CHAPTER TWO

Historical Overview of Geological and Paleontological Studies within the White River Badlands

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Introduction

Thomas Jefferson, one of the chief author's of the Declaration of Independence, a two-term President, and the person most responsible for the Louisiana Purchase and the Lewis and Clark *Corps of Discovery*, was also an amateur paleontologist and archeologist. He published an article in 1797 describing fossil remains of extinct giant sloth. Jefferson later collected and described mastodon remains from Big Bone Lick in Kentucky as well as excavated an American Indian (Monacan) burial mound near his home in Virginia. Although Jefferson may have been one of the earliest fossil collectors, vertebrate paleontology, the study of present animal life through an examination of fossil remains and their geological context, did not become a recognized scientific discipline until 1812 with the publication "Researches on Fossil Bones," by George Cuvier, a Frenchmen. Although many early paleontologists were little more than "bone collectors," today vertebrate paleontology requires a multi-disciplinary approach that combines elements of zoology, biology, anatomy, geology, ecology, and other related studies.

The person widely recognized as the "Father of American Vertebrate Paleontology" is Joseph Leidy, who was born in Philadelphia in 1823 and earned a Doctor of Medicine degree at the University of Pennsylvania before abandoning his practice to pursue research and teaching. Beginning in the late 1840s, many of Leidy's early publications describe mammalian fossils sent to him by various collectors that had been to the White River Badlands. Studies of fossil remains from the White River Badlands of South Dakota contributed greatly to the science of vertebrate paleontology in North America. The number, diversity, and high degree of preservation of the fossils exposed in the White River Badlands not only spawned the growth of vertebrate paleontology in America, but the fossils contained within the White River Group also provided a wealth of information regarding the evolution of Cenozoic mammals. Within a matter of decades the White River Badlands became a mecca for vertebrate paleontologists.

This chapter, which presents a historical summary of some of the more significant scientific discoveries that have occurred in or near the Park over the last 160 years, is divided into two primary subsections. The first subsection discusses the various expeditions (individuals, museums, universities) to the White River Badlands between 1846 and 1950. Given the nature of this historic resources report, the focus of this section is more on the history of research (or researchers) and its impact on the growing discipline of vertebrate paleontology and less on descriptions of the actual discoveries. In some regards the application and refinement of research methods developed in the Badlands represents a microcosm of the developments within the discipline as a whole.

That is to say, some of the earliest "paleontologists" were more concerned about collecting large samples of fossil remains than the context and integrity of the samples.

The second subsection of this chapter discusses the contributions to various geological and paleontological subdisciplines that have occurred within the last 55 years as result of on-going research in the White River Badlands. Some of the newer studies within the Badlands include, but are not limited to, biostratigraphy, micro-paleontology, paleoenvironmental reconstructions, paleomagnetic correlation, tectonic studies, geochronology and paleopedology (i.e., the study of old soils), and Quaternary geology and geomorphology. Paleontological and geological research has occurred in both the North and South Units of the Park. Work continues within the Park as each new investigation or discovery results in as many new questions as it answers.

Summary of Previous Paleontological Investigations (1846-1950)

Early Fossil Discoveries and Contributions to American Paleontology (1846-ca. 1890)

<u>Early Discoveries and Exploration in the Badlands (1846-1870s)</u>

The first published discovery of fossil remains from the White River Badlands was authored by Dr. Hiram Prout, a St. Louis physician, in 1846. Prout, who obtained the bone from a fur trapper working for the St. Louis (or American) Fur Company, stated that the fur trapper had discovered the fossil in the *Mauvises Terre* (Badlands) on the White River about 150 miles south of Fort Pierre and 60 miles east of the Black Hills.[1] The fossil was described as a maxillary fragment of an extinct life form he called *Paleotherium*, or an ancestor of the "horse." The fossil was later classified incorrectly as a titanothere (i.e., the term "titanotheres" is no longer a valid name and these animals were eventually reclassified as "bronotheres"), an early (and extinct) mammalian life form that exhibited various morphological elements that were similar to the horse and the rhinoceros. Several months later Dr. Leidy described the fossil remains of an early camel that he named *Poebrotherium.* The publication sparked interest among other geologists, and in 1849, Dr. John Evans, under the direction of David Dale Owen, visited the White River Badlands for the purpose of observing the geology of the area and collecting fossils. The fossils collected by Evans ultimately ended up in the hands of Joseph Leidy, and he along with Evans and Owens, published some of these discoveries.[2] Shortly thereafter, Thaddeus Culbertson led an expedition from the Smithsonian Institution to the Badlands in 1850 and published his findings the following year.[3] Unfortunately, Culbertson was not a healthy man, and he died soon after his article was published. Leidy subsequently studied Culbertson's fossils as well as many others that were sent to him. In 1851 Dr. Prout sent his fossils to Leidy, who reclassified the *Paleotherium* remains as a titanothere/bronothere. Leidy, who previously described *Poebrotherium* (early camel) and titanotheres/bronotheres, also described the ubiquitous oreodont fossils. Oreodonts represent a strange sheep-sized ruminant animal with teeth designed for both grazing and browsing, along with sharp canines, and individual digits on each foot. The more Leidy published, the more famous he became, and eventually nearly all the fossils recovered in the Badlands in the 1850s and 1860s were sent to him for analysis. It was through these beginnings as well as his attention to detail and description that Joseph Leidy (1823-1891) became known as the "Father of American Vertebrate Paleontology."

One of the early pioneers in American geology and paleontology was Ferdinand Vandiveer (F.V.) Hayden. Hayden, a doctor of medicine, but better known for his knowledge of geology and mineralogy, first traveled to the Badlands region in 1853 where he collected fossils for James Hall, State Geologist of New York. Hayden later joined several military expeditions to Nebraska and Dakota Territory as the topographical engineer and chief geologist. In 1855 and 1857 Hayden joined the Geological Survey of the Territories under the direction of General William S. Harney and Lieutenant G.K. Warren. The 1855 expedition, often referred to as the "Warren Survey" was designed to provide topographic mapping of "Sioux Country." Hayden worked closely with Warren, and together they produced a large body of data on the western territories. Warren and Hayden also surveyed in and around the White River Badlands in 1856 and 1857 (note the 1857 expedition went through the middle of the Badlands on Harney's Fort Laramie to Fort Pierre march following the Harney massacre of a Lakota Indian camp near Ash Hollow Cave in Nebraska—see discussion in chapter 4). In 1859 and 1860 Hayden joined expeditions to the region that were led by Captain William Reynolds. Hayden prepared a number of publications on the geology and topography of the areas he surveyed, and in all cases, Hayden collected a variety of fossil material that he sent to Professor Leidy for analysis.[4] Following the 1855 expedition, Hayden described the Badlands in the following terms, "Contrasted with most of the country on the Upper Missouri, the White River Valley is a paradise, and the Indians considered it one of the choice spots on earth."[5] During the Civil War, Hayden served as a surgeon in the US Army, but he spent his time collecting fossils and mapping geological formations. He returned to Nebraska Territory and the Badlands in 1866 and 1869.[6]

In 1869, Leidy published a large summary volume on all of the fossil material that had been sent to him during the preceding 20 years. The report identified over 40 extinct mammalian species and described and cataloged thousands of individuals, including no less than 700 individual sheep-like mammals called oreodont or *Merycoidodon culbertsoni*.[7] The report also presented a description of the geological formations that produced the fossils.[8] The work by Leidy established a firm foundation for the study of Cenozoic mammals in North America. In addition, Leidy and Hayden established that the fossiliferous formations of the White River Badlands were the result of erosion and not the result of downward faulting. Leidy's large and meticulous volume brought together over 20 years of knowledge and formed the basis for all subsequent research in the White River Badlands for the duration of the nineteenth century. At one point, Leidy estimated that he received three to four million tons of fossils between 1846 and 1869, including the collections from Dr. Hiram Prout (1846), the American Fur Company (1847), Dr. David Dale Owen and Dr. John Evans (1849-1852), Thaddeus Culbertson (1850), Dr. John Evans (1853), and F.V. Hayden (1855-1857, 1866).

Leidy, following Hayden's interpretation of the data and despite his meticulous descriptions and illustrations of the fossil remains, agreed with Hayden and incorrectly interpreted the White River Badlands as lacustrine (lake) deposits of Miocene age, and it would be several more years before paleontologists and geologists more accurately interpreted the nature and origin of the fossil-bearing deposits and even longer before the majority of the deposits were assigned to the Late Eocene to Late Oligocene time periods. (Note: Through paleomagnetic correlation, with other radiometrically dated deposits, sediments preserved at Badlands National Park are now dated from the Late Eocene to Late Oligocene.) As will be discussed later in this chapter, some recent studies suggest that White River beds are primarily late Eocene and early Oligocene in age. Some of the key genera identified and described by Leidy included: *Oreodon, Titanotherium, Hyopotamus, Hyracodon, Anchitherium, Hyoenodon, Machairodus, Trionyx, Testudo, Helix*, *Planorbis*, and Limnoea.[9] It should be noted that many of the genus names reported by Leidy are no longer current. Leidy correctly demonstrated that the overwhelming majority of animals, except for the ubiquitous turtles and tortoises, were mammalian herbivores and carnivores that lived in a grassland or savannah habitat that was void of both marine and brackish animals or habitats. He also noted that some species, such as *Merycoidodon culbertsoni* in particular, were gregarious animals that were attacked by predatory animals such as *Hyoenodons*, *Dinictis*, and *Drepanodon*.[10] Despite poor contextual data (or at best limited provenience information) Leidy was able to describe evolutionary sequences for the following taxonomic lineages (again it is pointed out to the reader that some genus names used by Leidy are no longer used): Carnivora (canines, mustelids, and felines), Pachydermata, Artiodactyla (poebrotheria, oreodonts, camelids, cervids), Perissodactyla (rhinoceros, equids, tapirs), Solidungula, Rodentia (castorids, gophers), and Insectivora.

Marsh vs. Cope: The Infamous "Bone Wars" (1872-1892)

The "Bone Wars" of the 1870s were soon to change the climate and direction of American paleontology and as a result Professor Leidy all but abandoned his work in the American West and left the identification and description of extinct mammalian fauna to a new generation of paleontologists. The so-called "Bone Wars" began in the 1870s between two of the biggest names in American paleontology, Othniel Charles (O.C.) Marsh (1831-1899) and Edward Drinker Cope (1840-1897). At the dawn of the 1870s, the American government experienced a short-lived and somewhat tenuous period of peace with the Lakota and other Plains Indians, and Leidy had just published his voluminous work on the extinct mammalian fauna of Dakota and Nebraska. Interest in the American West was at full throttle and the White River Badlands was the place to be if one was interested in collecting fossils.

O.C. Marsh, born in 1831 near Lockport, New York, was the nephew of the wealthy philanthropist, George Peabody. Marsh obtained his MA from Yale in 1862 and then went to Germany for several years to complete his education in geology, biology, and evolutionary biology. He studied in Europe for several years and returned to the United States a strong proponent of Darwinian theory and natural selection. In 1869, George Peabody died and left a considerable sum of money to his nephew that he used to finance field expeditions, collect fossils, and otherwise improve his career.

Edward Drinker Cope was born the son of a moderately wealthy Quaker family in 1840 in Philadelphia. Cope was a student of Leidy's and after graduating from Princeton in 1861, he worked for the Smithsonian Institution for a brief time before his father sent him to Europe where he visited professors and museums. Unlike Marsh, Cope was not a believer in Darwinian Theory, rather he was a leading Neo-Lamarckian theorist (i.e., he believed changes in developmental (embryonic) timing and not natural selection was the driving force behind evolution).

During the early years of American paleontology, most collectors sent their fossils to Dr. Leidy for analysis, description, and taxonomic classification. By 1870 the climate within the paleontological arena began to change. Both Marsh and Cope had financial backing that Leidy could not hope to duplicate. When these ambitious newcomers entered the paleontological arena, research took a back seat to the accumulation of fossils, and fossil collections were sold to the highest bidders, namely Marsh and Cope. Marsh, who was aware of the abundance of fossil remains sent to Dr. Leidy each year, decided to organize a research trip for Yale University and the Peabody Museum to the American West in 1870. Although Marsh also accompanied the field teams from 1871-1873 and had a brief field visit in 1875, thereafter he rarely ventured into the field, preferring to hire assistants and collectors, while he remained at the museum or traveled to Washington to bend the ear of various political figures or other influential people.

In 1875, Marsh entered the field one last time. He traveled to the White River Badlands to study the brontothere beds. These elephant-sized animals, similar to the fossils first described by Prout and Leidy nearly 30 years prior, were distantly related to the horse and the rhinoceros, which he had studied extensively in the past. In November 1875, the expedition of scientists and soldiers was stopped by Lakota warriors who were convinced that Marsh was going to the gold fields in the Black Hills. Marsh displayed his usual charm and political savvy and was allowed to proceed after he promised to spend a considerable amount of time with Chief Red Cloud.[11] Marsh and Chief Red Cloud became good friends, and in fact, one of the men in the Marsh expedition later married Chief Red Cloud's daughter. Marsh became such good friends with Chief Red Cloud, that when he learned that the federal government and the Indian agents were not providing the Lakota with their promised rations of food and clothing, he publicly blasted the federal government and Indian agents for their harsh and inhumane treatment of Indians and demanded that the promised food rations be provided to the starving tribes. Marsh's influence in Washington helped to procure the withheld rations.[12]

During his western trips, Marsh collected a number of fossils from the Badlands region, and he eventually published a number of articles detailing the evolution of the horse. It was during these trips that Marsh acquired the nickname "Big Bone Chief" and "Bone Medicine Man" from the Pawnee and Sioux. In addition to Marsh's contribution deciphering equine evolution, his published works helped to fill in gaps in the Darwinian evolutionary tree. Following Thomas Huxley, he also suggested that birds evolved from dinosaurs and published several articles in support of this position. Marsh also described

Apatosaurus (he later identified Brontosaurus which is also an Apatosaurus, hence Brontosaurus is no longer a valid scientific name), Stegosaurus and Triceratops.

One of Marsh's more significant contributions to paleontology included his efforts to determine the geological formation for each fossil locality in order to establish horizon markers; a method, first introduced by William Smith around 1800, but heretofore was not widely practiced, yet today it constitutes a basic element of biostratigraphy. Marsh also sought to amass an enormous collection of fossils (which he did) in order to display these unique specimens in the Peabody or Smithsonian museums. To that end, Marsh also introduced the practice of reconstructing and displaying the entire individual based on the fossil remains. In so doing, he indirectly encouraged his hired workers to seek and extract complete specimens, which was also a novel idea for its time.

During the late 1870s the United States government sponsored four geological and topographical surveys of the American West. Two of the surveys, led by F.V. Hayden (survey of the territories) and G. M. Wheeler (survey of the 100th meridian) hired Cope as the vertebrate paleontologist for the expeditions. The other two surveys, led by Clarence King (survey of the 40th parallel) and John Wesley Powell (survey of the Rocky Mountain region) hired Marsh as the vertebrate paleontologist. In 1879 the various surveys were combined to form the United States Geological Survey (USGS). The first director was Clarence King, who resigned after one year, and he was followed by John W. Powell. Both King and Powell were good friends with Marsh, and Marsh was able to parlay these political connections to his benefit.

The Cope and Marsh feud continued throughout the 1870s and 1880s. Leidy publicly expressed his disgust at their actions and declared that he had no stomach for this type of behavior. His distaste for professional name-calling and ill-will among his peers, coupled with the fact that he lacked the financial backing to keep pace with fossil collectors like Cope (his protégé) and Marsh (a great admirer), both of whom were able to hire multiple teams to scourge the western fossil beds for new materials, ultimately led Leidy to withdraw from the "Bone Wars" competition. At the time of his death in 1891, Leidy had authored nearly 230 publications on vertebrate paleontology and described over 130 new genera and over 300 species of fossil vertebrates, many of which derived from the formations of the White River Badlands. One of Leidy's last publications in vertebrate paleontology was his summary work in 1873 entitled, "Contributions to the Extinct Vertebrate Fauna of the Western Territories, Part I, USGS of the Territories, vol.1."

Formative Years of American Vertebrate Paleontology (1880-1890s)

In addition to being the founding fathers of American vertebrate paleontology, Leidy, Cope, and Marsh worked with and trained a long list of students and associates that transformed the budding field of paleontology from a fossil collecting exercise to the rigorous scientific discipline that we know today. The formative years of American paleontology started in the 1880s and 1890s when universities, museums, and the USGS began to send field expeditions to the White River Badlands and elsewhere. Although Marsh did not return to the Badlands after his 1875 visit, he sent parties from the

Peabody Museum to the area for the purpose of collecting fossils from 1886-1890, and from the USGS from 1894-1898 (with the exception of 1896).[13] The materials collected by the USGS were eventually transferred to the Smithsonian Institution. Marsh's students and associates included a number of well-respected and famous professionals, including Erwin H. Barbour (later with the University of Nebraska), George Baur, Oscar Harger, John Bell (J.B.) Hatcher (then with the USGS and later with Princeton University), Samuel W. (S.W.) Williston, George Bird Grinnell (anthropologist and ethnographer), Marcus Farr, and Richard S. Lull to name but a few. Hatcher, it should be noted, was among the first to collect intact and complete specimens, a technique still practiced today.

Cope was a mentor, close friend, and associate with Henry F. Osborn (1857-1935) and William B. Scott (1858-1947), both of whom graduated from Princeton University. After graduating from Princeton, Scott elected to complete his studies in Germany. He then returned to Princeton University where he remained throughout his career. Osborn, a fellow student with Scott at Princeton, also traveled to Europe to complete his education and later returned to Princeton University as a professor of comparative anatomy from 1881-1890. In 1891 he moved to Columbia University to organize the Biology Department (1891-1896) and later was Professor of Zoology from 1896-1910. In 1891 Osborn also founded the Department of Vertebrate Paleontology at the American Museum of Natural History in New York, and he remained with the museum for 45 years until his death in 1935. Osborn also joined the USGS staff in 1900 (after Marsh's death) and became senior geologist in 1924. Scott and Osborn, along with a number of other famous paleontologists (like J.L. Wortman) from the American Museum of Natural History and/or Princeton University, visited the White River Badlands on almost an annual basis from the 1890s to the 1910s, and they published their findings in a number of professional journals.

Princeton University, under the leadership of Scott and his friend and colleague H.F. Osborn, made their initial visit to the Badlands in 1882. Upon their return to the East Coast, Scott and Osborn learned that the New York papers had erroneously reported that the entire Princeton party, including military escort, had been attacked and killed by Sioux warriors. Scott and others from Princeton returned to the Badlands for many years, including 1890, 1893 (with Hatcher), and in 1894, under the leadership of Hatcher. O'Harra notes that these expeditions were of "very great importance," and he notes "the abundant fossil remains collected enabled Professor Scott to describe in a most complete manner a number of the more noted extinct animals and to indicate with more certainty their proper classification and relationship."[14] Later research teams from Princeton were led by Harold R. Wanless, William J. Sinclair, Glenn L. Jepsen (a student of C.C. O'Harra's at South Dakota School of Mines [SDSM]), and John Clark.[15]

H.F. Osborn, along with several other capable researchers, led expeditions from the American Museum of Natural History to the fossil beds of northwestern Nebraska and southwestern South Dakota in 1892-1894, 1897, 1903, 1906, 1908, 1911-1914, and 1916. The expeditions were well-financed and well-organized, and from the start the researchers were blessed with extraordinary discoveries. The research, discoveries, and publications generated by these expeditions provided an opportunity to more accurately establish, "the details of stratigraphy and correlation and to indicate with greater certainty the characteristics and habits of the various animals while in the living state."[16] The well preserved and nearly complete skeletons collected by these expeditions allowed researchers and museum staff to reconstruct the animals with skin, fur, and other lifelike appearances. The work conducted by Osborn and his staff contributed greatly to the understanding of the geology, paleontology, and biostratigraphy of the Badlands region.

University and Museum Contributions to Badlands Geology and Paleontology (ca. 1892–1950)

University and Museum Researchers (1890–1950)

The decades between the 1890s and 1950 saw a transformation in the geological and paleontological research in the White River Badlands. Because the majority of researchers came from the academic community, scientific investigations were elevated to new levels. Researchers finally stopped competing with one another for collecting the most fossils or describing the first fossil remains of a new species and began to accurately describe and interpret the fossil data and the geological formations that produced the fossils. In addition to the aforementioned expeditions that were led by Scott or Osborn, numerous other researchers traveled to the White River Badlands (or adjacent areas of Nebraska and eastern Wyoming). Some of the researchers that ventured to the area during this period included the following:

- Erwin H. Barbour (initially as a student under Marsh and later as a professor at the University of Nebraska),
- John E. Todd (1894 and 1896, University of South Dakota),
- J.B. Hatcher (Yale University and USGS) and O.A. Peterson (1902 Princeton University and subsequently for many years, Carnegie Museum, Pittsburgh),
- F.B. Loomis (1903 and 1907, Amherst College),
- W.D. Matthew (mid 1890s to 1910s, American Museum of Natural History),
- O.C. Farrington (1904, Field Museum),
- N.H. Darton (1897, 1899 Yale Peabody Museum and in later years USGS),
- C.C. O'Harra (1899-1920, SDSM).

O'Harra took students to the Badlands area, in particular to School of Mines Canyon, near Sheep Mountain Table, to learn geology and collect interesting fossils. Although O'Harra spent a considerable amount of time in the Badlands, he did not establish a formal field school. Nonetheless, the tradition started by O'Harra was continued by his successors, like Glenn Jepsen, James Bump, John Clark, Philip Bjork, James Martin and others. In 1924, Jepsen initiated the first true field school for the School of Mines as he took a group of students to the School of Mines Canyon near Sheep Mountain Table. The tradition of annual field schools to the Badlands continued into the 1960s and 1970s. In 1924 the field camp was held at the Everett's Ranch, and in 1926 the camp was located two miles south of Olsen's Ranch and one mile west of Beard's Ranch near the north edge of Cuny Table. Field crews also prospected near Stronghold Table (northeast corner of Cuny Table). In his 1920 book on the *White River Badlands,* O'Harra includes a picture of one of the field cabins near the head of Indian Draw.[17]

E.H. Barbour, a professor at the University of Nebraska and director of the university museum, visited the tri-state (Nebraska, South Dakota, and Wyoming) area on numerous occasions as he led parties to the area in 1892, 1894, 1895, 1897, 1905, 1907, and 1908. Barbour was one of the first of several paleontologists to work the fossil beds on the James Cook ranch. This land was eventually donated to the NPS by his son and is better known today as the Agate Fossil Beds National Monument. Barbour is also credited with discovering several archeological sites during his trips to the Badlands area, and in later years his name is associated with the excavation of some important archeological sites (Scottsbluff Quarry and Paleo-Indian sites associated with extinct bison remains) for the University of Nebraska Museum.

The Carnegie expeditions to the Badlands region are credited with the discovery of new, strange, and wonderful species. In addition to work in the Whiter River Badlands, the Carnegie Museum also worked for many years at the important fossil bed deposits near Agate Springs, Nebraska,[18] which are now part of Agate Fossil Beds National Monument. One locality at the Monument is named Carnegie Hill while another locality is named University Hill, in honor of the various university teams that worked at the site.

Despite roughly 100 years of fossil collecting and scientific expeditions and scores of collectors, paleontologists, geologists, and other scientists, the fossil localities of the early collectors and the location of their associated campsites remains an enigma. Both the fossil bed localities and the researcher's campsites should be considered significant cultural and historical resources that are eligible to the National Register of Historic Places. Discussions with Park staff (Ms. Marianne Mills, Dr. Rachel Benton, and Mr. Bill Supernaugh), and Mike Greenwald and Dr. James Martin, staff at the Museum of Geology and Paleontology at the South Dakota School of Mines and Technology (SDSMT), Rapid City, and review of the archeological sites files at OSA (Rapid City) failed to reveal the location of any early campsites or fossil collecting localities. It is recommended that the Park and the NPS, in conjunction with the SDSMT, the OSA, and other universities and museums that historically worked in the area, make a concerted effort to locate, record (including GPS mapping, site plans, verbal descriptions, and photographs), and preserve these paleontological and archeological sites. Unfortunately, many of the early fossil localities and camp sites can not be located because USGS topographic maps did not exist at the time when these early sites were being excavated.

Contributions to Badlands Geology and Stratigraphy

The White River Badlands constitute a small component of the Great Plains physiographic region. The Great Plains, which extend from Mexico northward into Canada and from the Rocky Mountains eastward to the Missouri River trench, have often been described as a vast featureless plain in a sea of blowing grass. In fact the Great Plains physiographic region exhibits tremendous variability. Trimble divides the Great Plains regions into no less than 10 sections or provinces, including the High Plains, Black

Hills, Unglaciated Missouri Plateau, and the Glaciated Missouri Plateau.[19] The Badlands lie with the Unglaciated Missouri Plateau, but are equally proximate to the High Plains province of northwestern Nebraska and eastern Wyoming and the Black Hills province directly to the west. The High Plains, which occupy portions of western Nebraska, Kansas, Oklahoma, and Texas and eastern Wyoming, Colorado, and New Mexico, constitute a vast, relatively flat plain that slopes eastward from the Rocky Mountain front. The Pine Ridge, directly south of the Badlands, separates the High Plains from the Unglaciated Missouri Plateau. The later province contains a number of small, more or less isolated mountain masses that rise above the rolling plateau. Numerous rivers bisect the plateau, typically exhibiting deeply dissected, broad alluvial valleys.

Prior to the Tertiary period, most of the Great Plains region was submerged beneath vast inland seas. The extended period of geological uplifting (the Laramide orogeny) that formed the Rocky Mountains also resulted in uplifting the area that we today call the Great Plains. The Great Plains, in general, and the Badlands, in particular, were shaped by the deposition and subsequent erosion of alluvial and eolian deposits. Thus, many of the deposits of the High Plains and the Unglaciated Missouri Plateau date to the Cenozoic Era although some Cretaceous or other Mesozoic sediments are exposed in some portions of these provinces. For example Pierre Shale, which is exposed in some parts of the Badlands and the surrounding area (like the Cheyenne River valley), dates to the late Cretaceous period.

During the 1850s and 1860s when the first fossils were being sent to Leidy and others for analysis, the geological history of the American West was poorly known, but this fact is not too surprising, given the limited amount of scientific research conducted in the American West prior to the 1860s. Scientists, geologists, and paleontologists knew that marine fossils (both vertebrates and invertebrates) were common in limestone (deep sea) and shale (deltaic) formations to the east of the Great Plains. Fossil remains of fish, various invertebrates, and swimming reptiles confirmed the presence of inland seas across much of western North America during the Cretaceous period. This fact, coupled with the presence of unconsolidated deposits of fine-grained sandstone, soft shale, mudstone, siltstone, and clay, in combination with the large quantity of fossil turtles (actually tortoises) and the absence of marine invertebrates and fish, led Hayden and most other researchers to conclude that the Badlands formations were derived not from marine deposits, but rather from large lakes that gradually dried up during the Cenozoic Era.[20]

Leidy and others recognized that the fossil beds of the White River Badlands belonged to the Tertiary period, but he initially believed the deposits dated to the Eocene epoch, or early Tertiary period.[21] When Hayden later argued that the deposits were Miocene in age, Leidy concurred with his colleague. Throughout most of the nineteenth century, researchers attributed the deposits to a lacustrine origin, but over time and with better collecting methods, more complete skeletons, and more comparative data (comparable fossils from Oregon, Utah, Wyoming, and Nebraska), researchers recognized the Badlands deposits as pre-Miocene in age. By the turn of the century, the fossil-bearing deposits of the White River Badlands were interpreted as belonging to the Oligocene (the lower deposits) and lower Miocene (upper deposits). As will be discussed in subsequent sections of this chapter, more recent studies and the development of new dating techniques have led to a refinement in both the geochronology of the various formations as well as the duration of the formations.

Given the uncertainty in dating the deposits as well as the correlation between these deposits and others in the western US, some early researchers elected to refer to the beds by index fossils contained within the different deposits. Thus, for example, Hayden and others referred to the lowest beds (Chadron Formation) as the Titanotherium beds, and the overlying beds (lower Brule Formation) were referred to as the Oreodont beds (or occasionally as the "turtle and oreodon" beds). As early as 1858 Hayden defined a White River series, and he used characteristic fossils to define the lithostratigraphic units. Late-nineteenth century researchers that helped to define (and later refine) the geologic history of these formations include J.B. Hatcher, J.L. Wortman, H.F. Osborn, and W.B. Scott.[22]

In 1893, Wortman recognized the *Titanotherium* beds of Hayden, and he subdivided the Oreodon bed into the lower-lying Oreodon beds (lower, middle, and upper unit) and upper barren clays. Wortman also recognized and described the *Protoceras* beds and the *Lepauchenia* (upper unit) as stratigraphically different and above the barren clays. Wortman defined a typical locality as the area where the Cheyenne and White rivers are nearest to each other (i.e., the area south of Scenic near Sheep Mountain Table and the South Unit of the Park). Near the lower portion of the Oreodon beds, Wortman noted a particularly thick (10-20 feet thick) and far ranging sandstone formation (stream channel deposits) that contained a distinctive and abundant ancestral aquatic rhinoceros (named *Metamynodon*). He labeled this formation the *Metamynodon* sandstone. Directly above the *Metamynodon* sandstone, he noted a "lower nodular" zone and 75-100 feet above that zone, he also noted a second or "upper nodular" zone. Both nodular units were considered highly fossiliferous. Wortman also extended the top of the Oreodon beds 100 feet above "upper nodular" zone, which heretofore were considered to be the top of the Oreodon beds.[23]

Wortman also defined the *Protoceras* beds (also stream channel deposits), formerly considered part of the Oreodon beds. This formation, which is poorly known outside of the White River Badlands, was named for an interesting and extinct fossil known as *Protoceras*. These fossils are described as "some of the most interesting mammals ever discovered."[24] The animal resembled a small "deerlet" of India or a musk deer of the Asiatic highlands, but was not related to either, rather this creature was a ruminant (even-toed or Artiodactyla) with four toes on the front feet and two toes on the hind feet. The males exhibited two or more pairs of horns or bony protuberances on the skull (some forms had as many as five pairs of protuberances), and the upper canines were particularly elongated. The appearance of horns on the *Protoceras* fossils marks the earliest appearance of horns among artiodactyls.

In 1899, W.D. Matthew challenged the theory of a lacustrine origin for the White River Badlands formation and suggested that most of the sediments were derived from eolian activity, whereas the sandstone formations were fluvial in origin.[25] In that same year and also in 1901, N.H. Darton published two reports in the USGS that first applied geographic names to geological units in the Badlands region rather than referring to the stratigraphic units by an index fossil or a number. Darton named the "Chadron Formation" (formerly referred to as the *Titanotherium* beds), the "Brule Formation" (formerly the *Oreodon* beds), and the Arikaree Formation. Although the geographic name given to the formation was for Chadron, Nebraska, Darton declined to describe a type locality, referring simply to the "typical beds" in South Dakota. Likewise, in naming the Brule Formation, Darton again referred to a typical locality as the "Big Badlands of South Dakota."[26] Darton also identified (but did not name) a unit that underlies the Chadron Formation in South Dakota and parts of Nebraska. Macdonald notes that Matthew in 1901 and Wanless in 1923 continued to refer to the formations as the "*Titanotherium* beds," and the "*Oreodon* beds," respectively, but in 1910 following O'Harra's work, nearly all subsequent researchers used the terms Chadron, Brule, and Arikaree Formations.[27]

One of the breakthrough studies at the turn of the century was by W.M. Davis in 1900 when he published an article in *Proceedings of the American Academy of Arts and Sciences* in which he suggested that the Tertiary deposits of the Great Plains were of fluvial origin. A fluvial origin for the Chadron and Brule Formations explained many unresolved issues related to a lacustrine origin for the White River formations. The presence of channel sandstones, nodular layers, gravel deposits, alternating layers of clay and/or silt interspersed with various sand layers coupled with the absence of marine invertebrates and fish were more easily understood and explained in a depositional environment with a fluvial origin. In 1910 and 1920, O'Harra noted the following regarding the origin of deposition for the White River formations:

> There now seems to be abundant evidence for the belief that the deposits were of combined lagoon, fluviatile, floodplain, and possibly eolian origin instead of having been laid down over the bottom of great and continuous bodies of standing water as was first supposed." He goes on to write, "…broad streams…developed across this vast area (by "area" he means the Great Plains between the Rocky Mountains and Black Hills and the Badlands) a network of changing channels, backwaters, lagoons, marshes, and grass-covered flats…Thus the clays, sandstones, conglomerates, eolian sands, and even the volcanic dust…are all accounted for and the life conditions of the time are in reasonable measure made plain.[28]

Given this understanding of the origin of the formations, geologists and paleontologists were able to finally understand that the White River Badlands were the result of numerous cycles of deposition-erosion-redeposition-erosion (and accompanied, at least during the Oligocene and Miocene periods, by uplift related to volcanic activity in the Rocky Mountains and Black Hills) controlled by changing climatic and environmental conditions. Given the nature of the various fossil lineages identified from the Badlands it was obvious to all that the region became increasingly more arid with time. Another geological breakthrough occurred in 1923 when H.R. Wanless published an article on Miocene stream channels in the Badlands.[29] By the time of this publication, it was generally agreed, based on fossil evidence, that the upper formations in the White River Badlands were late Oligocene to early Miocene in age. Among other findings, Wanless demonstrated that a thick, white ash layer (subsequently named the Rockyford Ash) overlay the Brule Formation and formed the lowest or basal unit in the Arikaree or Rosebud Formation. The Rosebud Formation of northwestern Nebraska and southwestern South Dakota is roughly the equivalent of the Arikaree Formation. Wanless correctly described numerous channel deposits and other fluvial depositional units within the White River Group, but he retained the earlier biological nomenclature in referring to the fossil beds and stratigraphic layers. The confusion in stratigraphic nomenclature was in part due to the influence of Wanless' dissertation advisor, William J. Sinclair.

In 1907 Matthew named the Rosebud Formation for his work near Porcupine Butte and noted that the white stratum at the base of this formation (i.e., the white ash layer) was nearly identical to the white stratum capping the White River Formation on Sheep Mountain Table in the Badlands. At the time, and in subsequent publications, Matthew, Osborn, Bump, and others used the Rosebud Formation to define the strata between the Brule Formation (Oligocene) and the Ogalalla Formation (Pliocene). Although it was believed at this time (early 1900s) that the Arikaree and Rosebud Formations were Miocene in age, researchers recognized even at this early date that the formations were not continuous between South Dakota and Nebraska.

In 1937 the Wood Committee was appointed to clarify the biological and geological nomenclature applied to the fossil beds and geological strata in the vicinity of the White River Badlands as well as across North America. The Wood Committee attempted to clarify a complex hybrid of local rock units and time units that had been delineated by the first and last occurrence of mammalian genera. The efforts of the committee were an important step in trying to organize and standardize the terminology surrounding the geological formations and fossil-bearing strata, but the named units they developed were not true stratigraphic units because they were not based on biostratagrahic zones.[30] The Wood Committee named three North American Land Mammal Ages (NALMA) in the Oligocene, namely the Chadronian, Orellan, and Whitneyan, from oldest to youngest. Identification of the Eocene-Oligocene boundary was thought to be critical to understanding major extinction events during the late Eocene.

In 1949 Wood published an article entitled "*Oligocene Faunas, Facies, and Formations.*"[31] In the article Wood noted that the White River Group demonstrated two types of facies gradation based on grain size. One gradation was from upstream to downstream, while the second gradation was lateral, ranging from the main river channel, to the minor stream channel, to backwater channels, to floodplain deposits and eolian deposits. Wood's work demonstrated that the various units within the White River Group were both time transgressive (i.e., the strata do not necessarily occur at the same point in time in the geological record) and geographically or spatially transgressive (i.e., the strata are not necessarily uniform across their area of deposition). Thus, he argued the formations within the White River Badlands should be viewed as gradational both chronologically and geographically from west to east, with older and thicker deposits to the west and more recent and thinner deposits to the east.

Other important contributions to the geology and stratigraphy of the Badlands were made by John Clark in 1937 and James D. Bump in 1951. Clark, who earned a Ph.D. from Princeton University in 1935, studied the stratigraphy and paleontology of the Chadron Formation in the Badlands of South Dakota. Through his research Clark divided the Chadron Formation into Lower, Middle, and Upper members, and he considered the sediments within the formation to represent "one major sedimentary cycle, with two subcycles, the first consisting of the Lower Member, and the second of the Middle and Upper Members."[32] Clark also noted a faunal and lithological change toward a Brule environment during or before Upper Chadron time. Clark later gave names to the Lower, Middle, and Upper Members of the Chadron Formation; from oldest to youngest they are Ahearn, Crazy Johnson, and Peanut Peak.[33]

Schultz and Stout provided the temporal names Orella Member and Whitney Member to the lower and upper parts of the Brule Formation from their work in western Nebraska.[34] Bump, in analyzing fossil mammals from the Brule Formation in the White River Badlands, also divided the paleontological remains into two major units, the Orella Member (lower) and the Whitney Member (upper). He further subdivided each major member into lower, middle, and upper units or zones.[35] In 1956 Bump described the strata of the Brule Formation and assigned geographic names to the members of the Brule Formation. The lower lying strata designated the Scenic Member, while the upper units were designated as the Poleslide Member.[36] Bump also noted that the "White Ash Layer," which was defined by Wanless in 1923, represented the basal unit of the Arikaree or Rosebud Formation.

Contributions to Paleontology

Through their field investigations and countless hours of laboratory study and comparative analysis, the early pioneers in the field of paleontology were able to demonstrate that the Tertiary deposits of North America contained a wealth of information regarding mammalian evolution. The fossil beds of the White River Group proved to be not only among the most important in the world, but also contained some of the longest continuous fossil sequences in all of North America. The fossils of the White River Group (early Oligocene to early Miocene in age) are among the most important in the world because they cover a period of time that was critical to the history of mammalian evolution. With the extinction of dinosaurs at the end of the Cretaceous period, mammals, which had existed since before the Cretaceous, were able to rapidly evolve and occupy the various environmental habitats and niches left vacant by the extinction of dinosaurs. The earliest mammals were extremely primitive and it is not until the Oligocene epoch that mammals begin to take on a more modern appearance and actually show some resemblance to their modern day ancestors. In addition, early paleontologists and their colleagues and students were able to demonstrate that the evolution of some lineages of herbivores (e.g., horse) and carnivores (canid) was contained within the North American fossil record.

Just as the geology of the White River Badlands was refined by academic study between 1890 and 1950, the knowledge of mammalian evolution during the Late Eocene to Early Miocene periods was significantly advanced during this same period. In 1902, C.C. O'Harra prepared an annotated bibliography for contributions to the geology and geography of the Black Hills region (including the Badlands) that were made between 1846 and 1900.[37] At the time he cautioned that readers should consider the work incomplete because lack of time precluded him from including all the articles on vertebrate paleontology. Nonetheless, the bibliography lists over 200 articles and papers, including over 30 articles written between 1892 and 1900 that are related to vertebrate paleontology from the Whiter River Badlands. The principal authors regarding paleontological studies from the White River Badlands include a list of familiar names.

- O.C. Marsh (prepared 6 articles, including articles on: Miocene mammals, *Miohippus* or *Protoceras* beds, Miocene artiodactyls, Tertiary artiodactyls, ancestral tapirs, descriptions on male and female protocerid skulls),
- H.F. Osborn (prepared 5 articles, including articles on: the rise of mammals, *Aceratherium*, cranial evolution of brontotheres, extinct rhinoceroses),
- J.B. Hatcher (prepared 4 articles, including articles on: titanotherium beds, two-horned rhinoceros (*Diceratherium)*, recent and fossil tapirs, and corrections on the previous *Diceratherium* article);
- W.B. Scott (prepared 4 articles, including articles on: *Agriochoerus*–artiodactyls, *Ancodus* (primitive animal resembling early pigs with some characteristics shared with hippopotamus), *Protoceras, Hyaenodon* (earliest evidence of carnivores-primitive wolf-like appearance but size of black bear));
- J.L. Wortman (prepared 5 articles, including articles on: differentiation of the *Protoceras* beds, evolution of *Protapirus* (ancestral tapirs), osteology of *Agriochoerus*-artiodactyls, and evolutionary history of camels);
- H.F. Osborn and J.L. Wortman (prepared 4 articles, including articles on: *Protoceras*, *Artionyx*-a new genus of Ancylopoda, fossil mammals from the lower Miocene, and Perissodactyls including discussion on the evolution of horses, tapirs, and brontotheres);
- and G.I. Adams (Felidae-extinct cats), M.S. Farr (*Mesohippus*-extinct horse), O.C. Farrington (Annual Report of the Field Museum, 1898 field investigations), and J.E. Todd (report of 1896 field investigations) each authored one article.

In addition to the contributions made by these authors, a number of other researchers studied paleontological remains from the White River Badlands during the first half of the twentieth century. Other paleontologists working in the Badlands included C.B. Schultz, G.L. Jepsen, J. Clark, R.W. Wilson, H.E. Wood, F.B. Loomis, W.D. Matthew, G.G. Simpson, A. Wetmore, and A.E. Wood.

Research from the White River Badlands was able to shed light on the evolutionary history of a number of ungulates (hoofed animals) and carnivores. The early paleontologists divided the ungulates into two groups: Perissodactyla (odd-toed herbivores) and Artiodactyla (even-toed herbivores). The Perissodactyla include five major groups; these include living groups such as tapirs (*Tapiroidea*), rhinoceroses Rhinocerotoidea), and horses (Equoidea), and two extinct groups Brontotheroidea (brontotheres) and Chalicotheroidea. The order had its peak in the Eocene and early Oligocene, but by the end of the Oligocene, 10 of the 14 families were extinct. *Hyracodon* (running rhinoceros) and *Metamynodon* (river rhinoceros) are among the more common fossils of extinct rhinoceros-like lineages to appear in the Chadron and Brule Formations within the White River Badlands.

The evolution of *Mesotherium (Mesohippus)* and *Miohippus* are particularly well-defined from fossils within the White River Badlands. The brontotheres (titanothere is the common name) evolved from a relatively small to medium-sized animal during the early Eocene to the incredibly large brontotheres (8-9 feet at the shoulders) with a large pair of nasal horns during the early Oligocene. These creatures became extinct during the early Oligocene and are not present in the Poleslide Member of the Brule Formation. The perissodactyls dominated medium- and large-sized herbivores during the early Tertiary period. With the exception of the horse, most members of this order are three-toed.

The *Artiodactyla* or even-toed ungulates generally express the loss of the first digit in all but the earliest Tertiary forms, but the second and fifth digits are present in almost all Tertiary taxa. Some of the extinct forms present in the White River Badlands include various lineages related to pigs and hippos (e.g., Anthracotheriidae), oreodonts (Merycoidodontidae), camels (e.g., *Poebrotherium, Stenomylus, Procamelus Camelops*), protocerids (Protoceritidae), and peccaries. The early radiation of artiodactyls during the early Eocene gave rise to many pig-like stocks, rooters, and browsers of the forests and woodlands. A second radiation of artiodactyls occurred during the late Eocene and early Oligocene and gave rise to the early ruminants (oreodonts, camels, protocerids) which diversified during the subsequent Miocene epoch to take advantage of the expanding savannah and grassland habitat.

In addition to herbivores, early paleontologists recovered a variety of fossil carnivorous mammals including both extinct groups (such as Creodonta) and ancestral groups (such as Canidae (dogs), Ursidae (bears), Mustilidae (skunks, minks), and Procyonidae (raccoons). The creodonts, an extinct and primitive type of carnivore, were represented by two genera from the Chadron Formation, but only one genus, *Hyaenodon*, survived into Orellan and Whitneyan times. Dogs are represented by the family Canidae as well as a more primitive family known as Amphicyonidae. There are ten genera of Canidae and Amphicyonidae present in the White River Badlands and the fossils show a number of similarities to modern dogs including a wide range of sizes. Within the family Nimravidae, the so-called saber-toothed cats of the Oligocene all possessed elongated canines, but only the genera *Hoplophoneus* and *Eusmilus* show the development of true saber-toothed cats. However, other cats such as *Dinictis*, *Pogonodon*, and *Nimravus* also had exceptionally long canines. Fossil remains of ancestral bears, mustelids, and raccoons are rare.

During the period of 1892 to 1950, as paleontologists learned more about the extinct fauna and the geological formations that produced the fossils, it became increasingly clear that biostratigraphic units and boundaries were not necessarily compatible with lithostratigraphic units. The Wood Committee attempted to clarify the biological and geological nomenclature applied to the fossil beds and geological strata in North America. The NALMA or provincial mammal ages present within or near the Park include from oldest to youngest: Duchesnean (Eocene), Chadronian (Eocene), Orellan, Whitneyan, and Arikareean (Oligocene), and Arikareean, Hemingfordian, and Barstovian (Miocene).

As originally established by the Wood Committee, the Chadronian was defined geologically (or lithologically) on the basis of the Chadron Formation (as defined near Chadron, Nebraska, and not the White River Badlands). Biologically, the Chadronian was defined as the time that *Titanotherium* (or *Brontotherium*) and *Mesohippus* coexisted.[38] Thus, the definition combined lithostratigraphy (the geochronology of the Chadron Formation) and biochronology (the overlapping temporal and geographical ranges of *Mesohippus* and *Brontotherium*). As long as *Mesohippus* was not known in strata older than the Chadron Formation and brontotheres were not known from above the Chadron Formation, the dual definition, while not internally inconsistent, remained workable.[39] As Prothero and Emry recently pointed out, confusion regarding the Chadronian-Orellan boundary resulted from the “uncritical definition” of the boundary by Schultz and Stout from their work in the Toadstool Park area of Nebraska. In 1987, Emry and others eventually recommended that the Chadronian be defined in faunal or biostratigraphical terms and argued that lithostratigraphic units had no role in the definition of a biochronologic unit.

The Wood Committee based the Orellan on the Orella Member of the Brule Formation in northwestern Nebraska and included the old term “Oreodon beds” in the definition. The Wood Committee based the Chadronian-Orellan boundary on the last occurrence of brontotheres and at the top of the Chadron Formation. This became a problem when it was discovered that at least four documented occurrences of brontotheres were known to exist above the Chadron-Brule contact as defined by Schultz and Stout. The Whitneyan was defined on the basis of the Whitney Member of the Brule Formation in northwestern Nebraska and included the old *Protoceras-Leptauchenia* beds. As Emry et al. pointed out some years later, there were a number of problems with this definition, not the least of which was basing a biochronological unit on a lithostratigraphic unit. Another problem they noted was the fact that many of the key index taxa are only known from one place and that most species of the Whitneyan are restricted to South Dakota and Nebraska. Suggested revisions to these biochronological units are discussed in subsequent sections of this chapter.

Despite the establishment of the NALMA, paleontologists soon recognized that biostratigraphic units were, at best, only loosely related to lithostratigraphic units. Of equal importance was the recognition that biostratigraphic and lithostratigraphic units were both spatially and temporally transgressive, thereby establishing the need to further refine the chronology of these units on a regional scale before trying to extend generalities across North America let alone trying to correlate North American events with similar events in Europe or Asia.

In 1967, Clark et al. identified a number of factors that affect the formation, preservation, and discovery of fossil remains. Some of the factors listed by these authors that affect preservation are the following:

(1) Biotic – a number of features influence the life of individuals or a species that in turn can affect the availability of individuals or species to be preserved in the fossil record. Such factors include range of the species, habitat or niche of the species, population density, pressure to leave preferred habitat, and osteological considerations like body size and bone density.
(2) Thanatic – circumstance surrounding the death of the individual which affect fossilization such as the cause of death, locus of death, age at death; to the authors it is a matter of the sum of fresh corpses on a surface prior to the burial of that surface by the next episode of sedimentation.
(3) Perthotaxic – factors such as climate, amount of time the bones have been exposed on the surface prior to burial, and degree of scavenging.
(4) Tapic – bone burial including time between episodes of sedimentation, thickness of sediments, velocity of depositional current, nature of sediment (texture, grain size), degree of post-depositional bioturbation, permeability of the sediment.
(5) Anataxic – factors serving to expose and destroy bones and fossils after burial such as weathering *in–situ*, exposure by erosion, degree of weathering and transportation.
(6) Methods of collecting fossils can bias the samples collected, including such factors as visual prospecting vs. excavation technique vs. mining fossils, or historic resampling, or biases due to differential cementation.
(7) Curation Factors – curation biases can bias the sampling procedures.[40]

Geological and Paleontological Studies Meet the Modern World (1950 to Present)

Geology and Stratigraphy of the White River Badlands Region

<u>Stratigraphy and Description of New Units (ca. 1950-1975)</u>

By the onset of the 1950s the stratigraphy of the White River Group of the South Dakota Badlands was widely recognized and accepted, at least on a generalized level, but many questions remained unanswered, and it would require years of additional research to refine the stratigraphy and geochronology of the region as well as develop correlations between the White River Group and similar formations in areas such as Nebraska and

Wyoming. As noted previously, in 1951 Bump divided the Brule Formation into the Orella and Whitney members and further divided each member into lower, middle, and upper units, and in 1954 Clark named the Ahearn, Crazy Johnson, and Peanut Peak members of the Chadron Formation,[41] Bump followed his earlier work with a 1956 publication in which he named the Scenic and Poleslide members of the Brule Formation.[42] The nomenclature and type descriptions worked well enough until C.B. Schultz and T.M. Stout of the University of Nebraska Museum took it upon themselves to publish a paper that placed the type sections for the two formations in Nebraska (rather than the South Dakota White River Badlands) despite the work of previous scientists such as Darton, Matthew, Osborn, Wortman, Wanless, Clark, and Bump.

In 1961, Harksen named the Sharps Formation for exposures near Sharps Corner, South Dakota.[43] The type sections for the Sharps Formation included a 270-foot exposure eight miles north of Sharps Corner and a 340-foot exposure five miles southwest of Sharps Corner. Together these exposures represent over 390 feet of basal Miocene deposits. Harksen defined the Sharps Formation as the basal unit of the Miocene-aged Arikaree Group.[44] Harksen also noted that the Sharps Formation was underlain by Rockyford Ash, which defines the boundary between the Brule Formation (late Oligocene) and the Arikaree Group (early Miocene), and is overlain by the Monroe Creek Formation. He characterized the Sharps Formation as a massive, tan-colored silt intermixed with volcanic ash layers.[45]

In 1969 Harksen and Macdonald prepared two articles on the stratigraphy of the "Big" Badlands. The purpose of the articles was both an attempt to define some typical sections on one hand and to clarify and/or correct some of the errors and misinterpretations of previous investigators. In discussing the recently named Sharps Formation and underlying Rockyford Ash, Harksen and Macdonald acknowledged that the use of the Rockyford Ash as the Oligocene-Miocene boundary was arbitrary and open to debate.[46] They justified this determination with the caveat that standard epoch boundaries are based on breaks in the European section, but in a continuous North American section the boundaries must be arbitrary until such time as an absolute date has been determined.[47] They also noted that the Rockyford Ash had long been acknowledged as a boundary marker, so they elected to retain that distinction. Their paper attempted to rectify earlier errors and misinterpretations regarding the Sharps Formation.

Harksen and Macdonald point out that in 1906 Matthew and Thompson of the American Museum of Natural History reported that the contact between the Oligocene and the Miocene beds was gradational and only recognizable by the fauna. Matthew believed that the entire post-Brule section should be referred to as the "Rosebud Beds." But in fact, Matthew and Thompson were looking at the gradational contact between the Sharps Formation and the Monroe Creek Formation and not the contact between the Brule and the Sharps Formation. In a 1907 article, Matthew divided the "Rosebud Beds" into upper and lower units. The lower unit began near the top of the Sharps Formation, included all of the Monroe Creek Formation, and the lower part of the Harrison Formation. The upper unit included the upper part of the Harrison Formation and the Rosebud

Formation.[48] Harksen and Macdonald bemoaned the fact that this misinterpretation and "nomenclatural confusion resulting from the transference of the name "Rosebud Beds" to include all of the post-Sharps Formation sequence and the mistaking of the Sharps Formation for the Brule Formation…effectively stalled further study for many years."[49] The Monroe Creek Formation conformably overlies the Sharps Formation, and in turn it is conformably overlain by the Harrison Formation. The Monroe Creek and Harrison Formations, originally defined by Hatcher in 1902, are considered part of the Arikaree Group, and for the most part have remained free of controversy. It should be pointed out that at the time of the Harksen and Macdonald article, the Monroe Creek and Harrison Formations were thought to be Miocene in age.

According to Harksen and Macdonald another source of confusion was the misidentification of the Rosebud Formation by Skinner and Taylor. The Rosebud Formation overlies the Harrison Formation and in turn is unconformably overlain by Pliocene deposits. In a 1967 article, Skinner and Taylor presented a definition of the type section for the Rosebud Formation that greatly restricted the temporal span yet at the same time their definition lacked a clearly defined top and bottom for the unit.[50] In contrast, Harksen and Macdonald examined a larger area along the Little White River and utilized the entire sequence of pink silts to define the Rosebud Formation. These authors argued that this interpretation was closer to the original definition intended by Gidley back in 1904. More importantly, their interpretation expands the temporal span for the Rosebud Formation and jeopardizes, if not eliminates, the concept of the Marsland Formation. They also argued that the Rosebud Formation in the vicinity of the Rosebud Agency is the temporal equivalent of the Sharps-Monroe Creek-Harrison-Rosebud sequence near Wounded Knee.[51]

Harksen and Macdonald concluded their work with a caution that researchers needed to remember that "formations may vary in time laterally and should not be based on taxonomic units to the exclusion of lithology," and they went on to suggest that

> Skinner and Taylor were disregarding lateral lithologic variation as a geologic fact and were striving to preserve the term Marsland Formation as a unit name despite its spotty history and roving type section." Must we always be reminding our colleagues that rock units are no respecters of time boundaries and need not be confined to a designated piece of time, be the same age from one end to the other, nor be defined on the basis of contained fossils.[52]

In 1969 Harksen and Macdonald published a second article that also sought to sort through the confusion in nomenclature, with specific reference to the Chadron and Brule Formations. The authors noted that the "whole story is one of name substitution and roving type localities."[53] Yet they point out that Evans clearly showed where the "*Paleotherium*" beds were located, that Darton related his Chadron Formation to the typical beds in the Badlands, and Osborn pinpointed the type locations both on a map and with photographs. The authors argued that the type section for the Chadron Formation, as defined by Bump in 1956, should be retained. They also designated and defined several type sections for the Brule Formation that they maintained should be used henceforth as the type sections for this formation. One of the more useful aspects of the article was a chart presented by the authors that depicted the development of the stratigraphic nomenclature in the White River Badlands. The chart summarizes no less than 13 different nomenclatures for this area. In discussing the nomenclature applied to the Chadron and Brule Formations (biological at first and later geographical) over the last 70 years, Harksen and Macdonald acknowledged that, with the exception of Osborn's work in 1929, the historical development of names and type sections applied by most other authors ignored Darton's original intentions.[54] As a result of this study, they reconfirmed the type area used by Bump for the Chadron Formation and designated a type section for the Brule Formation.[55]

As part of the guidebook to Cenozoic deposits in South Dakota, Harksen prepared a detailed chapter, complete with graphic resumes of Tertiary strata, on the Cenozoic history of southwestern South Dakota.[56] The chapter provided a good summary of the history of the nomenclature as well as generalized descriptions of the various units. Harksen notes that the most fossiliferous portion of the Chadron Formation in the White River Badlands is the Indian Creek-Battle Creek area where Clark (in 1937 and 1954) defined the Ahearn, Crazy Johnson, and Peanut Peak members. Unfortunately, the lithologies of the Ahearn, Crazy Johnson, and Peanut Peak members can only be traced for a few miles. According to Harksen, the explanation lies in the fact that the area selected by Clark is a structural trap and collects sediments from the surrounding area, and consequently, the lithology of the area is dissimilar to the rest of the Chadron.[57] The Brule Formation contains an aggregate depth of about 460 ft of both fluvial and eolian sediments. Because of the different hardness of the beds in the Brule Formation, it weathers into a tread and riser topography as opposed to the haystack topography of the Chadron Formation.

Overlying the Peanut Peak Member, the uppermost unit of the Chadron Formation, is the Scenic Member of the Brule Formation. Within the Scenic Member are the so-called *Metamynodon* channels. These river channel deposits were so-named because they contain numerous fossils of the extinct river rhinoceros called *Metamynodon*. The Poleslide Member, the upper unit of the Brule Formation, contains the famous *Protoceras* channels, so-named because it is the only place where the artiodactyl *Protoceras* fossils have been recovered.[58]

The Rockyford Ash overlies the Brule Formation and forms the base of the Sharps Formation, which itself is the basal formation of the Arikaree Group.[59] Harksen noted that the Rockyford Ash actually represents reworked wind-blown ash deposits that are of varying thickness across the region. The remainder of the Sharps Formation consists primarily of pink, wind-blown silt and clay deposits. Harksen also noted that at some point during deposition of the Sharps Formation, an extended period of erosion occurred. The overlying Monroe Creek Formation, which primarily represents paleo-loess deposits, contains a higher percentage of volcanic ash compared to the Sharps Formation. The high percentage of paleo-loess in the Monroe Creek Formation accounts for the vertical weathering profile. The Harrison Formation overlies the Monroe Creek Formation and is the uppermost unit of the Arikaree Group.[60] In South Dakota, the Rosebud Formation overlies the Harrison Formation and, at the time of the 1969 field trip, constituted the end of the Miocene sequence in southwestern South Dakota. According to Figure 3 of Harksen's field guide article, the Rosebud Formation is unconformably overlain by the Pliocene-aged Ogallalla Formation.[61] The unconformity represents a period of extension erosion during the Miocene-Pliocene boundary. Conversely, northwestern Nebraska contains a nearly complete sequence of late Miocene to late Pliocene deposits.

According to Harksens's Figure 3, Pliocene deposits are essentially absent from the geological record in southwestern South Dakota.[62] During late Pliocene times, renewed uplift of the Rocky Mountain region and the Black Hills triggered an extended period of violent erosion that continued into the early Pleistocene. The last significant fluvial sediments in the White River Badlands are the Medicine Root Gravels, which Harksen estimates to be Nebraskan (early Pleistocene) in age.[63] The Medicine Root gravels were deposited at a time when Nebraskan glaciation turned the streams of the Black Hills into raging torrents and the streams became choked with course materials from the core of the Black Hills. When conditions returned to a more normal status, the stream valleys were filled with coarse gravels. The fine-grained sediments (sands and silts) within the coarser grained gravels were eroded leaving behind the coarse gravel sediments as cap deposits on the interfluves.[64] Harksen noted Medicine Root gravels capping hills in Shannon and Jackson County as well as a high area on the south edge of Cuny Table, which marks the westernmost exposure of these gravels.[65]

In 1974, Harksen prepared an article on "Miocene Channels in the Cedar Pass Area Jackson County, South Dakota" in which he commented on the presence of an unconformable contact between the Brule and Sharps Formations.[66] Harksen noted at least two locations in the Cedar Pass area of the Park where Miocene channels cut into the underlying Oligocene-aged Brule Formation. These erosional channels deposited channel sandstones similar to the *Protoceras* channels in the Poleslide Member. The *Protoceras* channels by definition are restricted to the Poleslide Member, so the presence of Miocene-aged (?) channel sandstone deposits at the same level constituted an interesting problem in need of resolution.[67]

Stratigraphic Revisions (1975 to Present)

Beginning in 1995, the National Park Service and the University of Nebraska entered into a cooperative agreement to study the geological and paleontological resources of the South Unit of the Park. The research focused on three primary areas: (1) geological mapping of the Chadron Formation and understanding associated depositional environments, (2) documentation of fossil resources and fossil theft within the South Unit, and (3) geological mapping of the Chadron Formation that relates depositional environments to the regional distribution of fossils. One result of the study was a proposed stratigraphic revision of the Chadron Formation. Dennis Terry and others suggested revisions to the lithostratigraphic nomenclature for the White River Group. It also became clear that the Chadron Formation, contrary to long held traditional thinking, dated to the late Eocene period and not the early Oligocene.[68] The White River Group (Eocene to Oligocene) is underlain by the Cretaceous-aged Pierre Shale and Fox Hills Formations and overlain by the Arikaree Group. At the close of the Cretaceous period, the Pierre Shale was severely altered by pedogenic weathering and development that resulted in the Yellow Mounds Paleosol, which is characterized by rounded mounds that are yellow, orange, and lavender in color and up to 26 m in thickness.[69] The Yellow Mounds Paleosol is the lower of the two paleosols within the Interior Zone. Overlying the Pierre Shale and the Yellow Mounds Paleosol is the Chamberlain Pass Formation, which Terry defined as the basal formation of the White River Group. The Chamberlain Pass Formation consists of white channel sandstones, red overbank mudstones, and greenish proximal overbank mudstones and siltstones.[70] Based on Retallack's work in 1983 on Cenozoic paleosols in the Badlands, it appears the red overbank mudstones were modified through pedogenesis to form the Interior Paleosol, and the greenish overbank mudstones were modified to form the Weta Paleosol Series.[71]

At some point near the end of pedogenic development of the Interior Paleosol, erosion of Clark's "Red River Valley" downcut through the Chamberlain Pass Formation and the Yellow Mounds Paleosol and into the Pierre Shale Formation. The paleovalley was subsequently filled with sediments that formed the Ahearn Member (up to 24 m of red and green sandstones and claystones) and the overlying Crazy Johnson Member (12-15 m of greenish claystones and sandstones). The last member of the Chadron Formation is the Peanut Peak Member, which unlike the Ahearn and Crazy Johnson members, is not confined to the paleovalley and in fact is more regional in extent. Evans and Terry provide a summary on the significance of stream incision and alluvial sedimentation in the basal units of the White River Group.[72]

The Crazy Johnson Member consists of 6-9 m of massive buff and green claystones that contain discontinuous limestone lenses near the top of the rock unit.[73] These discontinuous limestone beds are discussed in more detail in the subsequent section. The paleosols contained within the White River Group indicate a trend toward increasing aridity, as indicated by changes in the size of the root traces from forested environments to drier more open grassland environments. As a result of this geologic mapping, "the channel sandstones of the Slim Buttes Formation are now included in the Chamberlain Pass Formation and the Peanut Peak Member has been expanded to include the massive clays of the eastern facies."[74]

In terms of fossil remains within the Chadron Formation in the South Unit of the Park, Terry concluded that the Crazy Johnson Member contained 77 percent of the significant (i.e., commercial or scientific value). Terry noted that this may in part be accounted for by the fact that the Crazy Johnson Member represents a greater proportion of the outcrops in the study area.[75] The Peanut Peak Member produced nearly 14 percent of the fossils while the Scenic Member of the Brule Formation and the Ahearn Member of the Chadron Formation each produced about 4.5 percent of the fossils. Nearly 61 percent of the fossils were recovered from sandstone lithologies while 39 percent of the fossils were found in mudstone lithologies.[76]

In terms of depositional environments, Terry determined that the Chadron Formation can be characterized as an "aggrading fluvial system that formed in response to local changes in base level. Channel morphologies changed from confined, lenticular deposits in the floor of the paleovalley to broad, thin deposits of shallow river systems with increasingly wider floodplains as the paleovalley filled."[77] Terry also notes that the changes in base level related to the retreat of the Cretaceous Interior Seaway and the formation of the Yellow Mounds Paleosol were eustatic in nature, whereas the changes in base levels during the Chamberlain Pass and Chadron Formations were the result of responses to tectonic uplift of the Black Hills and Rocky Mountains.

In a related article that compared the stratigraphy of the lower portion of the White River Group in South Dakota with comparable exposures in northwestern Nebraska, Terry recommended the following revisions:

(1) abandon the term Interior Paleosol Complex because it is actually composed of two separate and distinct soils (the Yellow Mounds Paleosol, developed on Pierre Shale, and the Interior Paleosol, developed on overbank deposits of the Chamberlain Pass Formation);
(2) abandon the term "Chadron A" as used by Schultz and Stout and reject the correlation of these deposits with the Ahearn Member in light of the fact that the Chamberlain Pass Formation is recognizable in Nebraska;
(3) reject the correlation of the "Chadron B" to the Crazy Johnson Member and instead expand the term Peanut Peak Member to include undifferentiated strata outside of the "Red River Valley" of South Dakota; and
(4) abandon the term "Chadron C" in favor of the Big Cottonwood Creek Member for deposits that overlie the Peanut Peak Member in northwestern Nebraska and reject the correlation of the Big Cottonwood Creek Member in Nebraska with the Peanut Peak Member in the White River Badlands.[78]

Within the last four years, Philip Stoffer, (and others) on behalf of the USGS, published two comprehensive works that summarize some of the more recent geological and biostratigraphic discoveries within the Park, including stratigraphic revisions and current nomenclature. The first report, prepared in 2001, presented data that was attributed to the Cretaceous-Tertiary (K-T) boundary within the Park.[79] The second report, prepared in 2003, discusses the geology of the Park.[80] The 2003 article presents a comprehensive overview of the Cretaceous through Tertiary formations contained within the Park as well as a summary of the Quaternary events that shaped the landforms that the Park visitor experiences today. The paper focuses on the revolutionary discoveries that have occurred within the last 20-25 years as scientists and students continue the long history of geological and paleontological research and field investigations within the Park in an effort to generate new information and apply new technologies and/or dating techniques to the growing body of data.

Stoffer et al. conducted several years of research on the interpretation and regional correlation of Late Cretaceous sections within the Park. Based on their research data, these authors argued that the Park contained a nearly complete, albeit condensed, Late Cretaceous section that could provide resolution to the Cretaceous/Tertiary (K-T) boundary question within the Badlands sequence. Stoffer et al. began their research in the lower, more fossiliferous zones exposed along Sage Creek and proceeded up-section into the more unresolved upper part of the section. During Cretaceous times the Badlands region as well as much of the Great Plains was part of the Western Interior Seaway. The Late Cretaceous, which is subdivided into the Campanian and Maestrichtian (also Maastrichtian) epochs (ca. 75 – 65.5 MA), consists of Pierre Shale and the Fox Hills Formation (from older to younger). Biozones within these ages are based on the presence or absence of various key index marine fauna (e.g., mollusks, ammonites, dinoflagellate cysts). One of the problems in finding a resolution to the K-T boundary in the Badlands has been the lack of fossils preserved in the upper part of this "historically enigmatic sequence."[81] Presumably, if the K-T boundary were present within the Park, evidence of its occurrence would appear in sediments between the Fox Hills Formation and the Yellow Mounds Paleosol.

Retallack (see discussion of Cenozoic Paleosols below) was the first to suggest that the K-T boundary was below the Chadron Formation, perhaps related to the Yellow Mounds Paleosol (named in 1966 by Pettyjohn). This interpretation suggested that the Pre-Chadron K-T boundary represented an extended period of weathering and erosion that removed the latest Cretaceous and early Paleocene sediments.[82] Stoffer et al. countered that the Badlands section showed evidence

> …to support interpretation of ongoing sediment deposition concurrent with regional and local uplift as far back as late Campanian and up through the mid-late Oligocene…Our observations suggest that uplift of the Black Hills, the Sage Creek Arch, the Chadron Arch, and other local and regional structures influenced sedimentation patterns of the Pierre Shale and Fox Hills Formations east of the Black Hills.[83]

One problem identified by Stoffer et al. was difference in sedimentation rates and deposition for the Fox Hills Formation. The authors indicated that changes in sea level, coupled with on-going tectonic activity, resulted in greater deposition in subsiding areas whereas as rising areas, like the Sage Creek Arch, experienced little if any deposition at this time.[84] Thus, the Late Cretaceous section in the Sage Creek area was missing the Fairpoint Member and the White Owl Creek Member. Another contribution by Stoffer et al. was the recognition of a "widespread interval of soft-sediment deformation."[85] The authors thought that that this stratigraphic unit, which they labeled as the Disturbed Zone (DZ), could be synchronous with the K-T boundary. Originally, Stoffer et al. interpreted the DZ unit to be representative of a slump zone, but upon further investigation they determined that the event was too widespread to represent slumping.[86]

The Disturbed Zone was studied at three locations in the Park, the Wilderness Access Trailhead, Grassy Tables Overlook, and Dillon Pass/Conata Creek area. According to Stoffer et al., the DZ lies unconformably between the Fox Hills Formation and the basal units of the Yellow Mounds Paleosol. Paleomagnetic data provide a basis for interpolating sedimentation rates within the DZ and the underlying Pierre Shale Formation. The authors noted a dramatic reduction in sedimentation rates from 6.0 to 6.5 meters every million years between the Campanian/Maestrichtian boundary (71.3 MA) and the K-T boundary (65 MA) versus a sedimentation rate of 1 meter per million years during deposition of the DZ. Marked changes in lithologies from clay and shale to silty sand facies were interpreted as indication of major hydrological changes.

Within the North Unit of the Park, Stoffer et al. focused their discussion about the alleged K-T boundary on a thin glauconitic marl unit near the bottom of the DZ. The presence of glauconite has traditionally been an "indicator mineral" of slow, shallow marine sedimentation, particularly during times of transgression.[87] Although glauconite has been observed in massive, bioturbated sandstone units in the Fox Hills Sandstone, the authors reject this model for the presence of the glauconitic marl near the bottom of the DZ. Rather they believe that the glauconite is associated with extraterrestrial meteor impacts. They also point out that the Badlands glauconite is not a true glauconite but rather a suite of different clay minerals such as iron (Fe), potassium (K), and silica (Si). The thin laminated red clam-bearing clay lies conformably on top of the glauconite layer and is overlain by the DZ. The DZ layer contains no Cretaceous fossils despite the fact that Stoffer et al. conducted five years of study that concentrated, among other things, on paleontological remains within the DZ. No Cretaceous bone fragments or mollusks have been recorded from the DZ, and glauconite is not present within a meter above the DZ.[88]

Based on the above data and their interpretations of that data, Stoffer et al. concluded that the DZ represents the K-T boundary of marine sediments deposited with the Western Interior Seaway. The authors further argued that the dates for the DZ as well as dates for units above and below this layer are within the timeframe for the giant meteor (Chicxulub) that impacted the Gulf of Mexico north of the Yucatan Peninsula.

> The DZ represents a late Maestrichtian regional environmental catastrophe with an associated intense seismic component and is younger than the belemnite-bearing unit dated around 67.1 MA. The differing fauna below and above a unique glauconitic marl layer suggests that a significant environmental change had already occurred a relatively short geologic time prior to the formation of the Disturbed Zone.[89]

Stoffer et al. concluded that the K-T boundary was present within the Park and was represented by the top of the Disturbed Zone. That is, the DZ allegedly marked not only a major change in fauna, but also a significant change in sedimentation patterns from interior marine sediments to terrestrial deposits. The presence of contorted sandstone beds and melted glass spherules coupled with the above data was interpreted by the authors to represent the K-T boundary.

More recent studies of the biostratigraphy and chronometric age of the Lower Fairpoint Member of the Fox Hills Formation have resulted in the dismissal of the idea that the Park contains evidence of the meteoric impact that defines the K-T boundary. Studies by Palamarczuk et al. and Chamberlain et al. have been paramount in dismissing the notion that evidence of the K-T boundary is present within the Park.[90] These studies examined dinoflagellate cysts, palynomorphs, and lithological data collected from a 30 m thick interval of the Fox Hills Formation. The study section consisted of a series of siltstones and sandstones, dark in color with massive bedding and glauconitic at the base.[91] Dinoflagellate cysts (microfossils used to date marine sediments) and palynomorphs (which include, but are not limited to, spores, gymnosperm and angiosperm pollen grains, and certain algae colonies) are present in sufficient quantities in the lower 4 m of the section to indicate that the section has a probable age of lower upper to middle upper Maestrichtian. Above this 4 m section is a .5 to 5 m thick disturbed zone (the same DZ as noted above). To recall, the DZ was thought to represent the K-T boundary on the basis of improvised macrofossil fauna, sedimentological interpretations, and small amounts of impact debris. As noted above, the DZ is characterized by contorted sandstone beds, shocked quartz and melted glass spherules that can be traced over an area of 1,000 km^2. The DZ, which expresses indeterminant polarity, is "bracketed by a reversed and normal magnetic polarity zone throughout the study region."[92]

The study section analyzed by Palamarczuk et al. and Chamberlain et al. overlies gray Pierre Shale and lies below a zone of sandy concretions that have been placed in the middle of the Fairpoint Member of the Fox Hills Formation. That is, although terrestrial palynomorphs are common, studies indicate that the abundant dinoflagellate cysts are diagnostic of the lower upper and middle upper Maestrichtian. Palamarczuk et al. also note that dinoflagellates are present in small numbers above the DZ. Based on these data, the authors conclude that the palynomorphs and sedimentological data indicate a near shore marine depositional environment for the basal 4 m that gradually grades upward to a fluvial or deltaic environment.[93] Chamberlain et al. conclude that the

> "… DZ impactite within the study interval is not associated with the Manson Impact (too old) nor the end – K Chixculub Impact (too young), but instead represents either a hitherto unrecognized local impact event, or a distal correlative of the impactite reported from the Raton Basin."[94]

One possible explanation for the DZ is that the DZ represents an earlier meteor impact that occurred prior to the "Chicxulub" impact that currently defines the K-T boundary. Chamberlain et al. argue that the dinoflagellate data are present to within 25 centimeters (cm) of the DZ, and thus, there is no convenient way to account for a million years of sedimentation in the intervening 25 cm of rock. As a growing body of data suggest, there was more than one meteor impact near the end of the Cretaceous, and in all likelihood the DZ represents one of these earlier impacts, but it does not represent the K-T boundary.

Miscellaneous Stratigraphic Studies

Another study that has both stratigraphic and paleoclimatic implications is a Master's thesis by Linda Welzenbach that focused attention on lacustrine limestone formations in the Lower White River Group.[95] She investigated four freshwater limestone units (the Bloom Basin Limestone beds) that occur at the contact between the Chadron and Brule formations. The area of study (ca. 300 square kilometers) was located north of the North Unit of the Park, about 2-3 miles southeast of Wall and 5 miles southwest of Quinn. The beds consist of a fining upward sequence of mudstone, wackestone, packstone, and algal bindstone.[96] The faunal assemblage expressed in the beds "reflect high abundance but low diversity and include two taxa of gastropods, ostracods, fish, aquatic turtle, charophytes, and algal filament ghosts."[97]

Welzenbach argued that the faunal assemblage indicates water depths of up to 10 m, with a fresh to brackish oxygenated water column. The presence of ostracods and charophytes indicated a low energy setting, and based on various lines of evidence, Welzenbach concluded that the lakes were fed by springs and ground water. She suggested that at this locality, the Chadron Formation fluvial system changed to a fully carbonate lacustrine system with a lake that was over 300 km^2 in areal extent and upwards of 10 m or more in depth.[98] Although the lake persisted for many years, it suddenly experienced a terminal emergence (evidenced by mud cracks and a faunal death assemblage), and was subsequently filled by the Brule Formation fluvial system. Welzenbach interpreted these changes to be the result of base level changes and major climatic changes during the Middle to Late Eocene and the Late Eocene to Early Oligocene.[99] She also concluded that the disruption in drainage or fluvial incision occurred prior to deposition of the Brule Formation.

In 1998 Welzenbach and Evans continued the study of carbonate deposition in a fluvial sequence in the Lower White River Group. They identified at least four lacustrine limestone beds in the upper part of the Chadron Formation from various locations in South Dakota and Nebraska, ranging from Wall, South Dakota, to Toadstool Park in Nebraska.[100] They examined the stratigraphy, lithology, and paleontology of Late Eocene-Early Oligocene freshwater limestone beds at 16 localities in the area. In addition to corroborating the earlier findings of Welzenbach, their study identified two notable discoveries.

> (1) "The lacustrine limestones are pure carbonate, indicating that these depositional systems were isolated or protected from the adjacent, overbank-dominated fluvial systems, and (2) the lacustrine limestones and paleogroundwater deposits are found adjacent to structural features (e.g., faults, fracture systems), suggesting that the deposits were the result of a localized, structurally controlled place of paleogroundwater discharge."[101]

The lacustrine limestones, which are confined to the upper Chadron Formation, do not occur in the underlying Chamberlain Pass Formation or the overlying Brule Formation. The authors interpreted this to mean that Black Hills uplift led to the initiation of regional paleogroundwater flow systems during deposition of the Chadron Formation. Increased aridity and decreased discharge of the paleogroundwater led to changes in the paleohydrology of the region (flow rates and flow direction) and termination of the paleogroundwater discharge, which in turn resulted in evaporation of the lakebeds and the subsequent deposition of the Brule Formation.[102]

Paleontological Discoveries

Macrofossil Studies

Since the Wood Committee's attempt to define biochronological units for the North American Land Mammal Ages, many researchers have pointed out the errors and inconsistencies in the definition and use of the NALMA units. Prothero and Emry provide a summary of the problems in the NALMA as defined by the Wood Committee and present a list of revisions and recommendations to rectify the problem.[103] As discussed previously, one of the problems with the Chadronian Land Mammal Age was the uncritical definition of the top of the Chadron Formation and the presence of brontotheres above the alleged top of the formation. The identification of the Big Cottonwood Creek Member (limited to Nebraska only) as the uppermost unit of the Chadron Formation corrected the problem of brontotheres supposedly occurring in rock units above the Chadron Formation. Prothero and Emry concluded that definition of the end of the Chadronian, as defined by the Wood Committee, is "insufficient by itself, and although it can be part of the definition, it is impractical as a means of recognizing the end of Chadronian time."[104]

It was "recommended that the Chadronian-Orellan boundary be placed at the first appearance of the distinctive taxon *Hypertragulaus calcaratus*, along with the first appearance of a number of additional reference taxa."[105] Prothero and Emry suggested the following time periods for the Chadronian: Earliest Chadronian (37 – 36.5 MA), Late Early Chadronian (36.5 – 35.7 MA), Middle Chadronian (35.7 – 34.7 MA), and Late Chadronian (34.7 – 33.7 MA). With the revision of the top of the Chadron Formation to include the Big Cottonwood Creek Member, the conflict regarding the occurrence of brontotheres above the Chadron (as it was defined by Schultz and Stout and the Wood Committee) was eliminated. In the article, the Prothero and Emry support recommended revisions to define the Orellan as the first appearance of *Hypertragulus calcaratus, Leptomeryx evansi, Paleolagus intermedius,* and *Miniochoerus chadronensis*; the boundary could also include the last appearance of *Poebrotherium eximium* and *Miohippus grandis.*[106] The authors proposed the following date ranges for the Orellan: Earliest Orellan (33.7 – 33.4 MA), Late Early Orellan (33.4 – 33.1 MA), Early Late Orellan (33.1 – 32.5 MA), and Latest Orellan (32.5 – 32.0 MA).

In discussing the original definition of the Whitneyan, Prothero and Emry noted that it was inappropriate and misleading to define a biochronological unit on the basis of lithostratigraphic units. Based on the limited geographical range of the key biostratigraphic units and the limited number of fossils present in the key beds, it was recommended that the Whitneyan be based strictly on biostratigraphic criteria. It was proposed that the Whitneyan be divided into two sections: the Early Whitneyan (32.0 –

31.4 MA) and the Late Whitneyan (31.4 0 30.0 MA). The end of the Whitneyan and the beginning of the Arikareean was defined as the first appearance of *Nanotragulus loomsi*, *Palaeolagus hypsodus*, *Palaeocastor nebrascensis*, *Leidymys blacki*, and *Mesoreodon minor*.[107] These taxa first occur in the lowest levels of the Sharps Formation (just above the Rockyford Ash) on the south side of Sheep Mountain Table. The end of the Whitneyan is marked by the last occurrence of a number of taxa including *Leptomeryx, Merycoidodon, Paratylopus, Paralabis, Colodon, Protapirus, Hesperocycon, Osbornodon, Dinictus*, and *Eumys*.[108] As a result of the revisions to the nomenclature and definitions of the NALMAs, there are now four distinct biostratigraphic intervals for the Chadronian, four proposed levels for the Orellan, and two formal zones for the Whitneyan. Collectively, these NALMAs span roughly 7 million years from 37-30 MA. More importantly the land mammal ages are based on biostratigraphic zones and radiometric dates. The authors conclude that the above revisions, if accepted, "offer the first high-resolution, well-calibrated chronostratigraphy for the White River Group. Such high-resolution data have already proven useful for a number of evolutionary and paleoclimatic studies where precise dating of faunal events is necessary."[109]

In partnership with other museums and universities, Rachel Benton, Ph.D., Park Paleontologist, Badlands National Park, continues to study and research paleontological remains within the Park. One study by DiBenedetto examined the sedimentology and taphonomy of the Brian Maebius site in the Tyree Basin of the Sage Creek Wilderness Area of the Park. DiBenedetto examined a variety of fossil remains, including a number of small mammals, from a locality situated in the "Lower Nodular Zone," Scenic Member, Brule Formation. The fossil remains included extinct squirrel, mouse, other rodents, rabbit, and an insectivore as well as extinct forms of horse, rhino, and a ruminant.[110] He also examined coprolites and the first preserved pollen grains from the Scenic Member. Pollen data indicate the presence of trees such as pine (*Pinus*), hickory (*Carya*), oak (*Quercus*), and elm (*Ulmus*) along with a mixed grassland community of ragweed and marsh elder (*Ambrosia*), goosefoot (*Chenopodia*), aster (*Composita*), and seed and grass plants (*Gramina*).[111] A sedimentological analysis of the locality suggested a natural levee or backchannel levee habitat with a freshwater swamp nearby surrounded by xerophytic (arid) elements. The assemblage suggests a climatic change from warmer to cooler conditions (15.1º C to 14.1º C) and increasingly xeric conditions (830 mm precipitation/year to 600 mm/year).[112] DiBenedetto concluded that strata were deposited by a laterally moving fluvial system with episodic deposition during fluvial cycles of about 700 year's magnitude. Based on the fossil mammals and pollen, DiBenedetto argued for a varied and abundant fauna assemblage within a fluvial system with grassland elements nearby.[113]

<u>Microfossil Studies</u>

The study of Cenozoic microfauna (e.g., small mammals such as moles, voles, mice, and squirrels) was rarely a concern among vertebrate paleontologists in the first 100 or more years of research in the White River Badlands. In 1896 Hatcher was one of the first to suggest that harvester ant mounds were likely to contain microvertebrate fossils. Paleontolgists operated under the assumption that because small mammals live and die within a particular environmental niche within limited geographical range, therefore a fossil assemblage from a given locality, when taken as a whole, would provide paleontologists with a rather unique opportunity to reconstruct the paleoenvironmental conditions of the formation from which they were derived. Gary Johnson conducted his master thesis study at SDSMT on microvertebrates from the Middle Oligocene deposits of the White River Group. Johnson collected 198 microfaunal samples from 330 harvester ant mounds. The mounds were located in Middle Oligocene deposits (Brule Formation).[114] Johnson recorded small vertebrate and invertebrate remains, representing 19 families and 22 genera. Six of the 22 genera were reported for the first time in middle Oligocene deposits. One of the more interesting finds was the recovery of the first primate premolar from Middle Oligocene beds of the White River Group.[115] Johnson also reported two new types of Sciuridae (squirrels), probably suggestive of *Proscirus*, which would be the first *Proscirus* in the middle Oligocene. Johnson also reported the first *Agnotocastor* (fossil beaver) remains in the Middle Oligocene beds.[116]

Several years later in 1972, Laurie Macdonald (now Laurie Bryant), also from SDSMT, conducted a study of microfossil remains from the Monroe Creek (Early to Middle Miocene) Formation near Wounded Knee.[117] The Monroe Creek Formation, which falls in the middle of the Arikareean NALMA, is a thick sequence of wind and stream deposited silt and volcanic ash. Like Johnson before her, Macdonald collected harvester ant mounds. She was able to collect small fish, frogs, lizards, snakes, birds, and mammals.[118] Macdonald noted that the overwhelming majority of mammalian remains were representative of burrowing animals that were able to burrow into the soft silty sediments. Among the fossil remains collected by Macdonald, she reported 68 percent were pocket gopher and pocket mouse, and 20 percent of the remains consisted of lizards, snakes, rabbits, hedgehogs, moles, ground squirrels, deer mice, and jumping mice.[119] More recently, Mike Greenwald, Research Scientist for the Geology Museum-SDSMT, has conducted numerous studies on microfaunal remains from various paleontological excavations and monitoring projects within the Park.

Paleomagnetic and Tectonic (Volcanic Tuffs) Studies

The discovery of various radiometric dating techniques and their inclusion into mainstream scientific research proved to be of great benefit to geologists and paleontologists beginning in the 1960s and1970s. New research techniques and areas of study, including magnetostratigraphic studies and paleomagnetic correlation, have rendered a number of startling interpretations to the geology and paleontology of the White River Badlands. Beginning in 1985 and continuing to the present, magnetostratigraphic studies and paleomagnetic correlation have resulted in changing time lines for various biostratigraphic boundaries during the Cenozoic Era. Prothero conducted magnetostratigraphic studies of the White River Group that produced “a network of paleomagnetic datum planes for detailed correlation.”[120] Prothero noted that detailed correlation of the stratigraphy of the White River Group has always been a problem. One reason for the problem is the difficulty in correlating land mammal biostratigraphy with the global marine record, especially given the few places were Oligocene mammal-bearing deposits interfinger with marine deposits in North

America.[121] He also noted that radiometric dates were currently available only for the Chadronian period, while rocks of the Orellan and Whitneyan periods have yet to produce reliable dates. Prothero suggested that magnetic polarity stratigraphic studies could resolve the aforementioned problems. Prothero maintained that,

> If the local microstratigraphy can be correlated with the global magnetic polarity timescale, both absolute dating and correlation with the worldwide geochronological record are possible. Once correlation with global record is established, local changes in the mammalian fauna can be related to the major paleoclimatic changes that took place during the Oligocene.[122]

Prothero collected numerous paleomagnetic samples at 5.5 foot intervals within each sampled stratigraphic column at various locations within and adjacent to the Park. The results of this initial work suggested the following boundaries of the land mammal ages: Duchesnean/Chadronian-36.5 million years ago (Ma), Chadronian/Orellan – 32.4 Ma, Orellan/Whitneyan – 30.7 Ma, and Whitneyan/Arikareean – 28.5 Ma. (Note: the above dates have been superseded by more recent studies and improved dating techniques. Prothero's work also suggested that the famous "Lower Nodular Zone," which yielded a large number of fossils and was considered a stratigraphic marker, is time transgressive with outcrops becoming progressively younger to the west. He cautioned that the "time transgressive nature of the nodular layers in the Big Badlands should serve as a caveat for lithostratigraphic correlations based on other widespread marker units."[123] Prothero also demonstrated that the "most crucial phases of the Chadronian/Orellan transition are not preserved in the Big Badlands" of South Dakota, but are present in the biostratigraphic ranges exhibited near Lusk and Douglas, Wyoming.[124]

Later magnetostratigraphic and paleomagnetic studies by Prothero and Swisher contradicted his initial findings. In a 1992 article, the authors argued that their new radiometric dates would change long-held interpretations of the age and correlation of NALMAs with the Eocene-Oligocene timescale. Revised dates of importance to the Big Badlands include the following: Duchesnean/Chadronian-37 million years ago (Ma), Chadronian/Orellan-33.9 Ma, Orellan/Whitneyan-(slightly predates) 31.8 Ma, and Whitneyan/Arikareean-(slightly post-dates) 30.05 Ma.[125] The revised dates of these NALMA boundaries affect the traditional interpretations of faunal changes. For example,

> …the minor faunal change between the Duchesnean and Chadronian, once thought to be the Eocene-Oligocene transition, is now within the late Eocene. The extinctions at the Chadronian/Orellan boundary, once touted as the Mid-Oligocene Event are now correlative with the Terminal Eocene….There is no significant faunal event during the middle Oligocene in North America, as is also true of the marine record….The shorter duration for the Chadronian also means that rates of species origination and extinction are now comparable with other NALMA events.[126]

Prothero and Swisher conclude that many of the more troublesome questions regarding correlations for the Eocene/Oligocene boundary are now resolved.

Other studies in the White River Group have sought to find the source of the numerous widespread volcanic tuff beds that occur throughout the formation. Larson and Evanoff studied White River tuffs from Colorado, Wyoming, and Nebraska.[127] The tuffs were classified according to geochemical properties, mineralogy, and radiometric dates. The tuffs range in age from 35.5 Ma to 30 Ma, with volcanic deposits older than 31 Ma containing mostly rhyolitic to rhyodacitic tuffs, and tuffs younger than 31 Ma are predominantly dacitic. These data, combined with radiometric dates and tuff composition, suggest that the source of the tuffs was derived from volcanic activity in Utah and Nevada.[128] Larson and Evanoff suggested that the White River fossils could provide detailed biostratigraphic data, but cautioned that on a regional scale only detailed stratigraphic ranges have been determined for the Brule Formation. They also cautioned that while magnetic polarity zones "provide the most detailed correlations for the White River sequence, magnetic polarity zones are not themselves uniquely diagnostic, and without the aid of additional stratigraphic indicators, correlation of magnetic zones in terrestrial sequences is problematic."[129] Based on their study of volcanic tuffs, these authors demonstrated that polarity zones can be completely missing in local sections. Because tuffs are more common than polarity zones, they suggest that studying volcanic tuffs can provide greater stratigraphic resolution.

In recent years, the study of tectonism has gained favor among geologists working within the Park. In 1996 the "Field Guide to Tertiary Tectonism in the Northern Great Plains: Road Log, Field Trip 1" reported that magnetostratigraphy, faunal correlations, and lithostratigraphy demonstrated that the boundary between the White River Group and the overlying Arikaree Group should be placed within the Sharps Formation which is Late Oligocene in age.[130]

From older to younger, the Chadron Formation is underlain by the famous "Yellow Mounds Paleosol" and the "Interior Paleosol." The White River Group rests unconformably on a surface that preserves at least two weathering profiles of different age. The older surface, the Yellow Mounds Paleosol, was recognized as a weathering surface since 1965 and if exposed, can be easily identified throughout the Park. In the northern and eastern parts of the Park, the Yellow Mounds Paleosol was formed on the Fox Hills Formation and Pierre Shale, while further to the west this paleosol developed on weathered Pierre Shale.[131] Both of the marine formations (i.e., Pierre Shale and Fox Hills) are of Late Cretaceous age, while the Yellow Mounds Paleosol is generally considered to be early Eocene in age.[132] Overlying the Yellow Mounds Paleosol is the Chamberlain Pass Formation, identified by Terry and Evans.[133] According to the authors, the Interior Paleosol developed on the weathered surface of the Chamberlain Pass Formation. The reddish color of the Interior Paleosol suggests development in a higher oxygenating environment compared to the Yellow Mounds Paleosol or green beds of the underlying marine sediments. The authors maintain that burial of the aforementioned paleosols by gray floodplain deposits of the overlying Chadron Formation indicates a significant change in base level between Late Cretaceous and Late Eocene.[134] Much of that change is believed to be the result of tectonic activity, as evidenced by a number of faults that occur in Late Cretaceous marine formations within the Park.[135]

Based on their work in 1998, Stoffer et al. reached somewhat similar conclusions regarding Late Cretaceous sediments and evidence of tectonic events within the Park. These authors demonstrated four cycles of eustatic sea level change that occurred during the Late Cretaceous period that are correlated with regression of the Western Interior Seaway and the onset of the Laramide regional deformation.[136] The authors conclude that tectonic uplift in the Badlands region during the late Cretaceous period is evidenced by (1) "the abundance of reworked sediments in some horizons, (2) the occurrence of buried slumps near fault zones, and the thinning of strata associated with the Maestrichtian ammonite range along the eastern flank of the Black Hills."[137]

Paleoecological and Paleoclimatological Studies

Thus far, this chapter has focused on geological and paleontological studies whose primary intent was to provide scientists and others with sufficient information to correlate regional biostratigraphic and lithostratigraphic data and discuss the timing and nature of evolution for various Cenozoic land mammals. Within the last 30-40 years, another interesting and equally useful purpose of geological and paleontological studies has emerged. Namely, the ability to infer and/or interpret paleoecological and paleoclimatic conditions during specific periods of geologic time. Early paleontological studies alluded to this type of interpretation, when stating that one period was warmer or cooler than another (e.g., Eocene vs. Oligocene) or one period was wetter or drier than another (again Eocene vs. Oligocene). However, beginning in the 1960s John Clark, while at SDSMT and later with the Field Museum of Natural History in Chicago, initiated studies that he hoped would not only interpret the climatic history of the Oligocene, but also allow others to predict where future areas of desert and jungle may occur and define and locate the boundary between well-watered soils and barren deserts.[138] Based on various field studies sponsored by the NPS and Badlands National Monument from 1957-1961, Clark attempted to interpret the geological history of the Park and reconstruct the paleoclimatic history of the late Cretaceous (Pierre Shale and Fox Hills Formation) through late Oligocene (Poleslide Member) periods in the White River Badlands of South Dakota.

Clark suggested that during the Laramide Revolution when the Black Hills were uplifted, the arching of Cretaceous strata, coupled with uplift, resulted in low structures east of the Black Hills. Thus, western South Dakota was transformed from low swamps and jungles watered by streams from mountains in Idaho and Wyoming to a broad, flat-bottomed valley trending southeastward with higher ridges to the north and south.[139] Clark argued that during the subsequent Paleocene-Eocene periods nothing spectacular happened in South Dakota. Streams from the Black Hills dome slowly down cut sedimentary rocks, warmer and cooler periods alternated, with grassy areas expanding at the expense of jungles during more arid times. This extended period of deep weathering and erosion presumably resulted in the Yellow Mounds Paleosol and the Interior Paleosol. According to Clark, during the earliest Oligocene (or perhaps during the Eocene-Oligocene transition) the climate must have been exceedingly warm and moist, giving rise to stream rejuvenation whereby quiet muddy rivers and streams became torrents, choked with sand and gravel. Following this relatively short period of deposition, the streams began to erode once more leaving behind heavier gravels as surface gravels on older soils.[140]

According to Clark, the sediments from the Poleslide Member of the Brule Formation were deposited during the mid to late Oligocene. The old trough that extended southeastward from the Black Hills at the end of the Laramide Revolution now contained a stream called the Red River. Clark estimated the stream valley to have been three to five miles in width, but only 70 feet or less in depth. The Cheyenne River was not in existence at this time.[141] Clark notes that at this time the Red River began to fill with sand and fine-grained gravels as well as some red clay from the Spearfish and Minnelusa Formations. The sediments that filled the Red River channel formed the Ahearn, Crazy Johnson, and Peanut Peak members of the Chadron Formation. Although these units are exposed south and west of Sheep Mountain Table, the Chadron Formation is not exposed on Sheep Mountain Table. Over time, the valley continued to fill and volcanoes in the west provided various layers of ash. He speculates that the climate at this time was cooler than in the preceding periods because the deposited materials, for the most part, were unweathered.[142] Based on paleontological remains from the Ahearn Member (oldest) of the Chadron Formation, the animals at this time (brontotheres, three-toed horses, four-toed camels, soft-shelled turtles, small tropical turtles) were "predominantly stream-loving, forest forms that thrived in a humid, warm-temperate forest."[143]

Following this period of stream aggradation, a new period of deposition began that covered the initial deposits and filled the trough with more sediments that eventually lapped over the edges of the parallel ridges. These greenish sands and clays, which buried numerous brontotheres, deposited 20 to 40 feet of fine gravel, sand, and clay that constitute the Crazy Johnson Member of the Chadron Formation. The Red River continued along its former course, but was joined by two tributary streams, one near Scenic, South Dakota and the other just east of Wall, South Dakota. Eventually, the streams lost both their volume and velocity and the resulting shrunken creeks deposited a layer of fine silt and clay 15 to 30 feet thick, while more easterly areas developed wide shallow swamps (or lakes) with calcareous algae that formed limy deposits at the bottoms of the swamps. These silts, clays, and limy zones constitute the Peanut Peak Member of the Chadron Formation. At the close of the Chadron times, the region consisted of a, "… broad, almost featureless swampy plain (mostly wooded) with small, gently flowing creeks (eastward and southeastward)…(and) open areas of thick grass alternated with woodland in the interstream areas."[144]

According to Clark, the Middle Oligocene (now Early Oligocene), represented by the Scenic Member of the Brule Formation, was characterized by a cooler and drier climate. Streams were smaller and less powerful, and narrow bands of riparian vegetation paralleled the stream banks, but grasslands were predominant in interfluvial settings. Eventually the streams began a period of deposition, known as the Lower Nodular Zone or Layer, that entombed numerous animals. At some point, the climate became more humid and the streams increased their volume and bedload and eventually deposited several feet of siltstone over mudstone.[145]

The sediments from the Poleslide Member of the Brule Formation were deposited during the mid to late Oligocene. The majority of these sediments have eroded with the only outcrops of the Poleslide exposed at the top of higher elevations such as Cuny Table, Sheep Mountain Table, the Pinnacles, and the Cedar Pass area. The sediments within the Poleslide Member are described as "massive, fine-grained mudstones (tan to buff colored), with abundant unweathered volcanic ash. They represent continued floodplain deposition under temperate arid conditions…"[146] Channel-fill sediments are noted at several places, including several that trend southeastward into the north face of Cuny Table, another trends eastward along the south face of Sheep Mountain Table, while another runs eastward, just north of the Wall between Norbeck Pass and Cedar Pass.[147] Clark speculates that during the Late Oligocene the climate became progressively more arid and cooler (with perhaps even frosty winters) than at any previous time.

In 1967, Clark et al. followed their earlier study with a larger more extensive research effort that culminated in a monograph entitled, *Oligocene Sedimentation, Stratigraphy, Paleoecology, and Paleoclimatology.*[148] The work included a 54-page chapter on the "Geology, Paleoecology, and Paleoclimatology of the Chadron Formation, and a 35-page chapter on the "Paleogeography of the Scenic Member of the Brule Formation." Among other innovative approaches, Clark et al. attempted to make an analogy between the depositional environments of the "Red River" of the Badlands and certain geographical and environmental regions of the Amazon River floodplain and delta. Unfortunately, the analogy also borrowed numerous Brazilian (and other foreign) terms that were unfamiliar to North American scientists, and the study gained little support. Clark et al. also attempted to calculate rates of deposition for the various members of the Chadron and Brule Formation, but these too were not widely accepted. Nonetheless, the book does provide a serious examination of fluvial deposits both longitudinally along the stream course and laterally across the terraces, backchannels, floodplains, and the main stream channel. The report resulted in 58 numbered conclusions (three pages) that ranged from the impacts of the Laramide Revolution at the end of the Cretaceous period to climatic and environmental events that took place at the end of the Oligocene epoch. Clark et al. addressed issues such as sedimentation rates, stratigraphic facies, and paleoenvironmental and paleoclimatological reconstructions.[149]

More recently, Dr. James E. Martin of SDSMT was able to reconstruct the paleoenvironmental conditions in the area during the late Pleistocene and early Holocene. Martin examined mammalian remains, particularly microfauna, from the nearby Lange-Ferguson Clovis Kill Site just south of the Park. The Clovis horizon produced 24 vertebrate taxa, including 14 small mammals.[150] Based on the modern geographical range of the various species recovered from the Clovis occupation (ca. 11,000 BP), Martin suggested an area of sympatry of northeastern North Dakota with elements of boreal forest, mixed deciduous forest, and grassland.[151] Locally, he suggested a paleo-mesic, riparian habitat with a low energy stream near a permanent water body. He also suggested that the greater effective precipitation during the Clovis period allowed for a more dense and diverse vegetation mosaic that in turn supported a more diverse faunal assemblage than current conditions can sustain.

Geochronology

Cenozoic Paleosols

The study of paleosols, or fossil soils, has provided scientists with a variety of new insights into the stratigraphy, taphonomy, paleoecology and paleoclimatology of the White River Badlands. The application of paleopedogenic studies in the Badlands is relatively new. One of the first studies was conducted by Greg J. Retallack of Indiana University. Retallack, who studied a 143 meter (m) stratigraphic column in the Pinnacles area of the Park, identified 87 paleosols ranging in age from Late Eocene to Late Oligocene.[152] Retallack noted that three criteria (root traces, soil horizons, and soil structure) can be used to differentiate fossil soils from soils that simply enclose sedimentary deposits (i.e., non-soils). Retallack characterized the paleosols into ten different kinds of fossil soils, each representing a distinctive ancient environment based on such factors as climate, organisms, topographic relief, parent material, and time of formation (i.e., degree of environmental stability). According to Retallack, the fossil soils evince a progressively drier climate "from humid during Late Eocene time to semiarid during Late Oligocene time. There was also a concomitant change in vegetation from Late Eocene forest, to Early Oligocene open woodland, to early Late Oligocene savanna with a stream-side gallery woodland, to mid-Late Oligocene savanna, and finally to latest Late Oligocene open grassland with scattered stream-side trees."[153] The mammalian faunal record during this time changed from forest and woodland species to a savanna dominated assemblage.

After several millions of years of uplift, streams eroded the Late Cretaceous marine deposits and began to fill with sediments during the Late Eocene period. Retallack suggests that topographic relief was generally low and uniform but occasionally interrupted by stream incision, particularly at the Eocene-Oligocene boundary and again during the later part of the Late Oligocene. Parent material for these paleosols generally consisted of volcanic ash, resorted soil material, and transported alluvium.[154] Retallack reports that resorted soil materials were most common in the wooded landscape of the Early Oligocene and volcanic ash became more prominent in parent materials of less developed, sparsely vegetated arid soils during the very end of the Oligocene. According to Retallack, the amount of time available for soil development changed "became progressively less with time, from strongly developed soils during the Late Eocene and Early Oligocene to moderately developed soils during the Late Oligocene."[155] Retallack also estimated the rate of sediment accumulation based on the time of soil formation and concluded that sediments accumulated at a progressively higher rate from the Late Eocene to the Late Oligocene. Retallack also provided block diagrams for various time periods that depicted paleoenvironmental conditions and preferred habitats for the prominent mammals during specific time periods.

In 1985, Retallack conducted a tour of fossils soils at three locations near the Pinnacles Lookout at the Park. The tour was part of the expeditions for the 45th Annual Meeting of the Society of Vertebrate Paleontology. In addition to the numerous paleosols, Retallack noted several major disconformities within the sequence that represent periods of landscape stability and erosion, that in part are related to climatic deterioration.[156] Unlike fossils recovered from paleostream channels, "fossil mammals in fossil soils are more likely to be close to where they lived and of about the same age as enclosing rocks… Each kind of fossil soil can be regarded as a unique kind of taphonomic situation in which some kinds of fossils were preserved but not others. Each fossil soil also represents a distinctive ancient ecosystem which may have supported distinctive assemblages of vertebrates."[157] Retallack pointed out that fossil soil horizons exhibit more graditional boundaries than sedimentary layering, with graditional changes to truncated surface horizons, and diffuse subsurface horizons composed of red argillic (Bt) horizons or calcic horizons (Ck) with calcareous nodules.[158] Retallack concluded that continued study of fossil soils and faunal assemblages have the potential to further delineate four new lines of research. (1) Paleosols may be used to assess the resolution of vertebrate biostratigraphy; (2) paleosols are useful indicators of old (or ancient) environments because they are independent of other indicators (and they provide evidence of ecosystems when vertebrate fossils are not preserved); (3) the variety of paleosols within a stratigraphic level reflect the range and diversity of sub environments within ancient landscapes; and (4) using independent evidence of ancient environments obtained from fossil soils, it may be possible to assess the degree to which animals were adapted or maladapted to their environment.[159]

Paleopedogenic studies are useful in interpreting local environmental conditions at fossil localities. For example, Terry conducted a stratigraphic and paleopedogenic analysis of the bone bed at the Conata Picnic Ground site or the "Pig Dig" within the Dillon Pass area of the North Unit.[160] The bones are contained within the lower portion of the Scenic Member of the Brule Formation. The White River Group, for the most part, was deposited within a fluvial environment that changed character as conditions became drier over time. For example, Terry reports that rivers associated with the preceding Chamberlain Pass Formation (i.e., during the early Chadronian NALMA) were typical meandering fluvial systems with multi-story channel deposits, lateral and vertical accretion, point bars, and cut banks. During the time of the deposition of the Chadron Formation the character of fluvial systems changed from channel sand facies within the Ahearn Member to a progressively more overbank mudstone facies system during the Crazy Johnson and Peanut Peak members. The degree to which climate controlled this shift from a channel-dominated system to an overbank facies-dominated system is unknown.[161] Channel systems within the Scenic Member of the Brule Formation are characterized by broad sheet sands, suggesting stream channels were braided to meandering in nature. The absence of stream channel deposits near the Pig Dig precludes interpreting the type of fluvial system associated with the bone bed.

Terry suggested four models for the formation of the Pig Dig: bog/swamp, pedogenic alteration, watering hole, and catastrophic flooding. Analysis and interpretation of the lateral extent of the bone bed layers favored the watering hole model. Sedimentological analysis suggested the water hole was formed on a floodplain near a stream channel during drought conditions.[162] The green coloration of the bone bed deposits is the result of anaerobic conditions, but Terry was not certain if the anaerobic conditions existed before burial and lithification, or if these conditions were the result of anaerobic decay of organic rich sediments during the development of anaerobic conditions. A study of the taphonomy of the Conata Picnic Ground site (Pig Dig) confirmed Terry's earlier findings, indicating the bone bed is the result of animals trapped and/or killed at a watering hole on a well drained floodplain but some distance from the main channel.[163] Among the remains analyzed for her thesis, Kimberlee Stevens identified a minimum of 8 *Archeotherium* (fossil pigs), 7 *Hyracodon* (ancestral rhinos), 3 *Mesohippus* (fossil horses), 3 *Leptomeryx* (ancient deerlet-sized ruminants), and 1 *Prosciurus* (fossil squirrel).[164] Stevens also noted that the fossil remains provided little evidence of predation or scavenging, which suggested the animals became trapped in the soils adjacent to the water hole and were then rapidly buried, thereby preserving the animal remains. The number of individuals has increased significantly since the time Stevens prepared her thesis.

Another recent MS thesis from SDSMT focused on environmental interpretations from paleosols that contained a fossil assemblage. Sarah Black conducted a site analysis of the Buffalo Alley Bone Bed, which is located in the lower Scenic Member of the Brule Formation.[165] The locality produced over 100 specimens including 80 specimens that could be identified and classified. Black argued that paleopedographic evidence suggests soil conditions were neutral to alkaline, and soils were well-developed compared to other weathering profiles observed within the Scenic Member.[166] Black also noted that the deposits were more typical of Badlands floodplain fossil accumulations. That is the Buffalo Bone Bed assemblage contrasts sharply with the Brian Maebius site in the Tyree Basin or the Pig Dig. The assemblage from the Brian Maebius site accumulated on a floodplain, but the assemblage exhibited strong evidence of carnivore predation or scavenging as a result of lying on the surface for an extended period of time before burial. Conversely, the fossils at the Pig Dig site represent complete, partially articulated skeletal remains that accumulated in or near a watering hole but were quickly buried and gave some evidence of predation or scavenging. In contrast to the above sites, the fossils from the Buffalo Alley Bone Bed site are represented by incomplete, disarticulated and fragmentary specimens.[167] The deposits from the site are mudstone and suggest deposition by a meandering stream, not direct channel deposits. The paleosols observed at the site range from very weak entisols with A/C soil horizons to well developed alfisols with A/Bt/C soil horizons. Another interesting note about the Buffalo Alley assemblage is the presence of coprolites. According to Black, the paleosols from this site do not match any of the four paleosol types defined by Retallack from the Scenic Member near the Pinnacles.[168] Black concluded that based on the presence of coprolites and the low percentage of scavenging, the bones were exposed on the floodplain surface for a short duration before burial.[169]

Quaternary Deposits and Geomorphological Studies

Although the geology and paleontology of the White River Badlands has been investigated for more than 100 years, it was not until the 1960s that researchers gave any serious consideration to Quaternary-aged (Pleistocene and Holocene) deposits and geomorphological studies. Today the White River Badlands stand in stark contrast to the surrounding featureless mixed grass plains of the Unglaciated Missouri Plateau. The extant topography is an expression of a complex history of Quaternary events (primarily erosional) acting on a number of former surfaces. The highest surfaces pre-date the actual formation (erosion) of the Badlands, while others represent terraces created when the Cheyenne and White rivers experienced a series of down cutting events during the Pleistocene. A number of alluvial and colluvial events combined to form the present Badlands surface. Some of the earliest studies regarding Quaternary deposits in the Badlands were conducted by J.C. Harksen of the South Dakota Geological Survey.[170]

<u>Eolian Studies</u>

In 1967 Harksen reported the presence of quaternary-aged loess (wind blown silt) deposits on tables and mesas in the southwestern part of South Dakota. Harksen argued that changes in base levels at the end of the Pliocene triggered an extended period of erosion of the White River Group and stream incising along the Cheyenne and White rivers. He suggested that the White River downcut more than 1,200 feet (ft) compared to only 600 ft for the Platte River.[171] Harksen noted that the White River Badlands were the ideal source for loess sediments during the Quaternary period.

In 1968, Harksen continued his studies of loess deposition in southwestern South Dakota and named the depositional unit "Red Dog Loess" after the type site, Red Dog Table.[172] At the type site, Harksen recorded 58 ft of loess, which was underlain by 30 ft of Quaternary-aged terrace deposits (silts and sands). The terrace deposits in turn lie unconformably on top of the "*Protoceras* channels" of the Poleslide Member of the Brule Formation.[173] Harksen noted that Cuny Table contains evidence of early Quaternary channel deposits as well as a loess cap and sand dunes on the eastern and western ends of the table. Harksen also reported Red Dog Loess deposits on top of Stirk Table, Sheep Mountain Table, Castle Buttes, and upwards of 90 ft of loess on top of Babby Butte. Harksen suggested the Red Dog Loess post dated 675,000 and was late Yarmouth (interglacial) to Illinoian (glacial advance) in age. Although Harksen acknowledged that downcutting of the Cheyenne and White rivers at this time provided source material along the exposed floodplains, he suggested that the White River Badlands were the major source for the Red Dog Loess.[174] He also suggested that the sand dunes on Cuny Table represented lag concentrations of courser-grained sediments after the finer-grained sediments were blown away during the Pleistocene.[175]

Within the last 10 years, the Park has sponsored several research projects that focused on the Holocene geomorphic evolution of the Park. Dr. Glen Fredlund, University of Wisconsin-Milwaukee, and his students initiated the earliest studies in the Park. Fredlund and others have noted for several years that eolian deposits are widespread across the North American Great Plains and are sensitive to climatic change. Prevailing thought argues that soils develop during mesic conditions while eolian deposits accumulate during xeric conditions. Recent studies suggest that Holocene droughts were of a greater magnitude and more frequent than historic period droughts.

Rawling et al. suggest the apparent lack of synchrony of drought events across the Great Plains has "three potential explanations that are not mutually exclusive: (1) real sub regional variability in climate, (2) non-climatic events reflected in the eolian geomorphic record, and (3) poor resolution in numerical chronology."[176] Rawling et al. studied soil stratigraphy from seven sections of eolian cliff-top deposits (ACT) at Cuny Table, Sheep Mountain Table, Bouquet Table, and Norbeck Pass. All sections examined contained buried soils formed in fluvial, eolian, or colluvial sediments that are overlain by ACT deposits.

The studies demonstrated that the soils beneath the ACT deposits are early Holocene (typically 7,900 years BP or older) at higher elevations (950 meters-Cuny Table and Sheep Mountain Table), and late Holocene (typically 2,900 years BP) at lower elevations (830 meters-Norbeck Pass and Bouquet Table). Buried soils within the ACT deposits exhibit weakly developed A-C or A-AC-C profiles. Organics within the top 5 centimeters (cm) were submitted for soil organic matter (SOM) radiocarbon dates. The sampled soils at these different locations returned roughly similar dates indicating late Holocene soils at 1,300 BP, 2,900 BP, and 3,700 BP.[177] The authors also reported that the correlation between the radiocarbon assays and infrared stimulated luminescence dates was good, thereby providing independent corroboration that the dates of the buried soils are regional indicators of paleoenvironmental conditions.

Fredlund and Rawling also noted that well-developed paleosols are frequently exposed in the terraces of the major creeks and larger tables or mesas, where they form distinct stratigraphic sequences. Geomorphological research, conducted by Fredlund and Rawling, focused on the buried soils contained in Holocene-aged eolian deposits such as large tables (mesas) and stabilized dunes that are common throughout the Badlands.[178] Holocene soils in the cliff-dunes are approximately 3 meters (m) in depth. Research at Sheep Mountain Table produced a series of stacked buried soil horizons, including three Holocene-aged A-C soils underlain by a truncated Bt horizon. Soil organic matter from these soils was dated. Although no recognizable A horizon was observed within the upper 100 cm, charcoal at 90 centimeters below surface (cmbs) was radiocarbon dated to 405 years BP. The first A-C soil measured 100-150 cmbs with a SOM date of 1,310 BP at the top and a date of 2,070 BP at the bottom. The second A-C soil (162-172 cmbs) produced a total SOM date of 2,390 BP, and the third A-C soil (180-190 cmbs) yielded a total SOM date of 3,800 BP.[179]

More recently, David Kuehn conducted a more extensive geoarcheological reconnaissance of the Park.[180] Kuehn's research, which stemmed from a paradigm of contextual archeology, focused on the temporal, landscape, stratigraphic, and paleoenvironmental contexts of the archeological record and site formation processes (and post-depositional events) associated with these sites. Kuehn's work was limited in scope and intended to lay the groundwork for multiyear archeological and geoarcheological studies. The stated project goals included (1) to identify landforms and depositional sedimentary environments within the Park that have the potential to contain buried, intact, prehistoric materials, (2) to provide archeologists with information regarding the temporal distribution of sites within the above landforms, and (3) to identify some of the archeological research questions that may be impacted by a better understanding of the geomorphic/pedogenic history of the region.

Kuehn examined eight stratigraphic sections at seven locations (five in the North Unit and two in the South Unit) within the Park. Kuehn numbered the profile sections #1-7, and the sections examined occupied four different geomorphic surfaces. Data collected at each section included the following: (1) identification and description of the lithostratigraphic units; (2) identification and description of buried soils; (3) preparation of profile maps for each section; (4) photographic documentation; (5) collection of soil and sediment samples as well as samples for radiometric dating.[181] The four major geomorphic surfaces investigated were labeled as follows: (1) Upper Prairie surface and Badlands Wall; (2) Pleistocene (?) Cheyenne River terraces; (3) early Pleistocene/late Tertiary (?) surface; and (4) the Lower Prairie surface, which is further subdivided into modern floodplains, Holocene terraces, and Holocene alluvial fans.

The Upper Prairie surface and Badlands Wall were examined in the North Unit in areas ranging in elevation from 800 to 820 m north of the road and along the Badlands Wall on the south side of the Wall. The stratigraphic sections studied within the Upper Prairie surface (sections #2, #5, and #6) are all associated with "sod tables," which are composed of reworked alluvial and colluvial sediments (and eolian materials) that have been deposited below, and away from, eroded bedrock remnants.[182] Pleistocene (?) Cheyenne River terraces were examined at the southern edge of Quinn Table at an elevation of 860-870 m. Section #1 is located at a steep cut (15+ m) southwest of the Sage Creek campground.[183] The oldest and highest surfaces in the Park were examined at sections #3 and #4 on the west edge of Sheep Mountain Table and the southeast corner of Cuny Table, respectively. These surfaces (roughly 950 m) are mantled by Quaternary-aged deposits of sand, silt, and several meters of loess.[184] The Lower Prairie surface, which refers to a myriad of surfaces and sedimentary deposits of various ages below the Badlands Wall, was examined at two sections (#7 and #7a) along the South Fork Sage of Creek, each of which includes terrace and alluvial fan environments.[185]

Studies by Kuehn (2003) of Sheep Mountain Table and Cuny Table, as well as large sod tables in the North Unit of the Park demonstrated that the upper 3-4 m of these landforms contain Holocene-aged eolian material (loess and fine-grained sand). These materials generally contain at least three to five buried soils, ranging in age from 12,000 BP (2.5 m below surface) to 1,450 BP (1.1 m below surface). Buried soils and radiometric dates were collected from all of the major geomorphic settings except the Pleistocene (?) Cheyenne River terraces.[186] At Sheep Mountain Table, Kuehn (2003) recorded five different buried soils within the top 2.7 m, and three soils in the top 1.1 m. Bone gelatin from a bison bone located between the second and third buried soils produced a date of

2,080 BP. These A horizon soils were poorly developed, suggesting the soils were developed during a short but relatively stable period of time and that soil development was arrested by longer intervals of unstable conditions that led to renewed eolian deposition. Kuehn demonstrated that the high upland surfaces such as Sheep Mountain Table and Cuny Table contain the "most complete sediment records (spanning the Pleistocene through the Holocene) of any major landform category in the White River Badlands."[187] Based on the results of his work, Kuehn concluded that,

> Badland settings are like no others when it comes to the dynamics, complexity, synchronicity, and overall impact of geomorphic processes on the archeological record. One of the benefits of utilizing a contextual approach to archeological research is the fact that data gathering is not limited to a single scientific discipline…It is this collaboration that will eventually fill in the remaining temporal and spatial gaps created by the badlands dynamic geologic history.[188]

<u>Alluvial Studies</u>

Alluvial studies of the Holocene period have tended to lag behind other studies in the Badlands. In 1974, Harksen identified and dated two Holocene terraces along Bear Creek in Pennington County.[189] Harksen noted that the age of the terraces was much younger than previously thought. One radiocarbon sample (Sample #2) from a buried soil located six feet below the terrace surface produced a date of 2,350 BP. A second sample (Sample #1), located in a depression nearly 16 feet below the terrace surface (and only 7 feet above the Pierre Shale), produced a date of 780 BP. Harksen suggested that after the deposition of charcoal in Sample #2 (which occurred on a well-developed A horizon soil), a period of stream incision occurred between 2,380 and 780 BP. The stream was entrenched about 10 feet before the initiation of stream aggradation. Harksen believes the charcoal sample was deposited shortly after the initiation of aggradation. Terrace infilling continued until the sample was buried beneath 13 feet of alluvial fill. This period of aggradation was followed by a period of equilibrium that allowed an upper, undated paleosol to develop two feet below the terrace surface.[190]

Jean Kowal, one of Fredlund's students, wrote a MS thesis on the "Recent Geomorphic Evolution of Sage Creek in Badlands National Park" in 1997.[191] The sequence of events reported by Kowal are similar in nature and timing to the events reported by Harksen along Bear Creek. The events reported by Kowal for Sage Creek are as follows:

- The Sage Creek valley eroded to the level of the Pierre Shale.
- Cycles of deposition and erosion occurred resulting in a series of fill deposits.
- Fluvial deposition filled the valley to a height of about 7 m (22 ft) above the current stream bed and created a fill unit topped by a floodplain. Radiocarbon dates of 2,230 and 800 BP indicate fluvial deposition occurred between about 2,400 and 800 BP.
- After 800 BP an erosional event was initiated that downcut into the earlier fill deposits. The stream incision caused the creek to abandon the floodplain and created a terrace tread and scarp that became the T2 terrace. The incising stream

continued to meander across the valley and eventually formed a new floodplain about 3.5 m below the T2 terrace.

- More vigorous down cutting and erosion began between 100 and 50 BP that resulted in abandonment of the floodplain and the creation of the T1 terrace. The current stream bed is about 2.5 m below the T1 terrace tread.[192]

Other researches have argued that a change from a period of terrace building to one of terrace erosion constitutes an "alluvial discontinuity." The discontinuities have been linked to changes in climate. A number of synchronous discontinuities have been identified at or about 800, 2,000, 3,050, 4,200, and 6,000 years BP. The work by Kowal confirmed the discontinuities at 800 and 2,000 BP. Kowal presented two conclusions as a result of her work at Sage Creek. "First, the landforms at Sage Creek represent a record of changes in fluvial processes and the timing of those changes. Second, climate change is the most plausible driving force behind the shifting processes that developed the landscape at Sage Creek."[193] Her work formed a baseline for similar studies in the area.

Although NPS-funded research over the last 25-30 years has provided new answers to old questions, many questions remain unanswered and new questions are constantly emerging. The geological and paleontological resources of the White River Badlands provide a unique opportunity to research questions regarding the regression of the Western Interior Seaway; the K-T boundary; volcanic tuffs, magnetostratigraphy, and tectonic activity, Cenozoic paleosols, mammalian evolution, and many other interesting questions. Continued stewardship and preservation of the unique geologic and paleontological resources contained within the Park is imperative to ensure that these resources are available for future generations to observe, enjoy, and study.

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[1] Hiram Prout, "Gigantic Paleotherium," *American Journal of Sciences,* Series 2 (1846): 288-289; "A Description of a Fossil Maxillary Bone of Paleotherium from near White River," *American Journal of Sciences,* Series 3 (1847): 248-250.

[2] Joseph Leidy, "Description of the Remains of Extinct Mammalia and Chelonia from Nebraska Territory," *Report of a Geological Survey of Wisconsin, Iowa, Minnesota, and Incidentally a Portion of Nebraska Territory,* ed. David Dale Owen, United States Geologist, Philadelphia, 1852, 533-572; David Dale Owen, "Incidental Observations on the Missouri River and on the Mauvaises Terres (Badlands)," *Report of a Geological Survey of Wisconsin, Iowa, Minnesota, and Incidentally a Portion of Nebraska Territory,* ed. David Dale Owen, United States Geologist, Philadelphia, 1852, 194-206.

[3] Thaddeus Culbertson, "A Journal of an Expedition to the Mauvaises Terres and the Upper Missouri in 1850," *Smithsonian Institution, Fifth Annual Report,* 1851, 84-145.

[4] F.V. Hayden, "Explorations in the Dacota Country in the Year 1855, by Lieutenant G.K. Warren, Topographical Engineer of the 'Sioux Expedition,' 35th Congress, 1st Session," 1856, 1-62; "Notes on the Geology of the Mauvaises Terres of White River, Nebraska," *Proceedings of the Academy of Natural Sciences of Philadelphia*, 1858a, vol. 9, 151-158; "Explorations under the War Department, Explanations of a Second Edition of a Geographical Map of Nebraska and Kansas, based upon Information Obtained in an Expedition to the Black Hills, under the Command of Lt. G.K. Warren, Topographical Engineer, United States Army," *Proceedings of the Academy of Natural Sciences of Philadelphia,* 1858b, vol. 10, 139-158; "Exploration of the 'Badlands' or the 'Mauvaises Terres' of the Upper Missouri Region," *American Journal of Science* 42 (1866).

[5] F.V. Hayden, "Explorations in the Dacota Country in the Year 1855, by Lieutenant G.K. Warren, Topographical Engineer of the 'Sioux Expedition,' 35th Congress, 1st Session," 1856, 1-62.

[6] J.R. Macdonald, "The Exploration and the Evolution of the Geologic Nomenclature of the White River Badlands of South Dakota," n.d., Unpublished Manuscript, Rapid City, SD, 13.
[7] Joseph Leidy, "The Extinct Mammalian Fauna of Dakota and Nebraska, Including an Account of Some Allied Forms form other Localities together with a Synopsis of Mammalian Remains from North America," *Journal of the Academy of Natural Sciences of Philadelphia* 7 (1869), 23-472; Reprinted Arno Press, New York, NY, 1974; J.R. Macdonald, "The History and Exploration of the Big Badlands of South Dakota," Unpublished Manuscript, n.d., Rapid City, SD, South Dakota School of Mines and Technology.
[8] F.V. Hayden, "On the Geology of the Tertiary Formations of Dakota and Nebraska," *Journal of the Academy of Natural Sciences of Philadelphia*, vol. 7, 1869, 9-21.
[9] Leidy, "The Extinct Mammalian Fauna of Dakota and Nebraska," 1869, reprinted Arno Press, 1974, 13.
[10] Ibid., 19.
[11]Url Lanham, *The Bone Hunters*, New York, NY, Dover Publications, Inc., 1991 edition, 1149-152.
[12] Ibid., 150-152.
[13] C.C. O'Harra, *The White River Badlands*, Rapid City, SD, South Dakota School of Mines, Bulletin no. 13, 1920, 25.
[14] Ibid., 26.
[15] Macdonald, "The Exploration and the Evolution of the Geologic Nomenclature," n.d., 22.
[16] Ibid., 27.
[17] C.C. O'Harra, *The White River Badlands*, 1920, Plate 90.
[18] Ibid., 27-28.
[19] Donald E. Trimble, "The Geologic Story of the Great Plains," *Geological Survey Bulletin* 1493 (1980), 4th reprinting 2001, Theodore Roosevelt Nature and History Association, Medora, NE.
[20] Macdonald, "The Exploration and the Evolution of the Geologic Nomenclature," n.d., 20
[21] C.C. O'Harra, *The White River Badlands*, 1920, 33-35.
[22] J.B. Hatcher, "The Titanotherium Beds," *American Naturalist*, 1893, vol. 27, 204-221; J.L. Wortman, "On the Divisions of the White River or Lower Miocene of Dakota," *American Museum of Natural History* 5 (1893), 95-105; H.F. Osborn and J.L. Wortman, "Fossil Mammals of the Lower Miocene White River Beds," *American Museum of Natural History* 6 (1894), 199-228; W.B. Scott, "The Later Tertiary Lacustrine Formations of the West," *Bulletin of the Geological Society of America* 5 (1894), 594-596.
[23] C.C. O'Harra, *The White River Badlands*,1920, 40-42.
[24] C.C. O'Harra, *The White River Badlands*, 1920, 128.
[25] W.D. Matthew, "Is the White River Tertiary an Aeolian Formation?" *American Naturalist* 33 (1899), 403-408.
[26] N.H. Darton, " Preliminary Report on the Geology and Water Resources of Nebraska West of the One Hundred and Third Meridian," *USGS, 19st Annual Report*, part IV, 719-814; "Preliminary Description of the Geology and Water Resources of the Southern Half of the Black Hills and Adjoining Regions of South Dakota and Wyoming." *USGS, 21st Annual Report*, part IV, 1901, 489-599.
[27] Macdonald, "The Exploration and the Evolution of the Geologic Nomenclature," n.d., 24-25.
[28] C.C. O'Harra, "The Badlands Formations of the Black Hills Region," Rapid City, SD, *South Dakota School of Mines*, Bulletin 9, 1910; and O'Harra, *The White River Badlands*, 1920, 49-50.
[29] H.R. Wanless, "The Stratigraphy of the White River Beds of South Dakota," *American Philosophical Society* 62 (1923), 190-269.
[30] Donald R. Prothero, "The Chronological, Climatic, and Paleogeographic Background to North American Mammalian Evolution," In *Evolution of Tertiary Mammals of North America, vol 1: Terrestrial Carnivores, Ungulates, and Ungulate-like Mammals*, ed. Christine M. Janis, Kathleen Scott, and Louis J. Jacobs (New York, Cambridge University Press, 1998), 9-36.
[31] Horace E. Wood, "Oligocene Faunas, Facies, and Formations." Geological Society of America, Memoir no. 39, 1949, 83-92.
[32] John Clark, "The Stratigraphy and Paleontology of the Chadron Formation in the Big Badlands of South Dakota," *Annals of the Carnegie Museum*, 1937, vol. XXV, 261-350.
[33] John Clark, "Geographic Designation of the Members of the Chadron Formation in South Dakota," *Annals of the Carnegie Museum* vol. XXXIII (1954), 197-198.

[34] C.B. Schultz and T.M. Stout, "Preliminary Remarks on the Oligocene of Nebraska," *Bulletin of the Geological Society of America* 49 (1938), 1,921.
[35] James D. Bump, "The White River Badlands of South Dakota," in *Guidebook, Fifth Field Conference of the Society of Vertebrate Paleontology in Western South Dakota*, Rapid City, SD, Museum of Geology, South Dakota School of Mines and Technology, 1951, 34-46.
[36] James D. Bump, "Geographic Names for the Members of the Brule Formation of the Big Badlands of South Dakota," *American Journal of Science*, 1956, 254:429-432.
[37] C.C. O'Harra, "A Bibliography: Contributions to the Geology and Geography of the Black Hills Region," (Rapid City, SD, South Dakota School of Mines, Bulletin No. 5, 1902), 44-86.
[38] H.E. Wood II, R.W. Chaney, Jr., J. Clark, E.H. Colbert, G.L. Jepsen, J.B. Reeside, and C. Stock, "Nomenclature and Correlation of the North American Continental Tertiary," *Geological Society of America Bulletin*, 1941, no. 52, 1-48.
[39] Donald R. Prothero and Robert J. Emry, "The Chadronian, Orellan, and Whitneyan North American Land Mammal Ages," in *Biostratigraphy and Geochronology*, ed. Michael O. Woodburne, (New York, NY, Columbia Press, 2004), 160.
[40] John Clark, James R. Beerbower, and Kenneth Kietzke, *Oligocene Sedimentation, Stratigraphy, Paleoecology, and Paleoclimatology in the Big Badlands of South Dakota*, (Chicago, IL, Fieldiana: Geology Memoirs, vol. 5, Field Museum of Natural History, 1967), 62-120.
[41] James D. Bump, "The White River Badlands of South Dakota," 1951, 34-46; John Clark, "The Stratigraphy and Paleontology of the Chadron Formation in the Big Badlands," 1954, vol. XXXIII, 197-198.
[42] James D. Bump, "Geographic Names for the Members of the Brule Formation of the Big Badlands," 1956, 254: 429-432.
[43] J.C. Harksen, J.R. Macdonald, and W.D. Sevon, "New Miocene Formation in South Dakota," *South Dakota Geological Survey, Miscellaneous Investigations* 3 (1961).
[44] Ibid.
[45] Ibid.
[46] J.C. Harksen and J.R. Macdonald, "Guidebook to the Major Cenozoic Deposits of Southwestern South Dakota" *South Dakota Geological Survey, Guidebook* 2, 1969, 5.
[47] Ibid.
[48] Ibid.
[49] Ibid., 6.
[50] Ibid., 8.
[51] Ibid., 9.
[52] Ibid.
[53] J.C. Harksen and J.R. Macdonald, "Type Sections for the Chadron and Brule Formations in the Big Badlands, South Dakota," *Report of Investigations,* no. 99, 1969.
[54] Ibid., 9.
[55] Ibid.
[56] J.C. Harksen, "The Cenozoic History of Southwestern South Dakota," in *Guidebook to the Major Cenozoic Deposits of Southwestern South Dakota*, ed. J.C. Harksen and J.R. Macdonald, South Dakota Geological Survey, Guidebook 2, 1969, 11-29.
[57] Ibid., 18.
[58] Ibid., 19.
[59] Ibid., 19-20.
[60] Ibid.
[61] Ibid., 14.
[62] Ibid.
[63]J.C. Harksen, "The Pliocene-Pleistocene Medicine Root Gravel of Southwestern South Dakota," *Bulletin of Southern California Academy Sciences*, 1966, vol. 65, no. 4, 251-257.
[64]J.C. Harksen, "The Cenozoic History of Southwestern South Dakota," 1969, 24.
[65] Ibid.

[66] J.C. Harksen, "Miocene Channels in the Cedar Pass Area Jackson County, South Dakota," *South Dakota Geological Society, Report of Investigations,* no. 111, 1974.
[67] Ibid., 1.
[68] Dennis O. Terry, "Stratigraphy, Depositional Environments and Fossil Resources of the Chadron Formation in the South Unit of Badlands National Park, South Dakota," in *Partners Preserving our Past, Planning our Future: Proceedings for the Fifth Conference on Fossil Resources,* ed. James E. Martin, John W. Hoganson, and Rachel Benton, Dakoterra, 1998, vol. 5, 127-138.
[69] Ibid., 127.
[70] Ibid., 128.
[71] D.O. Terry and J.E. Evans, "Pedogenesis and Paleoclimatic Implications of the Chamberlain Pass Formation, Basal White River Group, Badlands of South Dakota," Paleogeography, Paleoclimatology, Paleoecology 110 (1994), 197-215.
[72] J.E. Evans and D.O. Terry, "The Significance of Incision and Fluvial Sedimentation in the Basal White River Group (Eocene-Oligocene), Badlands of South Dakota," *Sedimentary Geology* 90 (1994), 137-152.
[73] D.O. Terry, "Stratigraphy, Depositional Environments, and Fossil Resources of the Chadron Formation in the South Unit of Badlands National Park," 1998, 128.
[74] Ibid., 130.
[75] Ibid., 133.
[76] Ibid., 134.
[77] Ibid., 136.
[78] D.O. Terry, Jr., "Lithostratigraphic Revision and Correlation of the Lower Part of White River Group: South Dakota to Nebraska," in *Depositional Environments, Lithostratigraphy, and Biostratigraphy of the White River and Arikaree Groups (Late Eocene to Early Miocene, North America),* ed. D.O. Terry, Jr., H.E. LaGarry, and R.M. Hunt, Jr., Geological Society of America, Special Paper, 325 (1998), 15-37.
[79] Philip W. Stoffer, Paula Messina, John A. Chamberlain, Jr., and Dennis O. Terry, Jr., "The Cretaceous-Tertiary Boundary in Badlands National Park, South Dakota," *United States Geological Survey, Open File Report 01-56*, Draft 2001.
[80] Philip W. Stoffer, "Geology of Badlands National Park: A Preliminary Report," *United States Geological Survey, Open File Report 03-35,* Draft 2003.
[81] D.O. Terry, Jr., J.A. Chamberlain, Jr., P.W. Stoffer, P. Messina, and P.A. Jannett. "Marine Cretaceous–Tertiary Boundary Section in Southwestern South Dakota," *Geological Society of America* 29, no. 11 (2001), 1055-1058.
[82] Philip W. Stoffer, Paula Messina, John A. Chamberlain, Jr., and Dennis O. Terry, Jr., "The Cretaceous-Tertiary Boundary in Badlands National Park, South Dakota, 2001, 5-6; and D.O. Terry Jr., J.A. Chamberlain Jr., P.W. Stoffer, P. Messina, and P.A. Jannett. " Marine Cretaceous–Tertiary Boundary Section in Southwestern South Dakota." *Geological Society of America* 29, no. 11 (2001), 1055-1058.
[83] Ibid., 6-7.
[84] Ibid., 20.
[85] Ibid., 7.
[86] Ibid.
[87] Ibid., 34.
[88] Ibid., 39-49.
[89] Ibid., 43.
[90] S. Palamarczuk, J.A. Chamberlain, Jr., D.O. Terry, Jr., "Dinoflagellates of the Fox Hills Formation (Maastrichtan), Badlands Area of South Dakota: Biostratigraphic and Paleoenvironmental Implications," Programs with Abstracts, Joint Meeting of the American Association of Stratigraphic Palynology, Ste. Catherines, Canada; October, 2003. J.A. Chamberlain, Jr., S. Palamarczuk, D.O. Terry, Jr., P.W. Stoffer, M.A. Becker, M.P. Garb, and P. Jannett, " Biostratigraphy and Age of the Lower Fairpoint Member of the Fox Hills Formation (Maastrichtian), Badlands Area of South Dakota," *Geological Society of America, Abstracts,* Annual Meeting of the GSA, 2005, p. 37.
[91] J.A. Chamberlain, Jr., S. Palamarczuk, D.O. Terry, Jr., P.W. Stoffer, M.A. Becker, M.P. Garb, and P. Jannett, " Biostratigraphy and Age of the Lower Fairpoint Member of the Fox Hills Formation

(Maastrichtian), Badlands Area of South Dakota," *Geological Society of America, Abstracts,* Annual Meeting of the GSA, 2005, p. 37.
[92] Ibid.
[93] S. Palamarczuk, J.A. Chamberlain, Jr., D.O. Terry, Jr., "Dinoflagellates of the Fox Hills Formation (Maastrichtan), Badlands Area of South Dakota: Biostratigraphic and Paleoenvironmental Implications," Programs with Abstracts, Joint Meeting of the American Association of Stratigraphic Palynology, Ste. Catherines, Canada; October, 2003.
[94] J.A. Chamberlain, Jr., S. Palamarczuk, D.O. Terry, Jr., P.W. Stoffer, M.A. Becker, M.P. Garb, and P. Jannett, " Biostratigraphy and Age of the Lower Fairpoint Member of the Fox Hills Formation (Maastrichtian), Badlands Area of South Dakota," *Geological Society of America, Abstracts,* Annual Meeting of the GSA, 2005, p. 37.
[95] Linda C. Welzenbach, "Limestones in the Lower White River Group (Eocene-Oligocene), Badlands of South Dakota: Depositional Environments and Paleoclimatic Implications," MS Thesis, Department of Geology, Bowling Green University, Bowling Green, OH, 1992.
[96] Ibid., 104.
[97] Ibid., 104.
[98] Ibid., 106.
[99] Ibid.
[100] James E. Evans and Linda C. Welzenbach, "Episodes of Carbonate Deposition in a Siliciclastic Dominated Fluvial Sequence, Eocene-Oligocene White River Group, South Dakota and Nebraska," in *Depositional Environments, Lithostratigraphy, and Biostratigraphy of the White River and Arikaree Groups (Late Eocene to Early Miocene, North America,* ed. D.O. Terry, Jr., H.E. LaGarry, and R.M. Hunt, Jr., (Denver, CO, Geological Society of America, Special Paper 325, 1998), 93-115.
[101] Ibid., 93.
[102] Ibid.
[103] Donald R. Prothero and Robert J. Emry, "The Chadronian, Orellan, and Whitneyan North American Land Mammal Ages," 2004, 156-168.
[104] Ibid., 162.
[105] Ibid.
[106] Ibid., 164.
[107] Ibid., 166.
[108] Ibid.
[109] Ibid., 167.
[110] DiBenedetto, Joseph N., "Sedimentary and Taphonomy of the Brian Maebius Site, Sage Creek Wilderness Area, Badlands National Park, Interior, South Dakota," South Dakota School of Mines and Technology, Rapid City, SD, Department of Geology, Master's Thesis, 2000.
[111] Ibid.
[112] Ibid.
[113] Ibid.
[114] Gary Johnson, "Small Mammals of the Middle Oligocene of the Big Badlands of South Dakota," *Proceedings of the South Dakota Academy of Sciences* 45 (1966), 78-83.
[115] Ibid.; Gary Johnson, "Small Mammals of the Middle Oligocene of the Big Badlands of South Dakota," South Dakota School of Mines and Technology, Rapid City, SD, Department of Geology, Master's Thesis, 1966.
[116] Ibid.
[117] Laurie Macdonald, "Monroe Creek (Early Miocene) Microfossils from the Wounded Knee Area, South Dakota," *South Dakota Geological Survey, Report of Investigations* 105 (1972).
[118] Ibid., 3-4.
[119] Ibid.
[120] Donald R. Prothero, "Correlation of the White River Group by Magnetostratigraphy," in *Fossiliferous Cenozoic Deposits of Western South Dakota and Northwestern Nebraska: A Guidebook for the 45th Annual Meeting of the Society of Vertebrate Paleontology,* ed. James E. Martin, (Rapid City, SD, South Dakota School of Mines and Technology, Dakoterra vol. 2, part 2, 1985), 265-276

[121] Ibid., 265-266.
[122] Ibid., 266.
[123] Ibid., 273-274
[124] Ibid.
[125] Donald R. Prothero and Carl C. Swisher, III, "Magnetostratigraphy and Geochronology of the Terrestrial Eocene-Oligocene Transition in North America," in *Eocene-Oligocene Climatic and Biotic Evolution,* ed. Donald R. Prothero and W.A. Berggren (Princeton, NJ, Princeton University Press, 1992), 46-68.
[126] Ibid., 64.
[127] Edwin E. Larson and Emmett Evanoff, "Tephrostratigraphy and Source of the Tuffs of the White River Sequence," in *Depositional Environments, Lithostratigraphy, and Biostratigraphy of the White River and Arikaree Groups (Late Eocene to Early Miocene, North America),* ed. Dennis O. Terry, Hannan E. LaGarry, and Robert M. Hunt, Jr. (Geological Society of America, Special Paper *325*, 1998), 1-14.
[128] Ibid., 1.
[129] Ibid., 11.
[130] A.C. Ashworth, R.C. Benton, R.F. Biek, E.C. Murphy, G.W. Shurr, K.K. Stevens, and D.O. Terry, Jr., "A Field Guide to Tertiary Tectonism in the Northern Great Plains: Road Log, Field Trip 1 (includes Field Trip 2)," in "Guidebook to the Geology of the Black Hills, South Dakota," ed. Colin J. Paterson and James G. Kirchner, (Rapid City, SD, *South Dakota School of Mines and Technology, Bulletin* no. 19, 1996), 9-19.
[131] Philip W. Stoffer, "Geology of Badlands National Park: A Preliminary Report," USGS, Open File Report, 2003, 47.
[132] Ibid.
[133] D.O. Terry and J.E. Evans, "Pedogenesis and Paleoclimatic Implications of the Chamberlain Pass Formation, 1994, 197-215.
[134] Ibid.
[135] Ibid.
[136] Philip W. Stoffer, Paula Messina, and John A. Chamberlain, Jr., "Upper Cretaceous Stratigraphy of Badlands National Park, South Dakota: Influence of Tectonism and Sea Level Change on Sedimentation in the Western Interior Seaway," in *Partners Preserving Our Past, Planning Our Future, Proceedings of the Fifth Conference on Fossil Resources*, ed. James E. Martin, John Hoganson, and Rachel C. Benton (*Dakoterra* vol. 5, South Dakota School of Mines and Technology, Museum of Geology, 1998), 55-62.
[137] Ibid., 55.
[138] John Clark, "Oligocene Drainages in the Big Badlands of South Dakota," Unpublished manuscript, (Rapid City, SD, South Dakota School of Mines and Technology, Museum of Geology), 1962, 13-14.
[139] Ibid., 3.
[140] Ibid., 6.
[141] Ibid., 7.
[142] Ibid.
[143] Ibid., 8.
[144] Ibid., 10.
[145] Ibid., 11.
[146] Ibid., 12.
[147] Ibid.
[148] John Clark, James R. Beerbower, and Kenneth Kietzke, *Oligocene Sedimentation, Stratigraphy, Paleoecology, and Paleoclimatology in the Big Badlands of South Dakota,* (Chicago, IL, Fieldiana: Geology Memoirs, vol. 5, Field Museum of Natural History, 1967).
[149] Ibid., 141-143.
[150] James E. Martin, "Paleoenvironment of the Lange/Ferguson Clovis Kill Site in the Badlands of South Dakota," in *Late Quaternary Mammalian Biogeography and Environments of the Great Plains and Prairies,* 1987, 314-333.
[151] Ibid., 328.
[152] Greg J. Retallack, "Late Eocene and Oligocene Paleosols from Badlands National Park, South Dakota," *Geological Society of America, Special Paper,* 193, 1983.

[153] Ibid., 1.
[154] Ibid.
[155] Ibid.
[156] Greg J. Retallack, "An Excursion Guide to Fossil Soils of the Mid-Tertiary Sequence in Badlands National Park, South Dakota," in *Fossiliferous Cenozoic Deposits of Western South Dakota and Northwestern Nebraska,* ed. James E. Martin, (Rapid City, SD, South Dakota School of Mines and Technology, Dakoterra, 1985, vol 2, part 2), 277-302.
[157] Ibid., 277.
[158] Ibid., 298.
[159] Ibid., 299-300.
[160] Dennis O. Terry, Jr., "Stratigraphic and Paleopedogenic Analysis of Depositional Sequences within the Pig Wallow Site, Badlands National Park, (Final Report)," Badlands National Park, NRPP Grant (BADL 1300-5711-NNZ), 1996.
[161] Ibid., 66.
[162] Ibid., 97-98.
[163] Kimberlee Kae Stevens, "Taphonomy of an Early Oligocene (Orellan) Vertebrate Assemblage in the Scenic Member, Brule Formation, White River Group, Badlands National Park," South Dakota School of Mines and Technology, Master's Thesis, 1996.
[164] Ibid.
[165] Sarah A. Black, "Site Analysis of the Buffalo Alley Bone Bed Located in the Lower Scenic Member of the Brule Formation, White River Group, Badlands National Park, South Dakota," South Dakota School of Mines and Technology, Rapid City, SD, Department of Geology, Master's Thesis, 2002.
[166] Ibid.
[167] Ibid., 55.
[168] Ibid., 56.
[169] Ibid.
[170] J.C. Harksen, "Quaternary Loess in Southwestern South Dakota," *Proceedings of the South Dakota Academy of Sciences* 46 (1967), 32-40; J.C. Harksen, "Red Dog Loess Named in Southwestern South Dakota," *South Dakota Geological Survey, Report of Investigations* 98 (1968), 1-17.
[171] J.C. Harksen, "Quaternary Loess in Southwestern South Dakota," *Proceedings of the South Dakota Academy of Sciences* 46 (1967), 32-40.
[172] Ibid.
[173] Ibid.
[174] Ibid.
[175] Ibid.
[176] J. Elmo Rawling, Glen G. Fredlund, and Shannon Mahan, "Aeolian Cliff-Top Deposits and Buried Soils in the White River Badlands, South Dakota, USA," *The Holocene* 13 (2003), 121-129.
[177] Ibid., 126-127.
[178] Glen G. Fredlund and J. Elmo Rawling, "Episodic Mid-Late Holocene Eolian Activity Evidenced by Buried Soils in Cliff-dunes at Sheep Mountain Table, Badlands National Park, South Dakota," Poster Paper presented at the Geological Society of America, Annual Meeting, Denver, CO, 31, no. 7 (1999).
[179] Ibid.
[180] David D. Kuehn, "Preliminary Geoarcheological Reconnaissance in Badlands National Park," Technical Report #88, National Park Service, Midwest Archeological Center, Lincoln, NE, 2003.
[181] Ibid., 11.
[182] Ibid., 13.
[183] Ibid., 19.
[184] Ibid., 20.
[185] Ibid., 24
[186] Ibid., 21.
[187] Ibid., 22
[188] Ibid., 32.

[189] J.C. Harksen, "Radiocarbon Dating of Terraces along Bear Creek, Pennington County, South Dakota," *South Dakota Geological Survey, Report of Investigations #108*, 1974.
[190] Ibid.
[191] Jean Kowal, "Recent Geomorphic Evolution of Sage Creek in Badlands National Park," MA Thesis, Department of Geography, University of Wisconsin-Milwaukee, 1997.
[192] Ibid., 58-60.
[193] Ibid., 70.