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Task 50 - Deposition of Lignites in the Fort Union Group and Related Strata of the Northern Great Plains

Topical Report
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DEPOSITION OF LIGNITES IN THE FORT UNION GROUP AND RELATED STRATA OF THE NORTHERN GREAT PLAINS

ABSTRACT

With the aid of a grant from the Philip M. McKenna Foundation and joint venture funding from the U.S. Department of Energy, Late Cretaceous, Paleocene, and early Eocene geologic and paleontologic studies were undertaken in western North Dakota, eastern and south-central Montana, and northwestern and northeastern Wyoming. These study areas comprise the Williston, Bighorn, and Powder River Basins, all of which contain significant lignite resources. Research was undertaken in these basins because they have the best geologic sections and fossil record for the development of a chronostratigraphic (time-rock) framework for the correlation of lignite beds and other economic resources. A thorough understanding of the precise geologic age of the deposition of sediments permits a powerful means of interpreting the record of geologic events across the northern Great Plains. Such an understanding allows for rigorous interpretation of paleoenvironments and estimates of resource potential and quality in this area of economically significant deposits.

This work is part of ongoing research to document change in the composition of molluscan fossil faunas to provide a paleoenvironmentally sensitive independent means of interpreting time intervals of brief duration during the Late Cretaceous, Paleocene, and Eocene. This study focuses on the record of mollusks and, to a lesser extent, mammals in the 1) Hell Creek–Tullock Formations, which include the Cretaceous–Paleocene boundary, in the western portion of the Williston Basin, Montana; 2) uppermost Cretaceous, Paleocene, and lowermost Eocene strata in western North Dakota, which includes the last interior seaway in North Dakota; 3) upper Paleocene and lowermost Eocene of the northern portion of the Bighorn Basin of south-central Montana and northwestern Wyoming; and 4) Powder River Basin of northeastern Wyoming and southeastern Montana. The geologic record in each area provides different physical and paleontological information to aid in interpreting the geologic record through the study interval. The results of these efforts have been published or submitted for publication. The following paragraphs summarize the biostratigraphic results in the study areas.

Western Williston Basin (Montana)—Latest Cretaceous–Earliest Paleocene. The record of freshwater bivalves (Unionidae) through the Latest Cretaceous (K) and earliest Tertiary (T) (early Paleocene) is marked by times of high and low diversity. The change in diversity appears coincidentally at or just below the K/T boundary. Where best documented in the northern plains of Montana, particularly in the stratotype of the Hell Creek Formation in the western portion of the Williston Basin, freshwater mollusks are abundant in fluvial channel systems. In uppermost Cretaceous strata, molluscan faunules are generally dominated by freshwater bivalves, including thick-shelled clams of both simple (*Plesielliptio*, *Rhabdotophorus*) and complex surface sculpture, and nonovate shell shapes (*Proparreysia*, *Plethobasus*, *Pleurobema*). Apparently, as in the distribution of dinosaurs, highly sculptured and/or trigonally shaped unionids range abundantly throughout the Hell Creek Formation but are absent in strata within a few meters or less of the K/T boundary. Throughout the Williston Basin and elsewhere in the Western Interior, Paleocene freshwater bivalves and nonmarine mollusks in general have been found, but at only a few localities that contain depauperate faunules. The only unionids found to date in the Tullock or Ludlow

Formations of the Fort Union Group are ovate–elongate in shape and are simply sculptured with concentric (nonchevron) umbonal corrugations (*Plesielliptio*) or dorsal postumbonal dorsally directed curvilinear ridges (*Rhabdotophorus*) or are without sculpture ("*Unio*"). This dramatic faunal change and the reduction in general abundance were long lasting. Freshwater bivalve localities remained relatively uncommon for at least four million years (late middle Paleocene, late Torrejonian). Simple sculpture and shell form persisted throughout the Paleocene and into the Eocene, and unionid diversity remained low. What molluscan record exists just below the boundary suggests a Paleocene faunal composition, but these occurrences are rare and possibly environmentally influenced. This history of unionids is presently not ascribable to a K/T event.

Williston Basin (North Dakota)—Latest Cretaceous–Earliest Eocene. The uppermost Cretaceous and Lower Tertiary (Paleocene–Eocene) strata of the North Dakota portion of the Williston Basin contain significant geologic sections including 1) the type area of the Fort Union Group; 2) the most complete record of the Cannonball Formation; and 3) the youngest Cretaceous (Fox Hills and Breien) and oldest Tertiary (Cannonball) marine strata in the interior of North America. Present studies have correlated these strata to the North America land mammal age biochronology and a current radiometric and polarity chronology. On the basis of palynomorphs, the Hell Creek–Ludlow formational contact is effectively isochronous and a near match to the K/T boundary across western North Dakota. Planktic forams from the main body of the Cannonball Formation indicate the unit as lower but not basal Paleocene. The Cannonball Formation is correlated to a radiometric timescale on the basis of current planktonic foram zone age dates. Three tongues of the Cannonball Formation have been recognized. Radiometric dates and mammalian fossils suggest a Puercan age for the lowermost tongue, while the Boyce and Three V Tongues are probably of Torrejonian (To) age. The diachronous nature of the Slope Formation appears to be confirmed by a radiometric date near the base of the Bullion Creek Formation and the middle Tiffanian (Ti3) Brisbane mammalian local fauna. The Bullion Creek–Sentinel Butte formational contact is temporally well controlled on the basis of a number of low-diversity mammalian local faunas. Fort Union strata, as examined by F.V. Hayden in the middle 1800s, can now be restricted to the Ti3 and Ti4 ages. The age of the Sentinel Butte–Golden Valley formational contact is not well controlled. Floral similarities between the Bear Den Member and the Fort Union southeast of Red Lodge, Montana, suggest an early Clarkforkian age for the lower part of the Golden Valley Formation in North Dakota. The mammals, mollusks, and flora of the Camels Butte Member indicate a Wasatchian (Wa) age. The mammals from the White Butte Locality further suggest the Wa3 biochron.

Bighorn Basin (Wyoming–Montana)—Late Paleocene–Early Paleocene. The nonmarine molluscan fauna in the Western Interior of the United States underwent large-scale changes during the time represented by the Laramide Orogeny. This period began with the loss of many bivalve and gastropod taxa near the Cretaceous–Paleogene boundary, followed by an increase in mesogastropod diversity in the late Torrejonian and Tiffanian, then a reduction in such diversity into the Clarkforkian that is associated with a dramatic increase in the representation of terrestrial prosobranch and pulmonate families prior to the beginning of the Wasatchian age. The latter portion of this record is well documented in the northern portion of the Bighorn Basin in Wyoming and Montana. The Clarkforkian–Wasatchian boundary, equated by some with the Paleocene–Eocene boundary, on the basis of the pattern of mammalian evolution and other evidence in this area, is delimited by aquatic and terrestrial mollusks, but the faunal change is less dramatic in the Bighorn Basin than changes associated with the increase in terrestrial taxa during the middle Clarkforkian. However, certain nonmarine molluscan taxa appear to be good indicators of an early Wasatchian age, whether they occur in the San Juan Basin of New Mexico or on the Wasatch Plateau of Utah. The present study shows that molluscan taxa appear capable of indicating Clarkforkian biochrons in the absence of mammalian fossils in the Powder River Basin of southeastern Montana and northeastern Wyoming. The approximate stratigraphic horizon of the early and middle Clarkforkian boundary is near the level of the Anderson coal bed, while Wasatchian-age strata occur just above the Arvada coal bed in the main body of the "Wasatch" Formation. The boundary is documented by both the loss and introduction of different species of mesogastropods and aquatic pulmonates, as well as a few species of unionid and pisidiid bivalves. The Clarkforkian–Wasatchian boundary in the Willwood Formation of the Clarks Fork Basin can be determined on the basis of these taxa and also by a well-differentiated and diverse terrestrial snail fauna.

ABBREVIATIONS AND NOTES

The following institutional abbreviations are used in this report: DOE (U.S. Department of Energy), the EERC (Energy & Environmental Research Center), UND (University of North Dakota, Department of Geology and Geological Engineering), and USGS (U.S. Geological Survey). Miscellaneous abbreviations include the following: K/T (Cretaceous–Tertiary).

All observations were plotted on U.S. Geological Survey 7.5-minute series topographic quadrangles. Geologists of the Montana Bureau of Mines and Geology are in the process of producing a new 1:500,000-scale state geologic map. Preprint versions of maps at various scales were graciously provided by Susan Vuke. The placement of some lithostratigraphic contacts and member nomenclature were revised subsequent to field work undertaken for this project.

Fossil locality and geologic observation numbering systems are employed throughout this report. All localities have an L-number for the purposes of computer-based data management. All locality and geologic observation data are maintained in databases designed in Version 4 of Q&A® by Symantec Corporation.

OVERVIEW OF COLLABORATION AND SUPPORT

This project was undertaken with the support of the DOE and McKenna Foundation. The principal investigator was Joseph H. Hartman. Besides the work of the principal investigator, Barry Roth of the University of California-Berkeley contributed to the research on the terrestrial mollusks of the Bighorn Basin and is coauthor on one paper (Hartman and Roth, in press) and senior author on another (Roth and Hartman, submitted); Allen J. Kihm contributed to the research on the mammals of the North Dakota portion of the Williston Basin and is coauthor on one paper (Hartman and Kihm, 1996) and senior author on others (Kihm and Hartman, submitted; in preparation). Others contributed their knowledge, resources, and/or facilities to aid in this research project: P.M. Gingerich and G.F. Gunnell (University of Michigan); T.J. Kroeger (Bemidji State University); S.P. Lund (University of Southern California), P.J. Morris (Amherst College); M.C. McKenna (American Museum of Natural History); W.A. Clemens, Jr., and P. Holryod (Museum of Paleontology, University of California, Berkeley); C.L. Gibson and D.E. Fastovsky of the University of Rhode Island; C.A. Edwards (U.S. Geological Survey); J.W.M. Thompson (Department of Paleobiology, U.S. National Museum of Natural History), and F.J. Collier (Museum of Comparative Zoology, Harvard University). An earlier phase of the project included the valuable field and/or laboratory assistance of the following students employed by J.H. Hartman at the EERC: T.J. Kroeger (graduated), W.D. Peck (graduated; now EERC staff), M.R. Rolland, and D.E. Heinen. Generous access to property, hospitality, and directions to fossil localities locally known were given by Lyle and Darlene Nelson (Fort Peck, Montana) and John and Sylvia Trumbo and their son Mike (Jordan, Montana). Permission to access private property throughout the study area is gratefully acknowledged. Thanks are also given for the cooperation extended by W.J. Berg of the Charles M. Russell National Wildlife Refuge.

DEPOSITION OF LIGNITES IN THE FORT UNION GROUP AND RELATED STRATA OF THE NORTHERN GREAT PLAINS

PROJECT OBJECTIVE

This research concerns the determination of the timing of coal deposition in the Fort Union Coal Region of the northern Great Plains. The project objective is to develop a time framework that allows for the temporal comparison of coal deposits, and thus coal-forming conditions, through the sequence of intercalated freshwater and marine deposits occurring from the uppermost Cretaceous through the Paleocene and into the lowermost Eocene in the Fort Union Coal Region. Thus the objective of this project is to better delimit the timing of coal formation to make possible more rigorous interpretations of the paleoenvironmental conditions under which lignite formed. Such knowledge potentially permits more precise prediction of coal quality and thickness, and thus contributes significantly to effective resource evaluation and subsequent utilization.

APPLICABILITY TO FOSSIL ENERGY OBJECTIVES

This research is part of a larger program designed to provide information on the timing of deposition of coal beds in the Fort Union coal region. Such temporal data allow for a means to reconstruct the depositional history of coal. The derived chronostratigraphic foundation represents an earth-based, or natural, organizational system in which to place associated coal composition and quality data that are especially important to sound decisions regarding coal extraction and utilization. Temporal characterization of coal-bearing strata is especially critical in considerations specific to nonstrippable coal, which represents the bulk of Western Interior coal resources (about 95 percent of North Dakota coal resources; see data in Averitt, 1975), and in which interest will increase as more accessible resources are depleted. Thus this study provides information of value to secure future energy supplies by expanding the recoverable coal resource through a necessary understanding of when and how the peat forming the coal deposit accumulated.

SUMMARY OF THE PROBLEM

Effective and efficient utilization of coal resources depends on appropriate characterization. To date, coal analysis and coal resource assessment have been almost exclusively conducted without regard for the temporal framework upon which regional geologic setting and specific paleoenvironmental interpretations must necessarily be based. In many cases, the varying composition and quality of coal are documented largely as analytical results without reference to their environmental meaning or as a reflection of paleoenvironmental conditions. Coal sample characterization, without temporal and geologic context, represents isolated observations that are generally incapable of providing information that would lead to a determination of regional trends in coal distribution, geochemistry, preservation, and thickness. Expensive drilling programs provide valuable coal correlation data, but without an understanding of the timing of coal deposition, the reconstruction of paleoenvironments may easily compare coals formed at different times, and thus lead to incorrect relationships and inaccurately interpreted paleoenvironmental conditions. Changes in climates, vegetation and vegetational patterns, and past land and water configurations produce different depositional histories. Presently, an understanding of trends in coal quality is made almost impossible by the absence of context for many, if not most, coal sample observations in the Fort Union Coal Region (Hartman, 1992b).

INTRODUCTION

Associated with the Laramide Orogeny (uplift of the Rocky Mountains) during the latest Cretaceous, Paleocene, and early Eocene, was the development of major river systems transporting sediment across the northern Great Plains (Figure 1). A succession of fluvial and lacustrine paleoenvironments is intercalated with marine and marginal marine conditions that represent the last occurrence of an epeiric sea in the interior of North America. This interval of time includes the record of a major change in the deposition of sediments. This change is from non-coal-forming environments to conditions under which peat accumulation was commonplace. This change in paleoenvironmental conditions occurs very near the Cretaceous–Paleocene boundary, which is marked by a very widespread coal (e.g., Z coal). The Paleocene is a time marked by numerous and sometimes thick coal accumulations in northeastern Wyoming, eastern Montana, southern Saskatchewan, and western North Dakota. This area has been referred to as the Fort Union Coal Region, which takes its name from the Fort Union Group (or Formation of others) that includes most of the coal-bearing strata of the Paleocene (about 65 to 55 million years before present; see Figure 2). As originally introduced by Meek and Hayden in 1862, the Fort Union Group was synonymous with the Great Lignite Basin (= Williston Basin). This study focuses on the record of mollusks, and to a lesser extent mammals, in the 1) Hell Creek–Tullock Formations, which include the Cretaceous–Paleocene boundary, in the western portion of the Williston Basin, Montana; 2) uppermost Cretaceous, Paleocene, and lowermost Eocene strata in western North Dakota, which includes the last interior seaway in North Dakota; 3) upper Paleocene and lowermost Eocene of the northern portion of the Bighorn Basin of south-central Montana and northwestern Wyoming; and 4) Powder River Basin of northeastern Wyoming and southeastern Montana (Figure 1). The geologic record in each area provides different physical and paleontological information to aid in interpreting the geologic record through the study interval (Figure 2). The results of these efforts have been published or submitted for publication. The paragraphs to follow later summarize the biostratigraphic results in the study areas.

This project is part of an Energy & Environmental Research Center (EERC) research program designed to document the timing of the deposition of peat in the Fort Union Coal Region. Temporal or time-rock data provide a means to relate the history of coal-bearing deposition across an entire region or between regions. Temporal data are primarily derived from the sequence of fossil occurrences and from paleomagnetic reversal documented in the orientation of magnetic minerals in geologic sections. These sequence-ordered observations can be significantly supplemented by geochemical data (such as impact fallout) that are usually derived from thin rock layers representing an instant in geologic time. A temporally controlled stratigraphic framework (= chronostratigraphy) is an organizational system that represents the accumulation of peat and associated fluvial and lacustrine deposits during a specified time interval. Without a temporally based framework, there is little hope of producing accurate models of the formation of coal-bearing strata throughout a coal region. Such models or reconstructions of ancient environments are important to understanding the reasons for, and thus to being able to evaluate and predict, the quality, thickness, and distribution of coal deposits. This becomes particularly important for the consideration of coal at depth, which cannot be observed directly.

One of the major continuing goals of paleontological research is to develop a better understanding of geologic time. The expression "better understanding" means to place into effect a scheme or framework that permits time to be more finely subdivided into relative time units of briefer and briefer duration. A relative timescale that permits high resolution allows researchers in other disciplines to interpret geological events with some assurance that these events are occurring at or nearly the same time. The timing of the record of sediments that are laid down on the continents by rivers and in lakes or as preserved in soils or other settings has been difficult to establish, in part because of the ephemeral nature of these environments compared to marine habitats. The most widely employed timescale for nonmarine strata that were formed at the end of the Cretaceous and on into the Tertiary (Paleocene, first epoch of the Tertiary) is that based on the evolutionary history of mammals. This system necessarily requires the occurrence of a sufficient number of fossil mammal taxa at a locality to provide some assurance that a biochron, which represents a particular portion of a fossil-based timescale, can be accurately recognized. Even with a knowledge of fossil mammals at a locality, the mammalian timescale is far from being completely established and is the subject of constant discussion and revision, as more and better data become available to affect previous interpretations. This project examines another component of the nonmarine biota to establish an additional fossil group to interpret geologic time in continental strata. To this end, nonmarine mollusks, representing freshwater clams and freshwater and terrestrial snails, are used to develop a temporal framework for strata primarily of Paleocene age in North America. This framework is being established initially in the northern Great Plains for the reasons discussed below, with a resulting nonmarine molluscan zonation for the interval studied (see figures for examples).

The Molluscan Record

The occurrence of nonmarine mollusks has been shown to be far more abundant than generally appreciated (Hartman, 1984a). A representation of this abundance is given in Figure 3, using the distribution of mollusks in the Williston Basin study area as an example. The Williston Basin (Figure 1) is a structural feature affecting the dip of bedrock strata across western North Dakota, eastern Montana, and southern Saskatchewan. The stratigraphic sequence of the Williston Basin includes the uppermost Cretaceous Hell Creek (Montana–North Dakota), Lance (Montana–Wyoming), and Frenchman (Saskatchewan) Formations. These formations include about 175 Lancian-age localities around the rim of the basin. The Fort Union Group (Formation) includes the Tullock, Ludlow, Lebo, Slope, Bullion Creek, Tongue River, and Sentinel Butte Formations and, along with the Bear Den Member, contains over 1100 nonmarine molluscan localities. In North Dakota, the Paleocene sequence is overlain by isolated outcrops of the Camels Butte Member of the Golden Valley Formation. Specimens from only three localities have so far been recovered from this unit, but they are indicative of a Wasatchian age (see Figure 2). The pattern of occurrence of these localities is largely coincident with available outcrop for sampling, indicating that nonmarine mollusks can generally be found in most areas of study. In total, over 1300 nonmarine molluscan localities are known from this sequence in the Williston Basin.

This record of nonmarine mollusks can be contrasted with the number of mammalian localities in the Williston Basin, which are depicted in Figure 4. The number of mammalian localities is far fewer than that known for mollusks, and, importantly, mammalian localities rarely occur in stratigraphic succession in a local outcrop area. In North Dakota, most of the Paleocene mammalian local faunas are known from only a few teeth, limiting their value in determining the precise age of the enclosing strata.

Molluscan Biostratigraphy

The evolution of nonmarine mollusk species has generally been considered too slow to provide a basis for using them in detailed biostratigraphic studies. Such studies are concerned with the documentation of the occurrence of selected species through sections of rock strata. The work of biostratigraphy is to determine the oldest (or first) and youngest (or last) record of a species. Thus biostratigraphic studies rely heavily on an understanding of the accurate correlation of formational contacts and marker beds to determine the relative position of fossil localities. An example of the placement of mollusk-bearing localities into a stratigraphic sequence is given in Figure 5 (derived from Hartman and others, 1993a). This geologic section includes all of the nonmarine molluscan localities known from the area of the Nesson Anticline along the Missouri River in northwestern North Dakota. Similar composite sections exist for all of the study areas. With this type of biostratigraphic control in various outcrop areas throughout the Williston and Powder River Basins, the range of existence of a species can be accurately fixed. An assemblage of species' ranges determined in this manner provide the basis for interpreting which species can be best used to determine a temporal framework or relative timescale for a portion of the earth's crust. An example of an assembled group of species, ordered by first and last occurrences, is given for the Powder River Basin in Figure 6 (derived from Hartman, 1990, 1992a, 1993b, and present studies). The time span represented by the Paleocene is about 10 million years, with the Wasatchian portion of the lower Eocene representing possibly as little as two million years. Figure 6 is constructed on the basis of stratigraphic thickness, with a thickness of 900 or more meters for Paleocene and Eocene strata in the basin. Thus the apparent longer duration of species in the "Wasatch" Formation is a reflection on the rate of sediment deposition and not length of time. The relative duration of species ranges indicates that the Paleocene and Eocene can be readily differentiated and that the Paleocene can be subdivided into a number of molluscan biozones representing relatively short periods of time. The best potential use of nonmarine mollusks for the recognition of biochrons of short duration is in the late Paleocene, after the final retreat of last epiric sea from North America (see below). Molluscan occurrences in the early and early middle Paleocene are fewer and less well preserved, leading to ambiguity in the determination of the duration of species' ranges. In the Powder River, the stratigraphic distribution of mollusks relative to major coalbed intervals (e.g., Roland–Anderson coalbed interval) indicate that these intervals can be recognized on the basis of molluscan distribution throughout the basin.

Broad–scale changes in the composition of the nonmarine molluscan fauna can also be useful in noting important changes in regional paleoenvironments and possibly more general changes in climate. The uppermost Cretaceous record of nonmarine mollusks was dominated by riparian clam faunas (Unionidae). These clams were generally abundant and highly diverse, including a number of taxa with highly sculptured shell surfaces (Hartman, 1991; in press). At or near the end of the Cretaceous, this Lancian-age fauna vanished. Clams of the Paleocene number only a few species of generally simple shell form, with none possessing tubercles, nodes, or chevron ridges common to Cretaceous taxa. The Paleocene nonmarine molluscan fauna was dominated by gill-bearing snails known only from families of the prosobranch Order Mesogastropoda. Towards the end of the Paleocene, a number of new air-breathing snail taxa (primarily belonging to the Subclass Pulmonata) are known from a few areas. Apparently, one of the earliest records of the transition from mesogastropod- to pulmonate-dominated faunas occurs in the latter portion of the Paleocene (mammalian biochron Tiffanian 4) of North Dakota (Hartman and others, 1993b; Hartman, 1994a, b; Hartman and Kihm, 1995; Hartman and Roth, in preparation). The introduction of these new pulmonate species is shown in Figure 7 by the taxa numbers 45 to 64, which occur in the lower part of the Sentinel Butte Formation (Hartman and Kihm, 1995). This figure illustrates the biostratigraphic ranges of species along the upper Missouri River in North Dakota and adjacent Montana (see Figure 1). The continuing development of this pulmonate-based fauna is seen next with a new assemblage of terrestrial snails occurring at the end of the Tiffanian and on into the Clarkforkian, which represents the last stage of the Paleocene. This record is developed in the Bighorn Basin of north-central Wyoming and in the Hoback Basin of northwestern Wyoming. As can be seen in Figure 6, a largely new fauna of nonmarine mollusks marks the beginning of the Eocene in the Powder River Basin.

From the above description of the nonmarine molluscan record in the northern Great Plains, molluscan taxa do not, in general, appear to go through long periods of evolutionary stasis. Changes in paleoenvironmental regimes at the end of the Cretaceous resulted from the influx of clastic sediments of the initial uplift of the Rocky Mountains, which was nearly coincident with the regression of the Fox Hills Sea. The resulting large river systems represented a time of tremendous clam diversification. The beginning of the Paleocene was a time of habitat instability, derived and maintained from a series of Cannonball Sea transgressive and regressive events. The slow recovery of the molluscan fauna, from a near virtual collapse at the end of the Cretaceous, resulted in low species diversity during the early and middle Paleocene. With a return of progradational sedimentation in the late Paleocene, freshwater snails diversified into a complex association of closely related species. With apparently little significant change in sedimentary environments, the molluscan fauna began to be constituted by species indicating drier conditions. By the beginning of the Eocene, few taxa representative of a Paleocene ecosystem remained in the northern plains.

PROJECT SCOPE

This project has as its goal the construction of a biozonation based on Paleocene and temporally adjacent nonmarine mollusks. There are important reasons why a Paleocene biozonation should be first configured in the northern Great Plains. The molluscan record in North Dakota, eastern Montana, northeastern Wyoming, and parts of southern Saskatchewan is one where specimens are relatively common and generally well preserved (Hartman, 1978, 1984b). Coincidently, but significantly, the first studies of nonmarine mollusks were conducted along the upper Missouri River in North Dakota and Montana. The field work of F.V. Hayden resulted in the collection of all of the significant specimens that would be named by F.B. Meek and Hayden. This assemblage would subsequently be referred to as the "classic Fort Union" fauna and be used to correlate the Paleocene stage throughout the Western Interior of the United States and Canada (Hartman, 1994a; Hartman and Kihm, 1992) for almost 100 years. In addition, Hayden and Meek's studies included the measurement of geologic sections and other observations that would result in the first standard reference section in western North America, comprising Upper Cretaceous and Tertiary strata.

This research utilized available collections to develop species concepts for the purpose of species recognition and use in biostratigraphy. A large number of specimens, collected by me and available from museums, were used to revise and diagnose many of the named species. Such systematic and taxonomic studies were conducted with the goal of publishing the results to provide a basis for conducting nonmarine molluscan systematic studies through this time interval (Hartman, in press; Hartman and Roth, in press; Hartman and Kihm, in preparation). Concomitantly, the results of the systematic studies continue to be incorporated into a biostratigraphic framework that has been under development by me for a number of years. A large number of the available geologic observations that have been previously made by others and me have been compiled and are available for use in the construction of composite reference sections (such as Figure 5) and other lithostratigraphic correlation diagrams. Biostratigraphic charts, similar to those shown as Figures 8 and 9, were constructed for outcrop areas in the northern Great Plains. Wherever possible, this relative timescale will be tied to mammalian local faunas for the purpose of assessing the mammalian ages represented by the molluscan biochrons.

SPECIFIC OBJECTIVES

The specific objective of the project is to disseminate information, through publication and other methods, relevant to providing a basis for delimiting time and the occurrence of lignites in the northern Great Plains.

METHODOLOGY

This section concerns the general methods employed through the course of the project. A number of activities can be noted specifically concerning research on the geology and paleontology in the study areas. Each research area has its own specific study needs because of differences in geology, in preserved paleontological record, and in how previous research in the area had been conducted. In practice, stratigraphic and paleontologic studies are kept separate as much as possible to avoid circular reasoning on the age of enclosing sediments. In other words, fossils are identified on the basis of morphology, avoiding significant inference on the basis of their relative stratigraphic position. This method represents the most unbiased means of being able to identify newly discovered fossils and interpret their biochronologic inference without regard to stratigraphic position. Each newly discovered, well-controlled stratigraphic occurrence of a species does represent, however, a test of the working hypothesis on the previous interpretation of the stratigraphic range of a species.

In the following topical sections each research area is discussed as studied in detail from personal field observations and published and unpublished information. The interpreted correlation of strata was constructed on the basis of the most currently available data.

Williston Basin

The study of the lignite resources, geology, and paleontology in the Williston Basin requires the most complicated approach to reinterpreting previous research and incorporating new observations to correlate strata across the basin. This is in part because of the lack of continuity of exposure across this vast area and, from a geological standpoint, because of the influence of sea movements (e.g., changes in eustatic sea level) during the uppermost Cretaceous and Paleocene marine deposition in North Dakota (Hartman, 1993a; Kroeger and Hartman, in press) and easternmost Montana (Diemer and others, 1996). However, there are areas of the Williston Basin where geologic exposures are sufficiently continuous to permit rigorous biostratigraphic studies. Examples noted in this project include the Garfield and McCone Counties, Montana (Figure 8), in the western portion of the Williston Basin and the Fort Union area of Roosevelt and Richland Counties, Montana, and Williams and McKenzie Counties, North Dakota (Figures 5 and 7). Other areas relevant to the conclusions presented here include exposures along the Little Missouri River in southwestern North Dakota (Kroeger and Hartman, in press), the grasslands of the southeastern portion of the Williston Basin, North Dakota (Kihm and Hartman, submitted, in preparation), and the badland exposures of Glendive area (Hartman, 1996; Hunter and others, in press).

In the western Williston Basin area, all of the fossil mollusks and associated stratigraphic data were studied. Susan Vuke and Edith Wilde of the Montana Bureau of Mines and Geology provided unpublished geologic maps of study areas. These were evaluated for compilation in the revised state geologic map of Montana. The extensive collections made by and my field crews in previous years were placed relative to stratigraphic markers and horizons in the field.

Bighorn Basin (Wyoming–Montana)

In the northern portion of the Bighorn Basin, the study area can be divided into two parts, the Clarks Fork Basin, Park County, Wyoming, and the Red Lodge–Belfry area, Carbon County, Montana. These two areas are remarkably different in their history of study, apparent preservation of fossils, and the occurrence of geologic exposures of differing ages. These differences are represented in the summary illustration of species' stratigraphic distribution in Figure 9. Most of the uncertainty that exists in the assignment of localities to specific stratigraphic horizons (not geographic location) occurs with records from the Montana portion of the basin. This is due to the greater difficulty of placing numerous previously collected specimens into a composite stratigraphic section for the area. The extensive and detailed work of P.D. Gingerich and his students and colleagues (e.g., Gingerich, 1980; Gingerich and Klitz, 1985; Gunnell and others, 1993; Rose, 1979), interpreting the mammalian record in the Clarks Fork Basin, provided the basis of the stratigraphic framework illustrated in Figure 9. This study greatly benefitted from the cooperation of Gingerich and Gunnell in providing current information on the stratigraphic distribution and biochronologic interpretation of mammalian local faunas throughout the northern portion of the basin. Thus, even though virtually no field work was undertaken in the Bighorn Basin, nearly all of the molluscan localities of the Clarks Fork Basin could be placed relative to stratigraphic markers or horizons. In some cases where this was not possible, the age of the strata for the area of a molluscan locality could be determined from associated mammalian data.

Powder River Basin (Wyoming–Montana)

The Powder River Basin differs from the other two study areas in that nearly all fossils from relatively well-described collecting sites made during the 20th century can be placed relatively precisely into a comprehensive lignite-based stratigraphic framework (Figure 6). The process of placing localities relative to stratigraphic markers would not have been possible, however, without the presently available detailed topographic maps (1:24,000) and extensive lignite drilling programs by state and federal geologic surveys, and access to unpublished data concerning location information about fossils (such information went typically unpublished).

EXPLANATION AND SUMMARY OF FINDINGS

This section provides interpretations and conclusions regarding project objectives and tasks. Of primary importance is the dissemination of information on the age relations of coal-bearing strata in the northern Great Plains and intermontane basins. Note, however, that biochronologic conclusions drawn from molluscan assemblages can be used throughout the Western Interior where similar faunas may be found.

Resulting Publications

Hartman, J.H., 1996, Extinction of sculptured nonmarine bivalves about the Cretaceous–Tertiary boundary (invited participant), *in* Wolberg, D.L., and Stump, E. eds., Programs and Abstracts: DinoFest II International Symposium (April 18–21, Arizona State University, Tempe, Arizona), p. 58.

Hartman, J.H., and Kihm, A.J., 1996, Bio- and magnetostratigraphy of the uppermost Cretaceous and lower Tertiary strata of North Dakota *in* Repetski, J.E., ed., Sixth North American Paleontological Convention (Washington, D.C.), Abstracts of Papers: Paleontological Society, Special Publications, no. 8, p. 163.

Diemer, J.A., Belt, E.S., and Hartman, J.H., 1996, Base level changes as a consequence of tectonic, eustatic and autogenic processes in Late Cretaceous and Paleocene strata, western Williston Basin: Geological Society of America, Abstracts with Programs, v. 28, no. 7, p. A373.

Hartman, J.H., 1996, Decimation of the freshwater molluscan fauna near the end of the Cretaceous—A North American perspective, *in* Bardet, N., and Buffetaut, E., eds., The Cretaceous–Tertiary Boundary - Biological and Geological Aspects: Séance spécialisée de la Société Géologique de France, Abstracts, p. 28.

Hartman, J.H., in press, The demise of diversity of Late Cretaceous freshwater bivalves from the western Williston Basin, Montana, U.S.A., *in* Johnston, P., Haggart, J., eds., International Symposium on the Paleobiology and Evolution of the Bivalvia, September 29–October 2, 1995, Drumheller: Geological Association of Canada, Special Papers.

Hartman, J.H., and Roth, B., in press, Nonmarine molluscan faunal change through the late Paleocene and early Eocene in the Bighorn Basin, northwestern Wyoming and south-central Montana, *in* Berggren, W.A., Aubry, M.-P., and Lucas, S.G., eds., Late Paleocene–Early Eocene Events: Columbia University Press.

Hunter, J.P., Hartman, J.H., and Krause, D.W., in press, Mammals and mollusks across the Cretaceous–Tertiary boundary from Makoshika State Park and vicinity, Williston Basin, Montana, *in* Hartman, J.H., guest editor, A festschrift in honor of Marshall

Lambert—Paleontology and geology in the northern Great Plains: University of Wyoming, Contributions to Geology, v. 32, no. 2.

Kroeger, T.J., and Hartman, J.H., in press, Paleoenvironmental distribution of Paleocene palynomorph assemblages from brackish water deposits in the Ludlow, Slope, and Cannonball Formations, southwestern North Dakota, *in* Hartman, J.H., guest editor, A festschrift in honor of Marshall Lambert—Paleontology and geology in the northern Great Plains: University of Wyoming, Contributions to Geology, v. 32, no. 2.

Roth, B. and Hartman, J.H., submitted to Paleobios, A probable *Cerion* (Gastropoda: Pulmonata) from the uppermost Cretaceous Hell Creek Formation, Garfield County, Montana.

Hartman, J.H., in preparation, Paleontology and Biostratigraphy of Latest Cretaceous and Paleocene Viviparidae (Mollusca, Gastropoda) of the Williston and Powder River Basins, Saskatchewan, North Dakota, Montana, and Wyoming.

Resulting Activities

Presentation (invited), DinoFest II International Symposium: "Extinction of sculptured nonmarine bivalves about the Cretaceous–Tertiary boundary," April 21, 1996, Arizona State University, Tempe, Arizona.

Poster, Sixth North American Paleontological Convention: "Bio- and magnetostratigraphy of the uppermost Cretaceous and lower Tertiary strata of North Dakota," Smithsonian Institution, June 9–12, 1996, Washington, D.C.

Presentation (invited), Séance spécialisée de la Société Geologique de France: "Decimination of the freshwater molluscan fauna near the end of the Cretaceous — Biological and Geological Aspects," December 2, 1996, Paris, France.

Poster (invited), Geological Society of America Penrose Conference on Paleocene–Eocene Boundary Events: "Western Interior nonmarine Mollusca and the Paleocene-Eocene boundary," April 24–29, 1996, Albuquerque, New Mexico.

Geologic Studies

The geologic observations derived through the course of this study provide the basis for accurate placement of fossil localities relative to significant geologic horizons providing the basis for the construction of robust biostratigraphic frameworks for a study area. Through the course of examining published and unpublished geologic data, any reinterpretations I have made concerning geologic contacts and mapping have been relayed to respective state geological survey mapping programs.

Western Williston Basin (Montana). The contact between the Hell Creek Formation and Tullock Member of the Fort Union Formation in the western Williston Basin in recent mapping efforts was being mapped almost solely on the basis of the first occurrence of lignite in an area.

Although the occurrence of even minor but relatively continuous beds of lignite are uncommon, using lignites alone can be shown to be inaccurate on the basis of both lithologic and paleontologic evidence. Differences of interpretation were reported to the Montana Bureau of Mines and Geology.

Williston Basin (North Dakota). Since the publication of the North Dakota state geologic map and related explanation by Clayton (1980) and Clayton and others (1977), certain assumptions have been made about the isochroneity of certain formational contacts. Ongoing studies (Hartman and Kihm, 1996; see Bibliography for other citations) directed toward the chronostratigraphic correlation of North Dakota strata has shown that both diachroneity and isochroneity of major formational contacts appear to be part of the North Dakota geologic record. Figure 10 illustrates that the Hell Creek–Ludlow and Bullion Creek–Sentinel Butte formational contacts are very nearly isochronous. On the basis of pollen, coal correlation, and other lithic criteria, the formational boundary may differ only a few meters relative to the Cretaceous–Tertiary (Paleocene) boundary. Exceptions occur where nonlignite environments persist through this section (see for examples Murphy and others, 1995). Also, on the basis of paleomagnetic data (Lund, written communication, 1995), the Hell Creek–Ludlow formational contact may be lightly older to the east, suggesting that interpreting the formational contact only in sections with like environments limits recognition of a possible minor diachroneity. In any case, recognition of the contact between the Hell Creek and Fort Union Formations, however, even with differing paleomagnetic interpretations (see for example, Lerbekmo and Coulter, 1985), place the K/T boundary within Chron 29r, with variations in placement being only a few meters in sections as distantly separated as Huff (south of Bismarck), North Dakota, and Hell Creek (tributary of the Missouri River), Montana.

The Bullion Creek–Sentinel Butte formational contact appears to be in mammalian biochron Ti4 of the upper Paleocene. There are sufficient constraining mammalian local faunas, however depauperate, to provide a strongly argued working hypothesis (Hartman and Kihm, 1991, 1995, 1996; Kihm and Hartman, submitted; in preparation). Distinctive Bullion Creek and Sentinel Butte molluscan faunas can be recognized on the basis of current studies (Hartman and Kihm, 1995), but the distinctive species of the Sentinel Butte fauna are rare (Hartman and others, 1993b). Insufficient paleontological data exist to interpret the diachroneity of the Golden Valley–Sentinel Butte formational contact.

The Ludlow–Slope–Bullion Creek formational contact is currently believed to be diachronous (Hartman and Kihm, 1996). Paleoenvironments through the lower and middle and even lower upper (lower Tiffanian) Paleocene were undoubtedly influenced by the movements of the Cannonball Sea. Available surface and subsurface data (Hartman and Butler, 1995) indicate three recognizable tongues of Cannonball Formation. The Boyce and Three V Tongues are associated with at least locally extensive lignite beds (Hartman, 1993a). Possible age relations of the tongues of the Cannonball Formation are presented in Figure 10. The retreat of the Cannonball Formation and the relative thinning of the overlying Slope Formation appear to be well documented on the basis of nonmarine mollusks, mammals, foraminifera, and geologic sections from western to central North Dakota.

The quantity and quality of lignites vary in the Fort Union Formation. Numerous and relatively thick lignites do not appear to form until the middle Paleocene and remain common, but of varying economic value, through the remainder of the Paleocene.

Bighorn and Powder River Basins. Mined lignites in the Red Lodge area, Carbon County, Montana, were used as part of a framework to stratigraphically organize nonmarine molluscan occurrences. All of these lignites appear to be present in strata of upper Paleocene (late Tiffanian) age (Figure 9). Lignites of significance are absent from the remainder of the Fort Union Formation and overlying Willwood Formation. The value of the nonmarine molluscan biostratigraphic framework developed for the northern Bighorn Basin, however, is that it provides a well-controlled chronostratigraphic basis for interpreting the age relations of the significant coal deposits of the Powder River Basin (Figure 6). Prior to this study, the age relations of mollusks to mammals in the late Tiffanian and Clarkforkian were not understood. Delimiting the stratigraphic occurrence of mollusks in the framework of Bighorn Basin mammal local faunas allows molluscan species to now be recognized as potentially indicative of the Clarkforkian, as well as certain biochrons. As there are few pre-Eocene mammalian localities known in the Powder River Basin (with only one Clarkforkian mammalian locality known) and hundreds of molluscan localities, age-diagnostic molluscan assemblages provide a rigorous basis for interpreting both the specific age of coal beds and assigning faunas to specific coalbed intervals.

Paleontologic Studies

Western Williston Basin (Montana). The record of freshwater bivalves (Unionidae) through the Latest Cretaceous and earliest Tertiary (early Paleocene) is marked by times of high and low diversity. The change in diversity appears coincidentally at or just below the K/T boundary. Where best-documented in the northern plains of Montana, particularly in the stratotype of the Hell Creek Formation in the western portion of the Williston Basin, freshwater mollusks are abundant in fluvial channel systems. In uppermost Cretaceous strata, molluscan faunules are generally dominated by freshwater bivalves, including thick-shelled clams of both simple (*Plesielliptio*, *Rhabdotophorus*) and complex surface sculpture, and nonovate shell shapes (*Proparreysia*, *Plethobasus*, *Pleurobema*). Apparently, as in the distribution of dinosaurs, highly sculptured and/or trigonal-shaped unionids range abundantly throughout the Hell Creek Formation but are absent in strata within a few meters or less of the K/T boundary. Throughout the Williston Basin and elsewhere in the Western Interior, Paleocene freshwater bivalves and nonmarine mollusks in general have been found, but only at a few localities that contain depauperate faunules. The only unionids found to date in the Tullock or Ludlow Formations of the Fort Union Group are ovate–elongate in shape and are simply sculptured with concentric (nonchevron) umbonal corrugations (*Plesielliptio*) or dorsal postumbonal dorsally directed curvilinear ridges (*Rhabdotophorus*) or are without sculpture ("*Unio*"). This dramatic faunal change and the reduction in general abundance were long lasting. Freshwater bivalve localities remained relatively uncommon for at least four million years (late middle Paleocene, late Torrejonian). Simple sculpture and shell form persisted throughout the Paleocene and into the Eocene, and unionid diversity remained low. What molluscan record exists just below the boundary suggests a Paleocene faunal composition, but these occurrences are rare and possibly environmentally influenced. This history of unionids is presently not ascribable to a K/T event.

Williston Basin (North Dakota). The uppermost Cretaceous and lower Tertiary (Paleocene–Eocene) strata of the North Dakota portion of the Williston Basin contain significant geologic sections including 1) the type area of the Fort Union Group; 2) the most complete record of the Cannonball Formation; and 3) the youngest Cretaceous (Fox Hills and Breien) and oldest Tertiary (Cannonball) marine strata in the interior of North America. Present studies have correlated these strata to the North America land mammal age biochronology and a current radiometric and polarity chronology. On the basis of palynomorphs, the Hell Creek–Ludlow formational contact is effectively isochronous and a near match to the K/T boundary across western North Dakota. Planktic forams from the main body of the Cannonball Formation indicate the unit as lower but not basal Paleocene. The Cannonball Formation is correlated to a radiometric time scale on the basis of current planktonic foram zone age dates. Three tongues of the Cannonball Formation have been recognized. Radiometric dates and mammalian fossils suggest a Puercan age for the lowermost tongue, while the Boyce and Three V Tongues are probably of Torrejonian (To) age. The diachronous nature of the Slope Formation appears to be confirmed by a radiometric date near the base of the Bullion Creek Formation and the middle Tiffanian (Ti3) Brisbane mammalian local fauna. The Bullion Creek–Sentinel Butte formational contact is temporally well controlled on the basis of a number of low-diversity mammalian local faunas. Fort Union strata, as examined by F.V. Hayden in the middle 1800s, can now be restricted to the Ti3 and Ti4 ages. The age of the Sentinel Butte–Golden Valley formational contact is not well controlled. Floral similarities between the Bear Den Member and the Fort Union southeast of Red Lodge, Montana, suggest an early Clarkforkian age for the lower part of the Golden Valley Formation in North Dakota. The mammals, mollusks, and flora of the Camels Butte Member indicate a Wasatchian (Wa) age. The mammals from the White Butte Locality further suggest the Wa3 biochron.

Bighorn Basin (Wyoming—Montana). The nonmarine molluscan fauna in the Western Interior of the United States underwent large-scale changes during the time represented by the Laramide Orogeny. This period began with the loss of many bivalve and gastropod taxa near the Cretaceous–Paleogene boundary, followed by an increase in mesogastropod diversity in the late Torrejonian and Tiffanian, then a reduction in such diversity into the Clarkforkian that is associated with a dramatic increase in the representation of terrestrial prosobranch and pulmonate families prior to the beginning of the Wasatchian age. The latter portion of this record is well documented in the northern portion of the Bighorn Basin in Wyoming and Montana. The Clarkforkian–Wasatchian boundary, equated by some with the Paleocene–Eocene boundary, on the basis of the pattern of mammalian evolution and other evidence in this area, is delimited by aquatic and terrestrial mollusks, but the faunal change is less dramatic in the Bighorn Basin than changes associated with the increase in terrestrial taxa during the middle Clarkforkian. However, certain nonmarine molluscan taxa appear to be good indicators of an early Wasatchian age, whether they occur in the San Juan Basin of New Mexico or on the Wasatch Plateau of Utah. The present study shows that molluscan taxa appear capable of indicating Clarkforkian biochrons in the absence of mammalian fossils in the Powder River Basin of southeastern Montana and northeastern Wyoming. The approximate stratigraphic horizon of the early and middle Clarkforkian boundary is near the level of the Anderson coal bed, while Wasatchian-age strata occur just above the Arvada coal bed in the main body of the "Wasatch" Formation. The boundary is documented by both the loss and introduction of different species of mesogastropods and aquatic pulmonates, as well as a few species of unionid and pisidiid bivalves. The Clarkforkian–Wasatchian boundary in the Willwood Formation of the Clarks Fork Basin can be determined on the basis of these taxa and also by a well-differentiated and diverse terrestrial snail fauna.

Powder River Basin (Wyoming–Montana). The study of fossil nonmarine mollusks in the Powder River Basin dates back to the 1850s, with an expedition by the U.S. Army Corp of topographic engineers. Fossil snails were first collected at this time under the absentee direction of F.V. Hayden along Clear Creek and the lower fork of the Powder River. A few of these specimens were later named as new taxa by Meek and Hayden in 1862 and Meek in 1876. Although Paleocene and Eocene mollusks were collected by geologists of the U.S. Geological Survey in 1896 and 1901, significant collections were not made until 1907. At this time, under congressional mandate, the USGS began a new and intensive coal resource evaluation program and collected specimens in unprecedented numbers.

T.-C. Yen (1948) of the USGS, summarized the taxonomy and stratigraphic distribution of 45 localities from the Montana portion of the Powder River Basin. These localities were all from Paleocene age strata, spanning most of the Tongue River Formation, and including the lowest part of the Wasatch Formation. Yen stated, tentatively, that it was possible to discriminate between fossil assemblages from above and below the Wall coal bed. Although many of Yen's identifications have since been revised, present studies confirm that certain taxa do not range above the Wall coal bed in the Powder River Basin and a number of different taxa occur above it. Subsequent to Yen, in the late 1950s and 60s, Dwight Taylor (1975), again of the USGS, reviewed the taxonomy of most of the Paleocene and Lower Eocene nonmarine Mollusca of the Powder River Basin. Like Yen, Taylor intervalized his identifications based on coalbed stratigraphy for the Tongue River Formation and lower part of the Wasatch Formation. Taylor proposed a Paleocene–Eocene boundary at the level of the Anderson coal bed. Taylor drew this conclusion based on the marked change in faunal composition above the Anderson horizon. I suggest that the Paleocene–Eocene boundary should be placed higher in the section, above the level of the Arvada coal bed. On the basis of present studies, the boundary noted by Taylor (1975) occurs within the Clarkforkian biochron, possibly at the Cf1/Cf2 boundary. This conclusion is drawn from examination of collections from over 300 localities that were placed stratigraphically in the context of about 200 sections.

The general abundance and speed of evolution of nonmarine mollusks in the Paleocene and early Eocene of the Powder River Basin is sufficient to permit recognition of the age represented by major coalbed intervals throughout the basin (Figure 6). Such results clearly indicate the value of mollusks for interpreting paleoenvironments penecontemporaneous with peat formation and subsequent coal correlation.

STATEMENT OF RESULTS

Fossil evidence tied to radiometric and paleomagnetic chronologies provides the basis for methodologies to refine the precise chronostratigraphic correlation of lignite beds. This ability permits a better interpretation of coal-forming environments over a broad region, such as the northern Great Plains. More realistic temporally controlled models for paleoenvironmental conditions will provide the potential for improved coal quality assessment in regional appraisals of available coal resources. The specific objective of the project was completed by publications and presentations listed above.

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FIGURE CAPTIONS

Figure 1. **Basins of the northern Great Plains and intermontane basins, United States and Canada.** Structural basins are delimited by Paleocene bedrock as mapped on state and provincial geologic maps. Abbreviations include standard two-letter North American state/province postal codes.

Figure 2. **Nonmarine molluscan chronostratigraphic control in the northern plains and intermontane basins, United States.** This figure summarizes the presently known useful geologic record of major study areas. Each geologic column (e.g., Western Williston Basin) represents the range in age of rocks in the stated area. Shaded portions of the columns represent intervals of geologic time well represented by fossil localities that can be arranged in sequential order for biostratigraphic studies. Stars in the middle of columns indicate important but isolated localities that can not be directly tied to a sequence of several localities in a particular geologic time interval. Stars on the sides of columns indicate radiometric dates available and correlated to a standardized geologic time framework (Berggren and others, 1995) (Ma = millions of years before present) and mammalian biochronology (derived from current studies and Prothero, 1995). Of the strata of the area indicated by this diagram, only the early and middle portions of the Torrejonian (To1 and To2) are not well represented by fossil mollusks. Marine strata is indicated by diagonal lines. The Fox Hills Formation underlies the Cretaceous nonmarine strata in the study area except in the Crazy Mountains Basin where marine and marginal deposits are mapped as the Lennep Formation. Marine strata of probable Lancian age occur as the Breien Member of the Hell Creek Formation. All Paleocene marine strata are known as the Cannonball Formation.

Figure 3. **Lancian, Paleocene, and Wasatchian nonmarine molluscan localities in the Williston Basin, North Dakota and Montana.** The bedrock geology displayed on this map was derived from Clayton (1980) and unpublished data provided by S.M. Vuke of the Montana Bureau of Mines and Geology and Foster Sawyer of the South Dakota Geological Survey (see Hartman and Kihm, 1995). Placement of localities is derived from Hartman (1984a) and subsequent studies.

Figure 4. **Lancian, Paleocene, and Wasatchian mammalian localities in the Williston Basin, North Dakota and Montana.** The bedrock geology displayed on this map was derived from Clayton (1980) and unpublished data provided by S.M. Vuke of the Montana Bureau of Mines and Geology and Foster Sawyer of the South Dakota Geological Survey (see Hartman and Kihm, 1995). Placement of mammalian localities is derived from Hartman and Kihm (1992).

Figure 5. **Stratigraphy of Nesson Anticline nonmarine molluscan localities, North Dakota.** Nonmarine molluscan localities in the area of the Nesson Anticline in Williams and McKenzie Counties, North Dakota, are placed in relative stratigraphic position in a composite stratigraphic section taken on the south side of the Missouri River. This

figure illustrates the relative abundance of mollusks relative to important lignite beds in the section (Hartman and others, 1993a).

Figure 6. **Biostratigraphy of Paleocene and Eocene nonmarine Mollusca of the Powder River Basin, Wyoming and Montana.** Nonmarine molluscan species of the upper Paleocene (58 to 55 Ma) and lower Eocene (55 to 54 Ma) exist over a relatively brief period of time as illustrated in this figure showing species ranges, arranged from first to last occurrence as they are found in the Powder River Basin. Note that the disposition of species occurrences is drawn on the basis of relative stratigraphic position. Thus the apparent length of the Wasatchian land mammal age only indicates a higher rate of deposition of sediments during this interval of time. The background gray shadings represent approximate assignments of portions of the geologic record to North American land mammal ages (Tiffanian, Clarkforkian, and Wasatchian). The correlation of these ages into the Powder River Basin, particularly for the Paleocene, is on the basis of the biochronologic correlation of molluscan species with those found in the Bighorn Basin.

Figure 7. **Nonmarine molluscan biostratigraphy in the type area of the Fort Union Group, upper Missouri River, North Dakota and Montana.** Preliminary nonmarine mollusk taxon ranges (numbers refer to a specific taxon) are shown as vertical solid and dashed lines on either side of the Bullion Creek–Tongue River and Sentinel Butte formational contact (e.g., taxa 17 and 18 are *Viviparus retusus* and *Pleurolimnaea tenuicosta*). Selected mammalian localities shown on the left by locality number are as follows: Locality L5554, Wannagan Creek (L361), Locality L5500b, Riverdale (L1), Red Spring (L3236), and Witter (L5608). Note that the west-to-east thinning of the Bullion Creek Formation effectively prohibits the placing of the Judson (≈Ti4) and Brisbane (Ti3) localities in this diagram.

Figure 8. **Biostratigraphy of K/T-interval freshwater bivalves, Garfield County, Montana.** Taxon number refers to species names and are ordered from first and to last appearances. Except for the youngest occurrence of any taxon, where the top of a square is placed on the horizon line, the base of a square is placed on a horizon line shown on either side of the diagram. White squares represent the two of the three horizons reported by Whitfield (1903, 1907) from Barnum Brown's original collections. The third horizon was omitted because its stratigraphic position appears to have been incorrectly reported (Hartman, in press). This figure highlights (by dashed ranges) the highly sculptured taxa of *Proparreysia* and *Plethobasus*. The determined range of each North American Land Mammal Age (LMA) is shown.

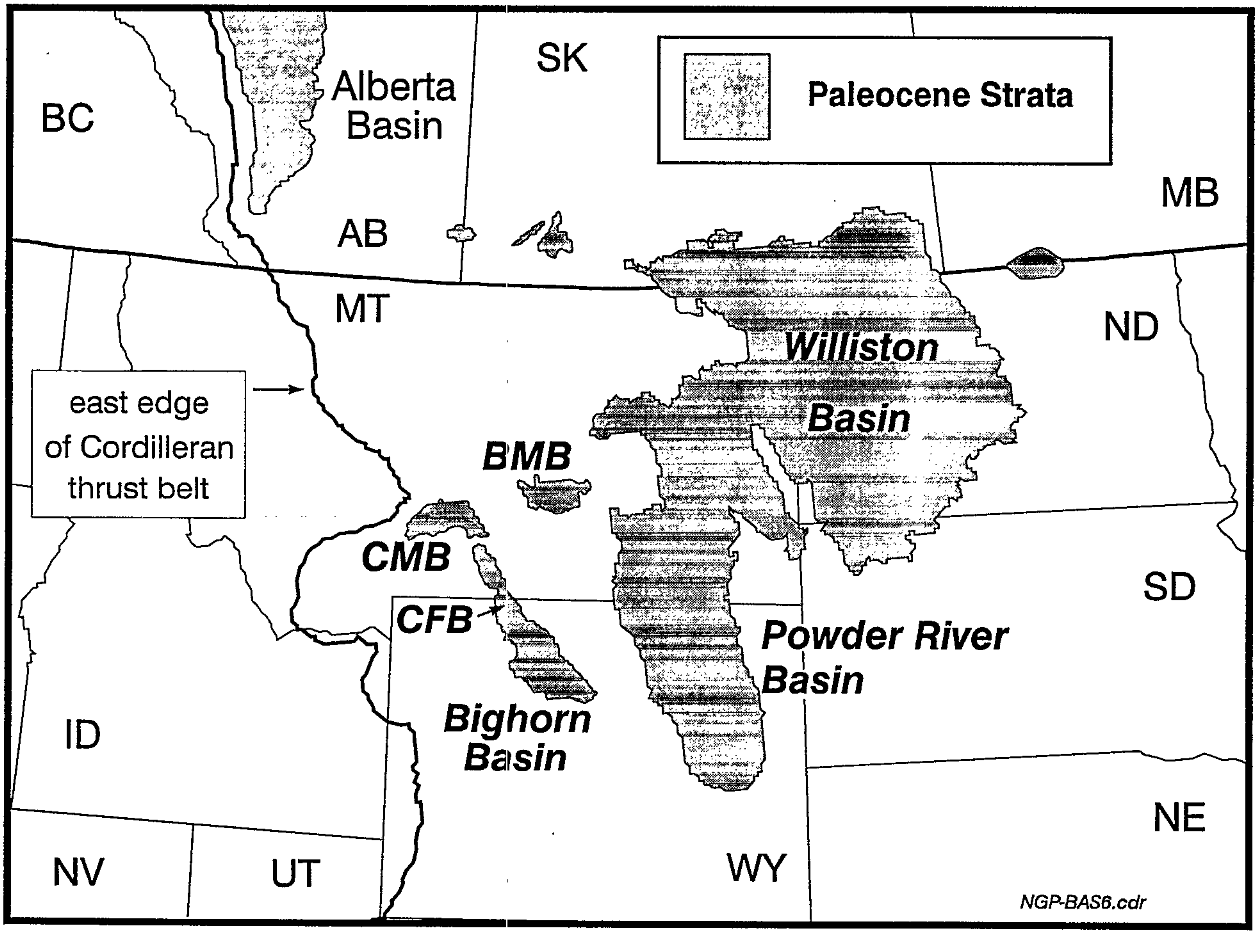
Figure 9. **Bighorn Basin nonmarine molluscan biostratigraphy, Wyoming and Montana.** The taxa shown in this figure represent the nonmarine molluscan identifications made as part of this project and does not include unreviewed identifications by others (Hartman and Roth, in press). The taxa are arranged from first to last occurrence as they are known from the Bighorn Basin. Some species have ranges, represented by a few localities with limited stratigraphic data, in older strata in the Bighorn Basin. In addition, a few taxa occur in older strata elsewhere in the northern Great Plains. As some of these records (e.g., occurrences in the Paskapoo Formation) cannot be tied

directly to a mammalian biochronology, they are shown in this figure without extended ranges. A questioned locality number indicates a questioned identification at that locality.

Figure 10. **Chronostratigraphy of North Dakota strata.** This figure represents a detailed comparison of uppermost Cretaceous, Paleocene, and Lower Eocene nonmarine strata of North Dakota with the global paleomagnetic reversal record. Previous versions (e.g., Hartman and Kihm, 1995) have been modified with unpublished magnetic, radiometric, and paleontologic data. The radiometric dates on the boundaries of magnetochrons are from Berggren and others (1995,). Interpretation of the correlation of mammalian ages with magnetochrons was derived from Clyde and others (1994), Gunnell and others (1993), and Prothero (1995). Other lowermost Paleocene paleomagnetic data were provided by Lund (written communication, 1995). Other radiometric dates were provided by D.A. Pearson (personal communication, 1995) and reported by Warwick and others (1995). Planktic foraminifera data of Fox and Olsson (1969) and correlation with radiometric dates were interpreted by L.S. Collins (written communication, 1994, 1995). Litho- and chronostratigraphic placement of mammalian localities was modified from Kihm and Hartman (1990, 1991), Hartman and Kihm (1991, 1992, 1995), Hartman and others (1993a), and Kihm and others (1993). Other mammalian data on new localities were provided by J.P. Hunter and D.A. Pearson (personal communication, 1994, 1995). Interpretation of the stratigraphy of the transgressive and regressive histories of the tongues of the Cannonball Formation was modified from Hartman and Butler (1995; and unpublished data). Symbols: The dotted line, representing the contact between the Sentinel Butte and Golden Valley Formations is temporally uncontrolled. The Bear Den Member of the Golden Valley Formation was interpreted to be Clarkforkian by Hickey (1977) on the basis of plants, but the age of the uppermost part of the Sentinel Butte Formation is unknown.

Figure 1

Basins of the Northern Great Plains and Intermontane Basins



BMB = Bull Mountains Basin
CFB = Clarks Fork Basin
CMB = Crazy Mountains Basin

Figure 2

Nonmarine Molluscan Chronostratigraphic Control in the Northern Plains and Intermontane Basins

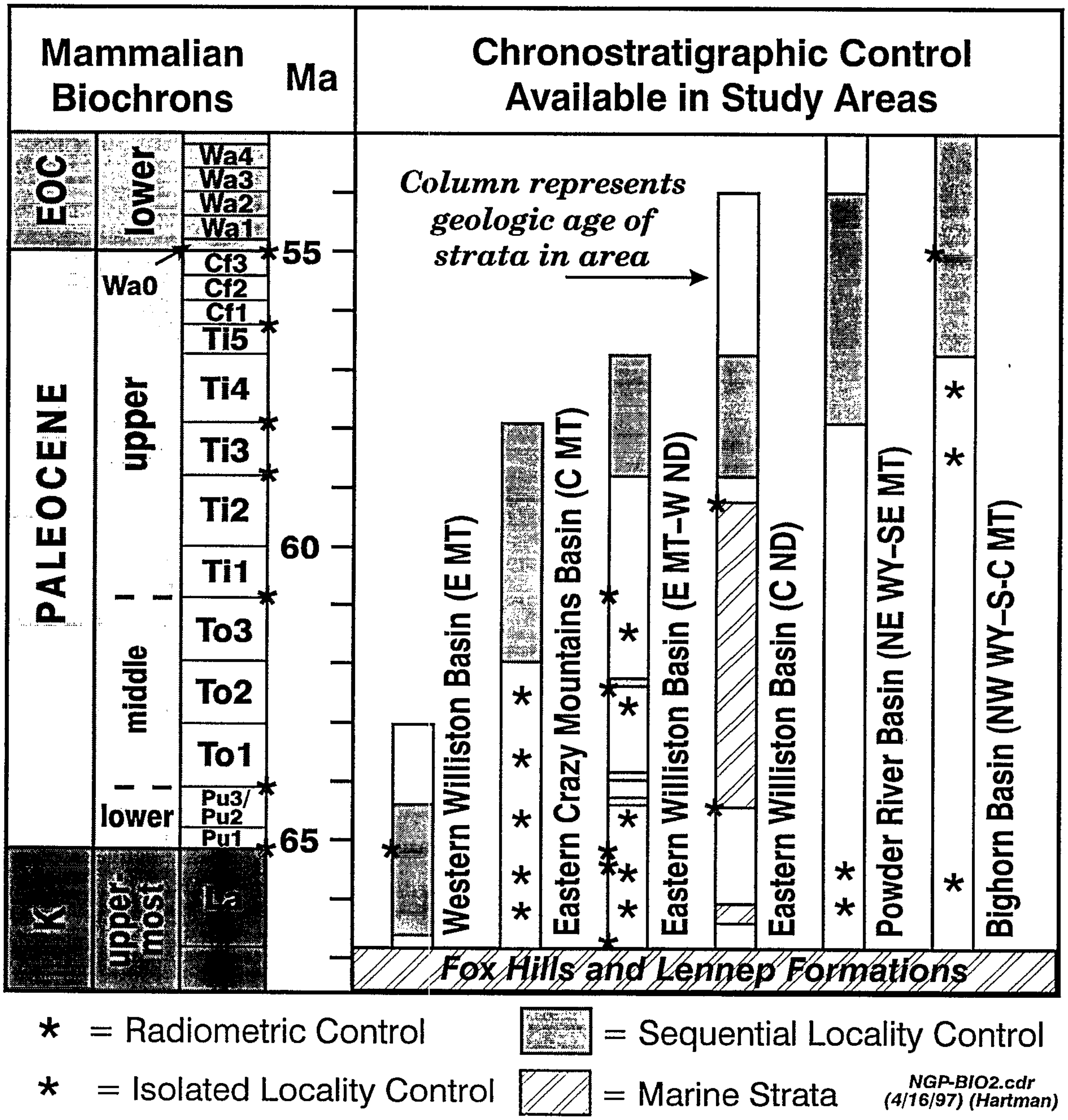


Figure 3

Lancian, Paleocene, and Wasatchian Nonmarine Molluscan Localities in the Williston Basin

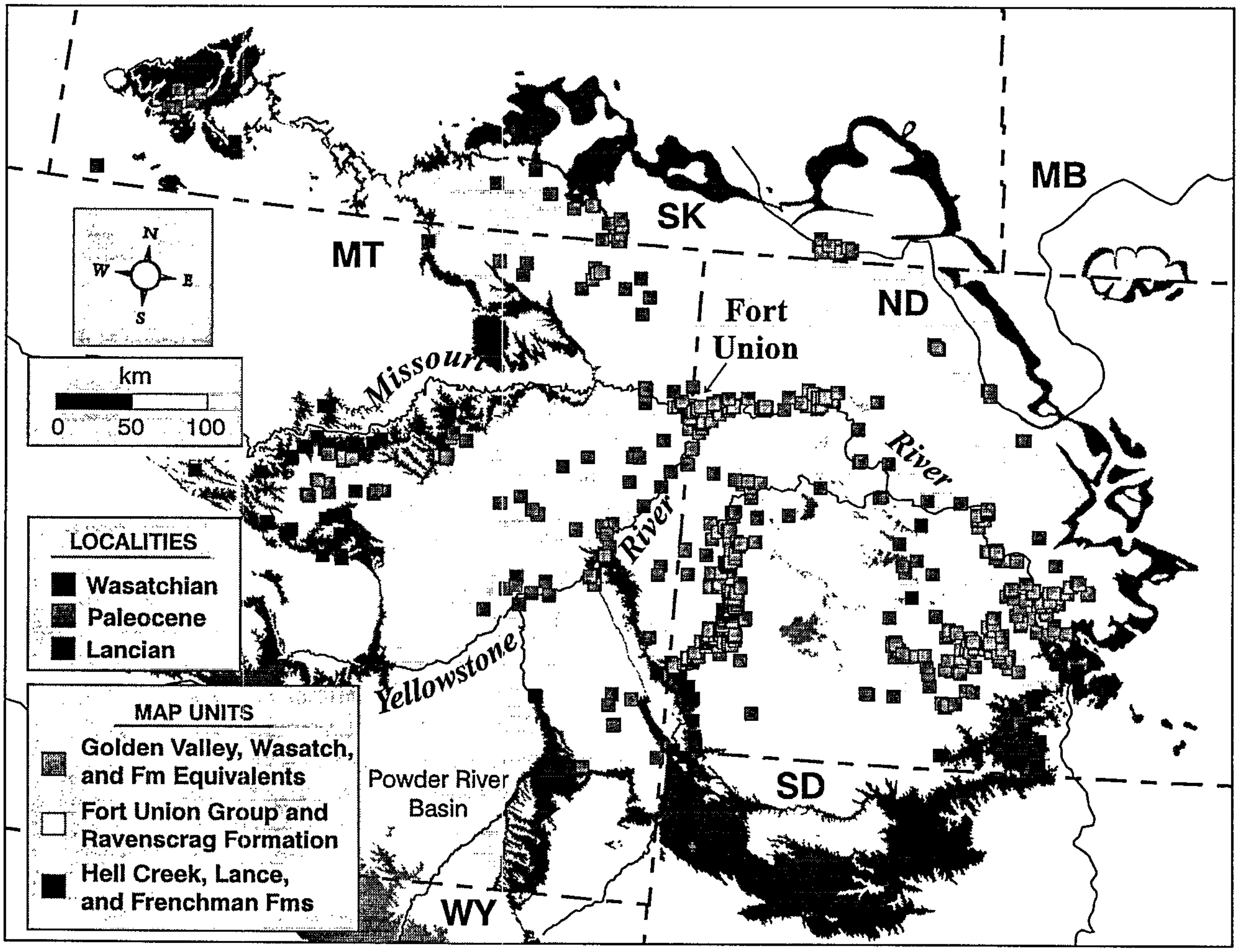
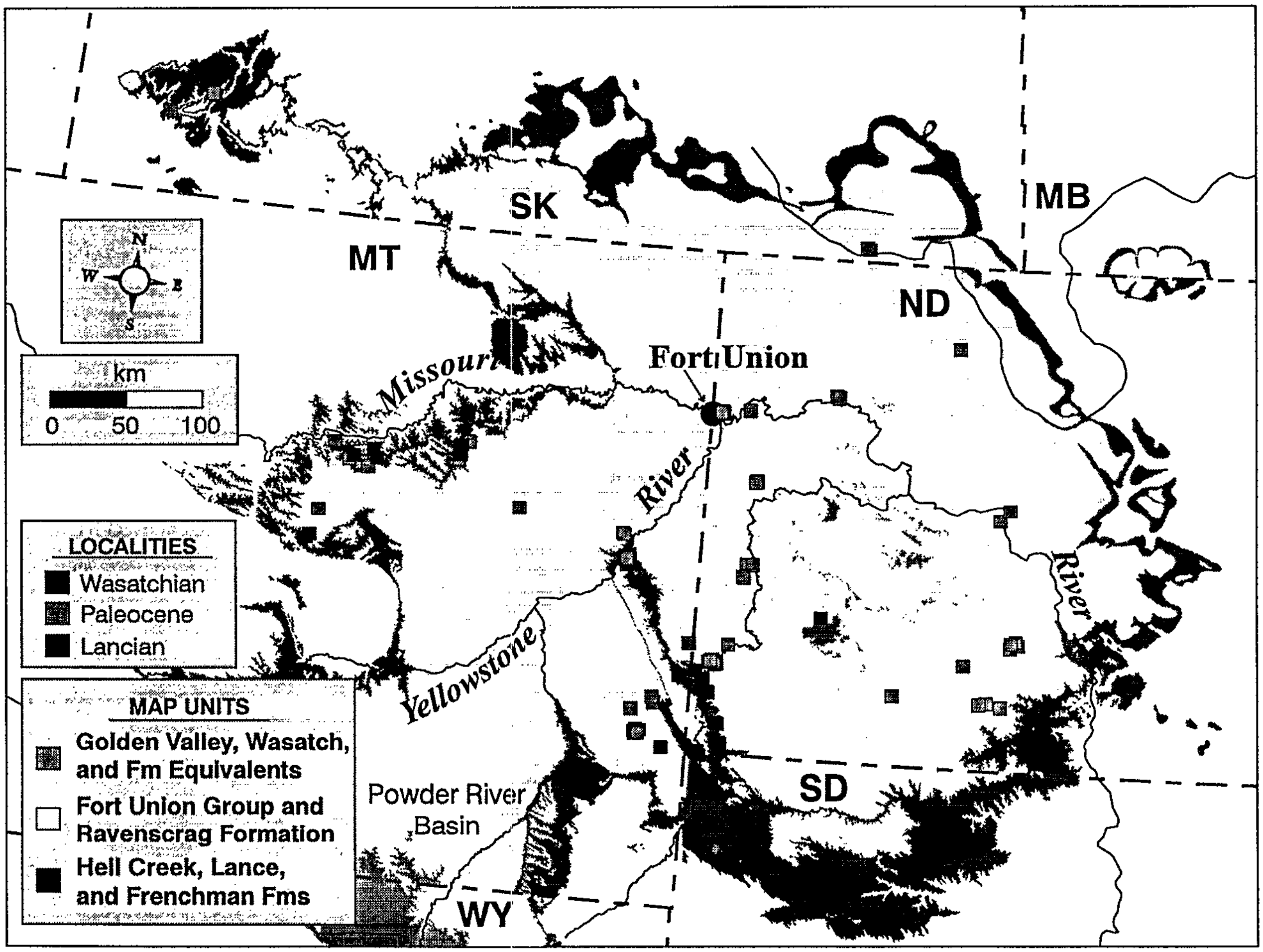


Figure 4

Lancian, Paleocene, and Wasatchian Mammalian Localities in the Williston Basin



WB_m2bw.cdr (Hartman and Kihm, 1995)

Figure 5

Stratigraphy of Nesson Anticline Nonmarine Molluscan Localities

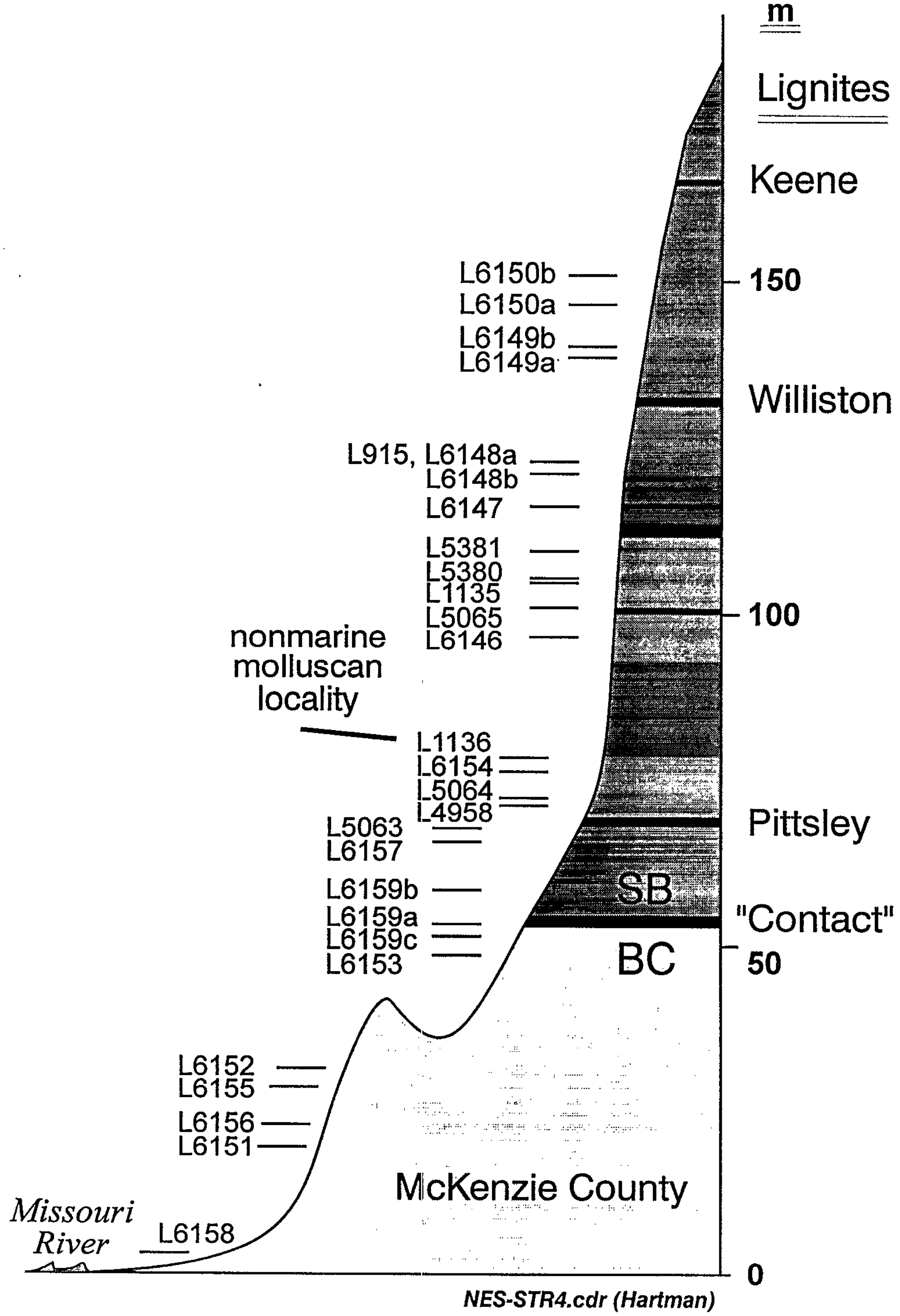


Figure 6

Biostratigraphy of Paleocene and Eocene Nonmarine Mollusca of the Powder River Basin

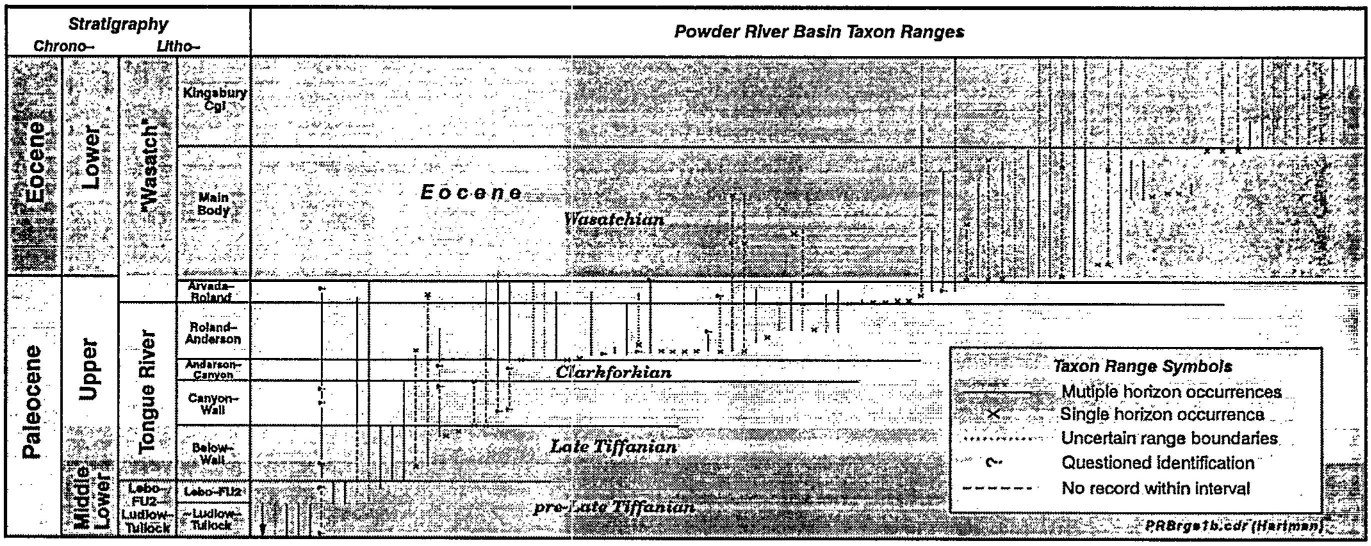
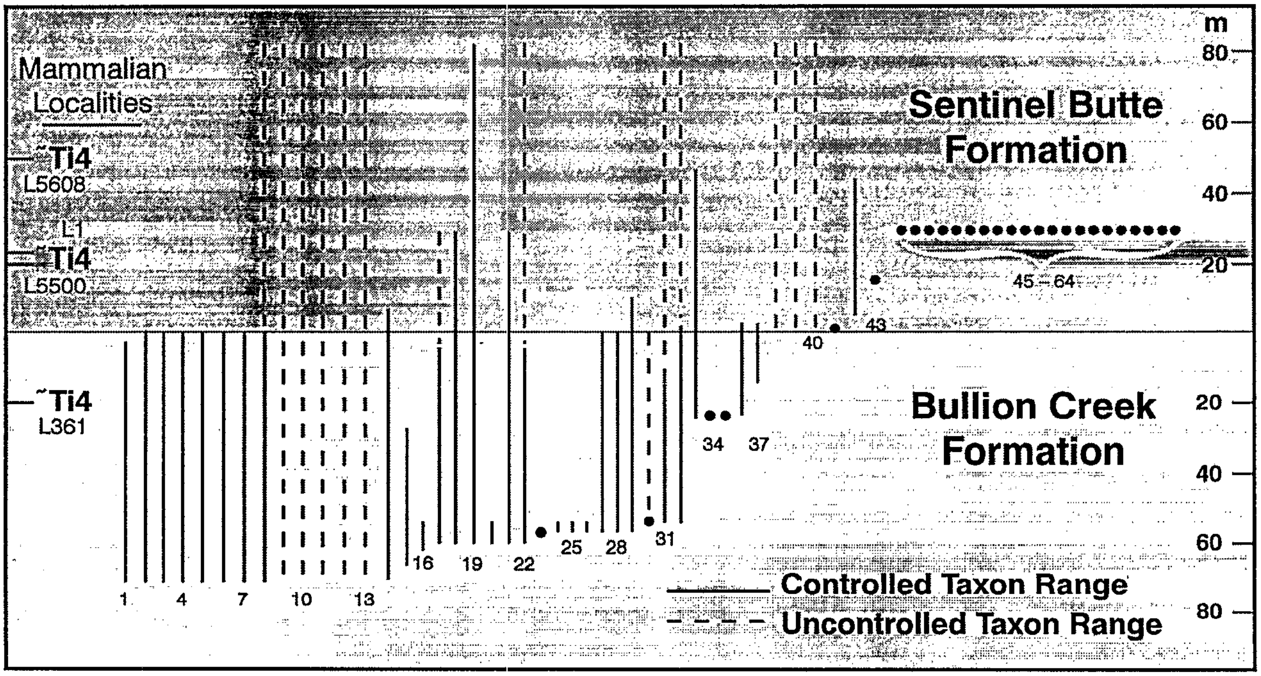


Figure 7

Nonmarine Molluscan Biostratigraphy in the Type Area of the Fort Union Group, Upper Missouri River, North Dakota–Montana



(Hartman and Kihm, 1995)

FU-BIOb.cdr (Hartman)

Figure 8
Biostratigraphy of K/T-Interval Freshwater Bivalves

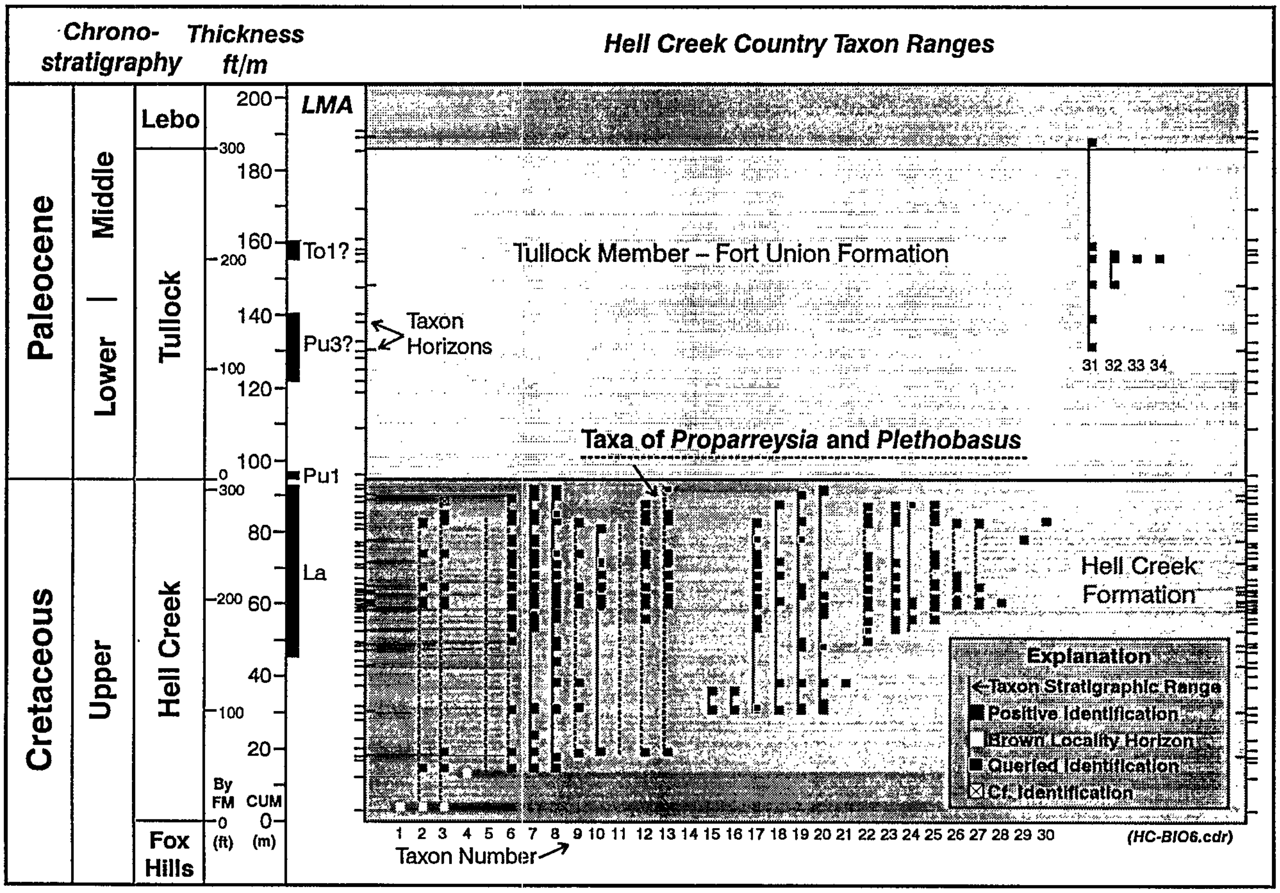


Figure 9

Bighorn Basin Nonmarine Molluscan Biostratigraphy

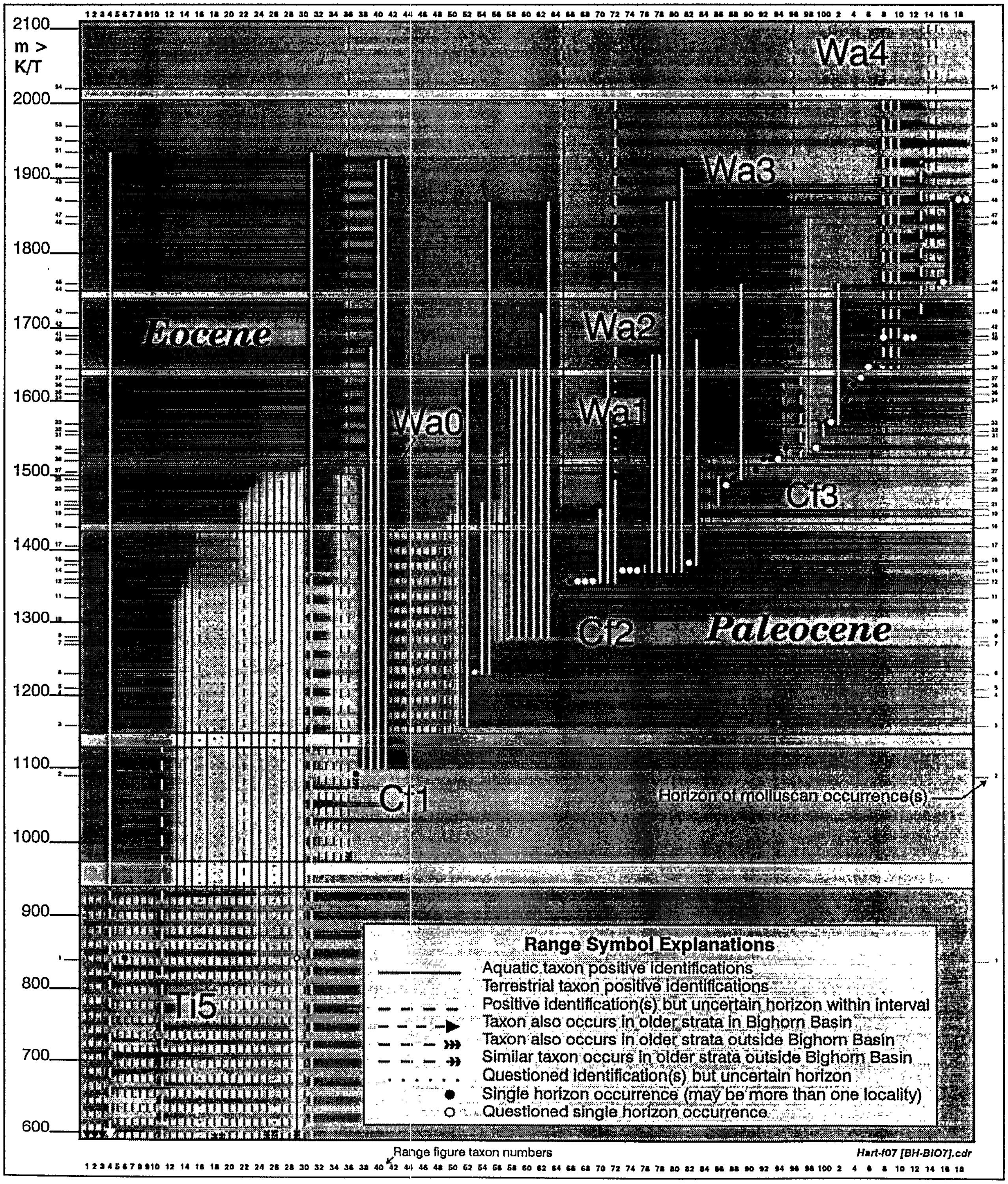
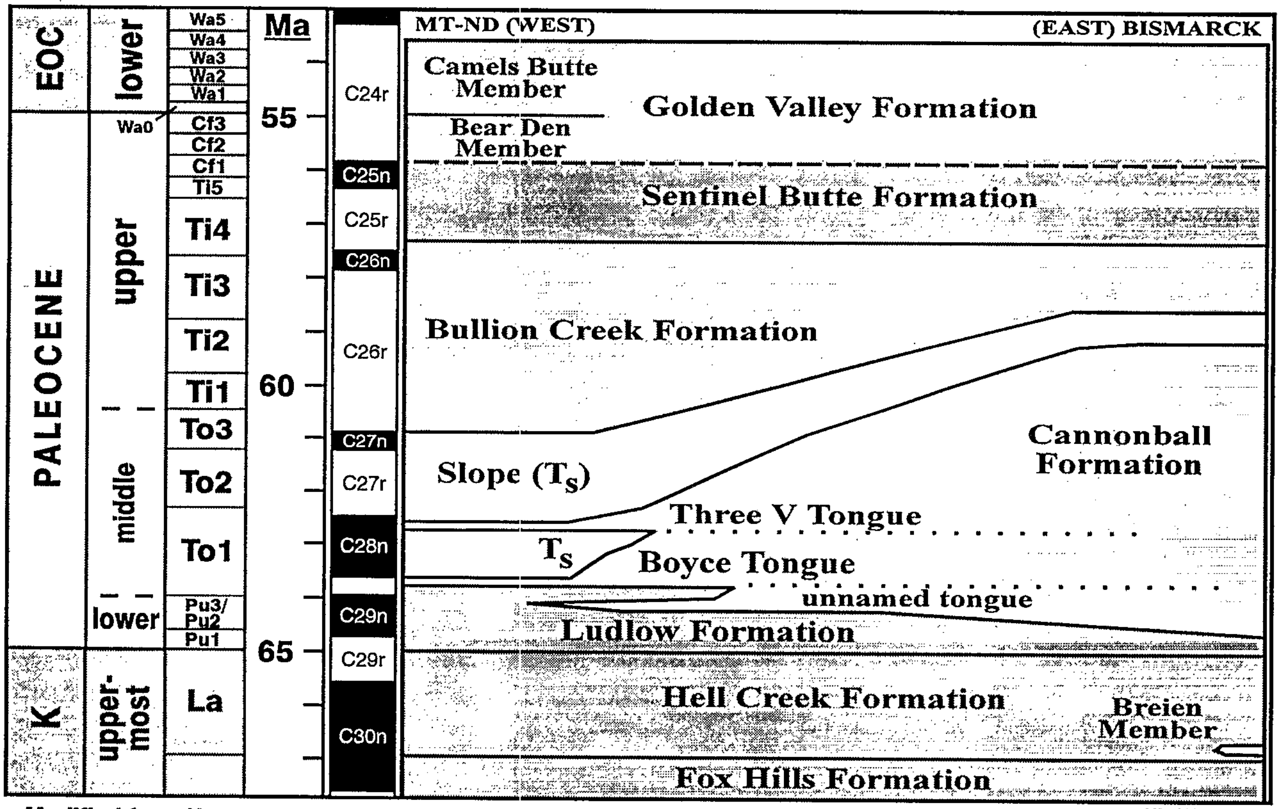


Figure 10

Chronostratigraphy of North Dakota Strata



Modified from Hartman and Butler (1995); Hartman and Kihm (1996)

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