0.3	Sandstone; gray/brown (weathered and fresh), very fine grained, poorly cemented.
23	7.0	Mudstone; gray to brown (weathered and fresh), silty, faint layering, iron stained, iron concretions, popcorn texture, plant fragments.
2	0.6	Mudstone; orange/brown (weathered and fresh), silty, carbonaceous, plant fragments, contains amber.
11	3.4	Mudstone; light brown (fresh), gray/brown (weathered), silty, plant fragments, popcorn texture.
12	3.7	Mudstone interbedded with sandstone; sandstone is gray/brown (weathered and fresh), very fine to fine grained, poorly cemented, iron stained, rooted, mudstone is gray brown to brown (weathered and fresh), silty, carbonaceous in places.
34	10.4	Sandstone; gray/brown(weathered and fresh), very fine to fine grained, moderately to poorly cemented, cross-bedded, contains numerous organic rich lenses, thin FeO layers.
13	3.9	Mudstone; light gray to tan (fresh), light gray/brown (weathered), silty, popcorn texture, faint layering, ironstone layers.
2.5	0.7	Sandstone; gray/green (weathered and fresh), fine grained, poorly cemented, clay lenses, iron oxide staining.
4	1.2	Mudstone; dark brown (fresh), light to dark brown (weathered), contains clay lenses, popcorn texture, carbonaceous, plant fragments.
12	3.7	Mudstone; gray to dark brown (fresh), light gray/brown (weathered), silty, contains lenses of sandstone and claystone, rooted, plant fragments.
3	0.9	Sandstone; gray/white (fresh), gray (weathered), fine grained, fines upward, moderately cemented, rooted, plant fragments.
11.5	3.5	Mudstone; interbedded sandstone and mudstone, sandstone is gray (weathered and fresh), very fine to fine grained, moderately cemented, iron stained, root traces, and leaf fossils, mudstone is dark gray (fresh) gray (weathered), silty, plant fragments.
3	0.9	Mudstone; brown to black (fresh), gray/brown (weathered), silty to sandy, carbonaceous, plant fragments, coal lenses, amber.
41	12.5	Sandstone; gray (weathered and fresh), fine grained, moderately to poorly cemented, cross-bedded, contains organic lenses, ironstone conglomerate at base of channel which includes quartz pebbles up to 4 inches (10 cm) in size.

APPENDIX C

List of Megafossil Taxa Identified during this Study and Their Geographic and Stratigraphic Distribution.

* Indicates that the taxon is interpreted to be reworked.

TAXA	MEASURED SECTIONS																																					
	Section #	1	3	4		5	6	7	9		10	11	13		18	20	22	23		24	25	26	27	28		29	30	31	32									
	Feet above(+) or below(-) Hell Creek/ Ludlow contact	+ 18	- 80	+ 28	- 11	+ 35	+ 120	+ 11	+ 0-10	- 21	- 49	+ 5	+ 47	- 41	- 8	+ 2	- 10	+ 46	+ 32	- 68	- 180	+ 9	- 247	- 123	- 183	+ 27	+ 28	- 128	+ 6-14	- 102	- 136	- 140						
	Formation	Quaternary	Hell Creek	Ludlow	Hell Creek	Ludlow	Cannonball	Ludlow	Ludlow	Hell Creek	Hell Creek	Ludlow	Ludlow	Hell Creek	Hell Creek	Ludlow	Hell Creek	Cannonball	Ludlow	Hell Creek	Hell Creek	Ludlow	Hell Creek	Hell Creek	Hell Creek	Ludlow	Ludlow	Hell Creek	Ludlow	Hell Creek	Hell Creek	Breien Mbr.						
PLANTS																																						
Family Taxodiaceae																																						
Sequoia dakotensis																														X	X							
Family Cercidiphyllaceae																																						
Cercidiphyllum sp.																														X								
Seed fossils indet.																														X	X							
Leaf fossils indet.					X	X						X	X	X	X	X	X		X	X		X	X			X	X	X	X	X	X							
Teredo-bored petrified wood									X												X																		
INVERTEBRATES																																						
Class Bivalvia																																						
Family Mytilidae																																						
Modiolus cf. *M. galpinianus*																																						X
Family Inoceramidae																																						
?*Inoceramus* sp.																																						X
Family Ostreidae																																						
Crassostrea sp.																																						X
Family Unionidae																																						
Unionidae gen. indet.																					X									X								
Family Sphaeriidae																																						
Sphaerium sp.																														X								
Bivalvia indet.								X													X									X								
Class Gastropoda																																						
Family Viviparidae																																						
Campeloma acroterion								X																						X								
Campeloma sp.								X																X						X								
Lioplacodes sp.								X																						X								
Family Physidae																																						
Physa sp.																														X								
Gastropoda indet.	*																				X									X								

TAXA	MEASURED SECTIONS																																		
	Section #	1	3	4		5	6	7	9		10	11	13		18	20	22	23		24	25	26	27	28		29	30	31	32			
	Feet above(+) or below(-) Hell Creek/ Ludlow contact	+ 18	- 80	+ 28	- 11	+ 35	+ 120	+ 11	+ 0-10	- 21	- 49	+ 5	+ 47	- 41	- 8	+ 2	- 10	+ 46	+ 32	- 68	- 180	+ 9	- 247	- 123	- 183	+ 27	+ 28	- 128	+ 6-14	- 102	- 136	- 140
	Formation	Quaternary	Hell Creek	Ludlow	Hell Creek	Ludlow	Cannonball	Ludlow	Ludlow	Hell Creek	Hell Creek	Ludlow	Ludlow	Hell Creek	Hell Creek	Ludlow	Hell Creek	Cannonball	Ludlow	Hell Creek	Hell Creek	Ludlow	Hell Creek	Hell Creek	Hell Creek	Ludlow	Ludlow	Hell Creek	Ludlow	Hell Creek	Hell Creek	Breien Mbr.
VERTEBRATES																																			
Class Chondrichthyes																																			
Subclass Elasmobranchii																																			
Order Hybodontiformes																																			
Family Hybodontidae																																			
Lissodus selachos																																	X		
Order Lamniformes																																			
Family Odontaspidae																																			
Carcharias taurus	*	*						X	*									X																	
Carcharias sp.							X																		*									*	X
Family Mitsukurhinidae																																			
?*Scapanorhnychus sp.*																																			X
Order Rajiformes																																			
Family Pristidae																																			
Ischyrhiza avonicola																									X										
Family *incertae sedis*																																			
Myledaphus bipartitus																									X								X	X	X
Subclass Holocephali																																			
Order Chimaeriformes																																			
Family Edaphodontidae																																			
Ischyodus sp.																																			X
Elasmodus sp..																																			X
Chimaeriformes indet.																																			X
Class Osteichthyes																																			
Order Lepisosteiformes																																			
Family Lepisosteidae																																			
Lepisosteus sp.				X					X		X														X								X	X	
Order Amiiformes																																			
Family Amiidae																																			

TAXA	MEASURED SECTIONS																														
Section #	1	3	4		5	6	7	9		10	11	13		18	20	22	23		24	25	26	27	28		29	30	31	32			
Feet above(+) or below(-) Hell Creek/ Ludlow contact	+ 18	- 80	+ 28	- 11	+ 35	+ 120	+ 11	+ 0-10	- 21	- 49	+ 5	+ 47	- 41	- 8	+ 2	- 10	+ 46	+ 32	- 68	- 180	+ 9	- 247	- 123	- 183	+ 27	+ 28	- 128	+ 6-14	- 102	- 136	- 140
Formation	Quaternary	Hell Creek	Ludlow	Hell Creek	Ludlow	Cannonball	Ludlow	Ludlow	Hell Creek	Hell Creek	Ludlow	Ludlow	Hell Creek	Hell Creek	Ludlow	Hell Creek	Cannonball	Ludlow	Hell Creek	Hell Creek	Ludlow	Hell Creek	Hell Creek	Hell Creek	Ludlow	Ludlow	Hell Creek	Ludlow	Hell Creek	Hell Creek	Breien Mbr.
Class Osteichthyes cont'd																															
Kindleia fragosa								X																					X	X	
Order Elopiformes																															
Family Albulidae																															
Coriops amnicolus																													X	X	
Order Aulopiformes																															
Family Enchodontidae																															
Enchodus sp.								*																							X
Osteichthyes indet.								X		X							X							X					X	X	X
Class Amphibia																															
Order Caudata																															
Family Scapherpetontidae																															
Scapherpeton tectum																														X	
Lisserpeton cf. *L. bairdi*																														X	
Family Sirenidae																															
?*Habrosaurus* sp.																														X	
Class Reptilia																															
Order Chelonia																															
Family Baenidae																															
Plesiobaena antiqua								X																						X	
Baenidae gen. indet.								X																						X	
Family Trionychidae																															
Trionyx (*Trionyx*) sp.																													X	X	
Trionyx (*Aspideretes*) sp.								X																					X	X	
Helopanoplia distincta																													X	X	
Trionychidae gen. indet.								X		X														X					X	X	
Family *incertae sedis*																															
Compsemys victa								X																					X		
Chelonia indet.						X		X		X																				X	X

TAXA	MEASURED SECTIONS																													
Section #	1	3	4		5	6	7	9		10	11	13		18	20	22	23		24	25	26	27	28		29	30	31	32			
Feet above(+) or below(-) Hell Creek/ Ludlow contact	+ 18	- 80	+ 28	- 11	+ 35	+ 120	+ 11	+ 0-10	- 21	- 49	+ 5	+ 47	- 41	- 8	+ 2	- 10	+ 46	+ 32	- 68	- 180	+ 9	- 247	- 123	- 183	+ 27	+ 28	- 128	+ 6-14	- 102	- 136	- 140
Formation	Quaternary	Hell Creek	Ludlow	Hell Creek	Ludlow	Cannonball	Ludlow	Ludlow	Hell Creek	Hell Creek	Ludlow	Ludlow	Hell Creek	Hell Creek	Ludlow	Hell Creek	Cannonball	Ludlow	Hell Creek	Hell Creek	Ludlow	Hell Creek	Hell Creek	Hell Creek	Ludlow	Ludlow	Hell Creek	Ludlow	Hell Creek	Hell Creek	Breien Mbr.
Class Reptilia cont'd																															
Order Choristodera																															
Family Champsosauridae																															
Champsosaurus sp.								X		X													X	X					X	X	
Order Sauria																															
Sauria indet.																													X	X	
Order Crocodylia																															
Family Crocodylidae																															
Leidyosuchus cf. *L. sternbergi*								X																					X	X	
Brachychampsa cf. *B. montana*																													X	X	
Alligatorinae gen. indet.	*																												X	X	
Crocodylia indet.								X		X													X						X	X	X
Order Saurischia																															
Family Dromaeosauridae																															
Dromaeosaurus sp.																													X	X	
Saurornitholestes sp.																														X	
Family Tyrannosauridae																															
Tyrannosauridae gen. indet.																								X					X	X	
Family *incertae sedis*																															
Paronychodon sp.																														X	
Order Ornithischia																															
Family Hadrosauridae																															
Hadrosauridae gen. indet.								*		X																			X	X	
Family Ankylosauridae																															
?Ankylosauridae gen. indet.																														X	
Family Ceratopsidae																															
Ceratopsidae gen. indet.																							X						X	X	
Dinosauria indet.		X						*	X	X													X						X	X	

TAXA	MEASURED SECTIONS																														
Section #	1	3	4		5	6	7	9		10	11	13		18	20	22	23		24	25	26	27	28		29	30	31	32			
Feet above(+) or below(-) Hell Creek/ Ludlow contact	+ 18	- 80	+ 28	- 11	+ 35	+ 120	+ 11	+ 0-10	- 21	- 49	+ 5	+ 47	- 41	- 8	+ 2	- 10	+ 46	+ 32	- 68	- 180	+ 9	- 247	- 123	- 183	+ 27	+ 28	- 128	+ 6-14	- 102	- 136	- 140
Formation	Quaternary	Hell Creek	Ludlow	Hell Creek	Ludlow	Cannonball	Ludlow	Ludlow	Hell Creek	Hell Creek	Ludlow	Ludlow	Hell Creek	Hell Creek	Ludlow	Hell Creek	Cannonball	Ludlow	Hell Creek	Hell Creek	Ludlow	Hell Creek	Hell Creek	Hell Creek	Ludlow	Ludlow	Hell Creek	Ludlow	Hell Creek	Hell Creek	Breien Mbr.
Class Mammalia																															
Order Multituberculata																															
Family Cimolomyidae																															
Meniscoessus robustus																													X	X	
Order Marsupialia																															
Family Didelphidae																															
cf. *Alphadon* sp.																														X	
Family Stagodontidae																															
cf. *Didelphodon* sp.																														X	
Mammalia indet.								X																							
Trace Fossils																															
Ophiomorpha sp.																															X

APPENDIX D. Representative fossils from the Hell Creek and Ludlow Formations.

A, *Lissodus selachos*, dorsal fin spine, Hell Creek Fm., Stumpf site (Sec. no. 32)(102 ft./31 m below Hell Creek/Ludlow contact), ND 93-77.5, width 72.2 mm.

B,C, *Ischyrhiza avonicola*, anterior and dorsal views of rostral tooth, Hell Creek Fm., (Sec. no. 28)(183 ft./56 m below Hell Creek/Ludlow contact), ND 95-14.1, height 4.9 mm.

D, Tyrannosauridae indet., lingual view of tooth, Hell Creek Fm., Stumpf site (Sec. no. 32)(136 ft./41 m below Hell Creek/Ludlow contact), ND 93-1.1, height 52.3 mm.

E,F, *Paronychodon* sp., labial and lingual views of tooth, Hell Creek Fm., Stumpf site (Sec. no. 32)(136 ft./41 m below Hell Creek/Ludlow contact), ND 93-1.2, height 14.2 mm.

G,H, *Myledaphus bipartitus*, basal and lingual views of tooth, Hell Creek Fm., Stumpf site (Sec. no. 32)(136 ft./41 m below Hell Creek/ Ludlow contact), ND 93-1.3, height 5.2 mm.

I, *Coriops amnicolus*, ventral view of dental plate, Hell Creek Fm., Stumpf site (Sec. no. 32)(136 ft./41 m below Hell Creek/Ludlow contact), ND 93-1.4, width 7.9 mm.

J,K, *Meniscoessus robustus*, occlusal and labial views of $M^{\frac{1}{}}$, Hell Creek Fm., Stumpf site (Sec. no. 32)(136 ft./41 m below Hell Creek/Ludlow contact), ND 93-1.5, width 9.3 mm.

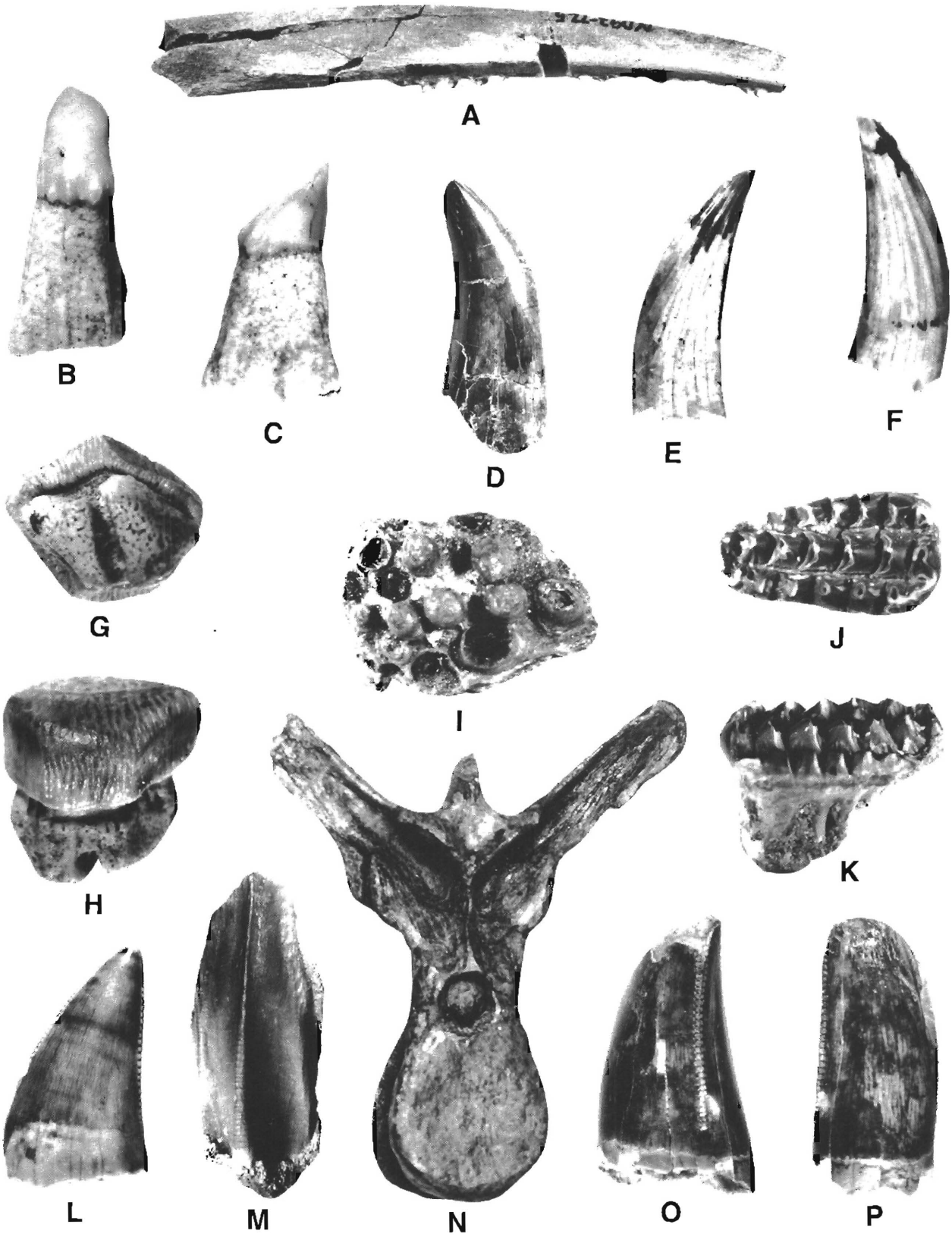
L, *Saurornitholestes* sp., lingual view of tooth, Hell Creek Fm., Stumpf site (Sec. no. 32)(136 ft./41 m below Hell Creek/Ludlow contact), ND 93-1.6, height 7.2 mm.

M, Hadrosauridae indet., crown view of tooth, Hell Creek Fm., Stumpf site (Sec. no. 32)(136 ft./41 m below Hell Creek/Ludlow contact), ND 93-1.7, height 19.0 mm.

N, Ceratopsidae indet., posterior view of vertebra, Hell Creek Fm., Stumpf site (Sec. no. 32)(136 ft./41 m below Hell Creek/Ludlow contact), ND 93-1.8, height 518.0 mm.

O,P, *Dromaeosaurus* sp., posterior and lingual view of premaxillary tooth, Hell Creek Fm., Stumpf site (Sec. no. 32)(136 ft./41 m below Hell Creek/Ludlow contact), ND 93-1.9, height 16.5 mm.

APPENDIX D



APPENDIX D (continued). Representative fossils from the Hell Creek and Ludlow Formations.

Q, *Lioplacodes* sp., Ludlow Fm., Keller site (Sec. no. 7)(11 ft./3.4 m above the Hell Creek/Ludlow contact), ND 95-16.1, height 18.3 mm.

R, *Leidyosuchus* cf. *L. sternbergi*, anterior part of left maxilla, Ludlow Fm., Katus site (Sec. no. 9)(about 5 ft./1.5 m above Hell Creek/Ludlow contact), ND 93-94.1, width 150.2 mm.

S, *Ischyodus* sp., occlusal view of right palatine, Breien Mbr., Hell Creek Fm., Stumpf site (Sec. no. 32)(140 ft./42 m below Hell Creek/Ludlow contact), ND 95-15.1, height 15.7 mm.

T,U, *Scapherpeton tectum*, left lateral and posterior view of dorsal vertebra, Hell Creek Fm., Stumpf site (Sec. no. 32)(136 ft./41 m below Hell Creek/Ludlow contact), ND 93-63.1, width of **T** 9.4 mm.

V,W, *Brachychampsa* cf. *B. montana*, occlusal and medial views of tooth, Hell Creek Fm., Stumpf site (Sec. no. 32)(136 ft./41 m below Hell Creek/Ludlow contact), ND 93-1.10, width 6.2 mm.

X,Y, *Carcharias* sp., lingual and labial views of lateral tooth, Breien Mbr., Hell Creek Fm., Stumpf site (Sec. no. 32)(140 ft./42 m below Hell Creek/Ludlow contact), ND 95-15.2, height 12.1 mm.

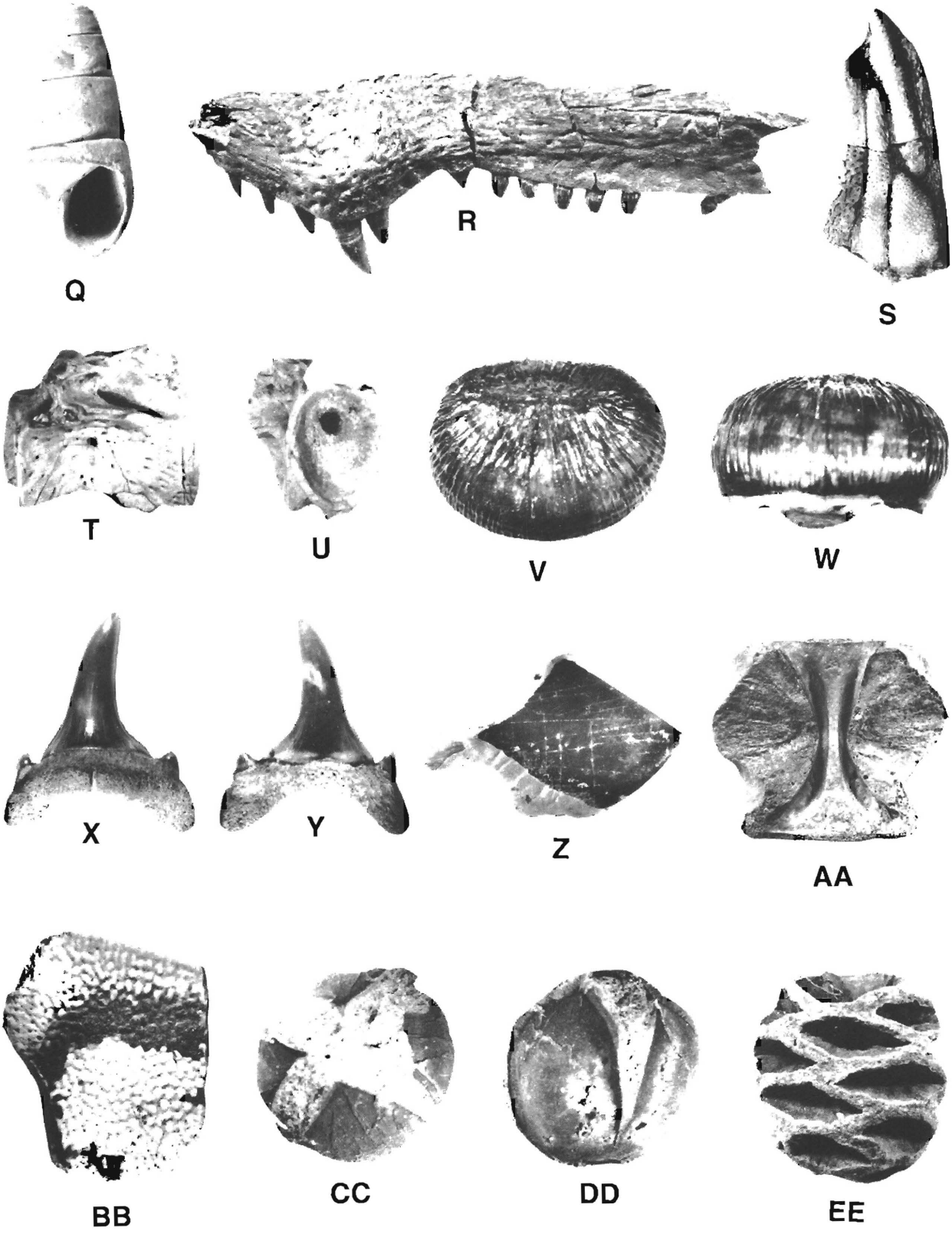
Z, *Lepisosteus* sp., scale, Ludlow Fm., Katus site (Sec. no. 9)(about 5 ft./1.5 m above Hell Creek/Ludlow contact), ND 93-94.2, width 5.7 mm.

AA, *Champsosaurus* sp., dorsal view of vertebra, Hell Creek Fm., Stumpf site (Sec. no. 32)(136 ft./41 m below Hell Creek/Ludlow contact), ND 93-1.11, width 30.4 mm.

BB, *Compsemys victa*, carapace fragment, Hell Creek Fm., Stumpf site (Sec. no. 32)(136 ft./41 m below Hell Creek/Ludlow contact), ND 93-1.12, height 14.6 mm.

CC,DD, Seed indet., dorsal and lateral views, Hell Creek Fm., Stumpf site (Sec. no. 32)(102 ft./31 m below Hell Creek/Ludlow contact), ND 93-77.6, width 7.8 mm.

EE, *Sequoia dakotensis*, lateral view of cone, Hell Creek Fm., Stumpf site (Sec. no. 32)(102 ft./31 m below Hell Creek/Ludlow contact), ND 93-77.7, height 19.1 mm.


Q
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AA
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CC
DD
EE

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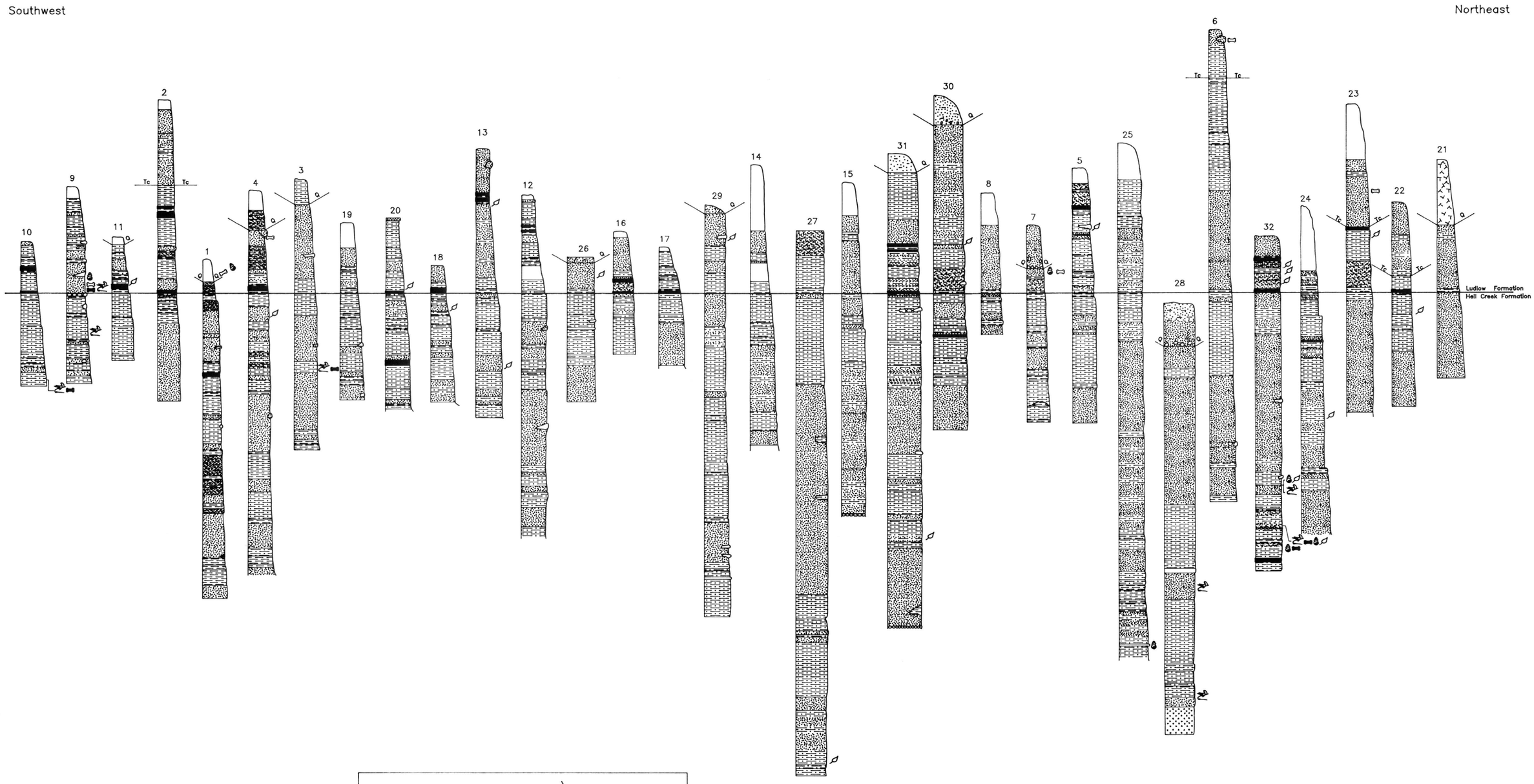
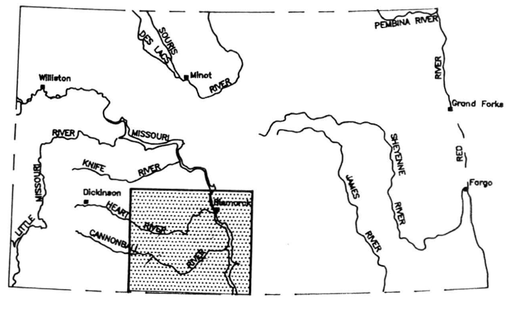
1995

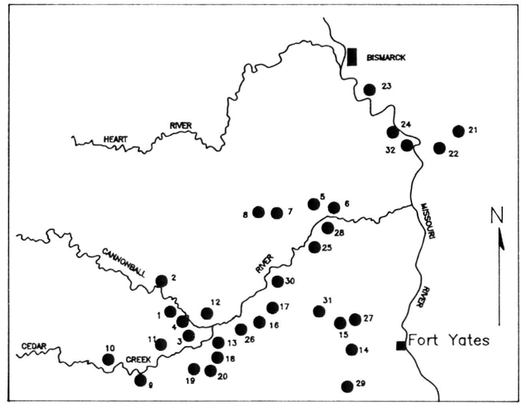
THE LITHOSTRATIGRAPHIC CONTACT BETWEEN THE HELL CREEK AND LUDLOW FORMATIONS IN SOUTH–CENTRAL NORTH DAKOTA

Southwest

Northeast







VERTICAL SCALE

Meters	Feet
0	0
10	
	50
20	
30	100

- Sandstone
- Siltstone
- Mudstone
- Claystone
- Lignite
- Concretion
- Covered Interval
- Volcanic Ash
- Till

- Q Quaternary Deposits
- Tc Cannonball Formation (Paleocene)
- Paleocene Vertebrates
- Cretaceous Vertebrates
  - Dinosaur
  - Non–dinosaur
- Invertebrates
- Leaf Fossils

The Cretaceous/Tertiary Boundary in South–Central North Dakota
by: E.C. Murphy, D.J. Nichols, J.W. Hoganson, and N.F. Forsman
NORTH DAKOTA GEOLOGICAL SURVEY REPORT OF INVESTIGATION NO.98
PLATE 1.

THE CRETACEOUS/TERTIARY BOUNDARY INTERVAL IN SOUTH–CENTRAL NORTH DAKOTA

SOUTHWEST

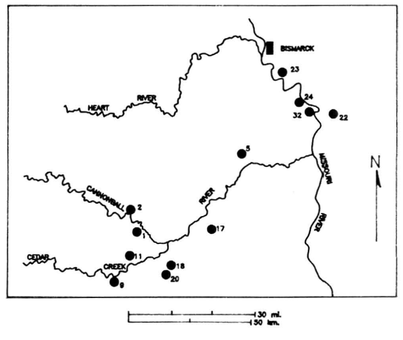
NORTHEAST

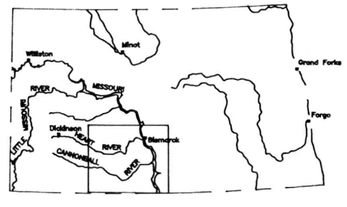
9 11 2 1 20 18 17 5 32 24 23 22

Displacement
meters feet
20 15 10 5 0 5 10 15 20

Ludlow Formation
Hell Creek Formation

VERTICAL SCALE
M. FT.
0 0
1 5
2
3 10
NO HORIZONTAL SCALE





- Sandstone
- Siltstone
- Mudstone
- Claystone
- Lignite
- Leaf Fossils
- Invertebrates
- Concretion
- Tertiary palynologic assemblage
- Cretaceous palynologic assemblage
- Cretaceous/Tertiary Boundary Interval
- Paleocene Vertebrates
  Cretaceous Vertebrates
- Dinosaur
- Non–dinosaur

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PLATE 2.