National Park Service
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Natural Resource Stewardship and Science

Paleontological Resource Inventory and Monitoring

Southern Plains Network

Natural Resource Report NPS/SOPN/NRR—2015/971



ON THE COVER
An ammonite in situ in the Middle–Upper Pennsylvanian Alamitos Formation at the Cañon de los Trigos within the main unit of Pecos National Historical Park (PECO). The extensive fossil record of PECO, consisting of both naturally occurring fossils and hundreds of fossils from cultural contexts, was not recognized before work began on this updated summary.
Photograph: Mario Armijo, PECO

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NOTE:

This report provides baseline paleontological resource data to National Park Service administration and resource management staff. The report contains information regarding the location of non-renewable paleontological resources within NPS units.

It is *not* intended for distribution to the public.

May 2015

U.S. Department of the Interior
National Park Service
Natural Resource Stewardship and Science
Fort Collins, Colorado

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Executive Summary

Paleontological resources (fossils) are any remains of past life preserved in a geologic context. Paleontological resources are non-renewable resources found in at least 259 National Park System units. Despite the abundance and diversity of these resources throughout the National Park Service (NPS), until recently, few parks have had adequate baseline paleontological resource data.

The NPS National Inventory and Monitoring (I&M) Program and the NPS Geologic Resources Division have developed various strategies to provide parks with the baseline paleontological resource data necessary for greater understanding and appropriate management of these resources. This report presents an updated paleontological resource summary for the parks of the Southern Plains Network (SOPN). The summary was compiled through extensive literature reviews, review of park records and archives, inventories of museum collections and records, and interviews with park staff and professional geologists and paleontologists. Preliminary paleontological resource management recommendations are also included for each park.

The fossil record of the parks of the SOPN is relatively sparse. This may be due to a combination of factors, including: many of the park units encompass relatively small areas; most of the units have been established to protect cultural resources rather than natural resources; and many of the sites are located within or near active floodplains, resulting in bedrock being covered by fluvial deposits. Unlike some other networks, the fossil record of the SOPN does not heavily represent one period of time or depositional setting. Instead, Alibates Flint Quarries National Monument (ALFL; Texas) and adjoining Lake Meredith National Recreation Area (LAMR; collectively AFLM) are best known for Neogene terrestrial vertebrate fossils (see the Appendix for a geologic time scale); Bent's Old Fort National Historic Site (BEOL; Colorado) has yielded Cretaceous bivalves and Pleistocene mammoth remains; Chickasaw National Recreation Area (CHIC; Oklahoma) has a long record of Paleozoic marine invertebrates; Fort Larned National Historic Sites (FOLS; Kansas) has several examples of invertebrate and plant fossils in Cretaceous building stone; Pecos National Historical Park (PECO; New Mexico) has Paleozoic invertebrates and some of the few Permian terrestrial vertebrates in the NPS, as well as hundreds of fossils found in archeological sites; and the non-network Santa Fe National Historic Trail (SAFE) passes over or near a diversity of Paleozoic and Mesozoic fossil sites. Five SOPN units are not currently known to have yielded fossils: Capulin Volcano National Monument (CAVO; New Mexico); Fort Union National Historic Site (FOUN; New Mexico); Lyndon B. Johnson National Historical Park (LYJO; Texas); Sand Creek Massacre National Historic Site (SAND); and Washita Battlefield National Historic Site (WABA; Oklahoma). Four of the five (FOUN, LYJO, SAND, and WABA) are located over or near fossiliferous rocks, though. In addition, the non-network unit Nicodemus National Historic Site (NICO; Kansas) includes several buildings constructed of potentially fossiliferous stone. A topic of potential interest is additional pollen studies: pollen studies have been conducted at several of the SOPN units, generally to document the environmental and climatological conditions that prevailed at the time of a significant event in the past two centuries. These studies show that deeper sampling to capture information over a longer span of the Holocene is a viable possibility for these sites. Such work would provide a longer record of conditions that affect the future of the parks.

As noted above, the fossil record of the SOPN is long but spotty. It spans the Ordovician to the Quaternary, and incorporates everything from deep continental seas to arid coastal plains. The most outstanding fossil record of any SOPN unit is found at CHIC, where folding, faulting, and tilting have brought marine rocks spanning most of the Paleozoic to the surface. Next is AFLM; most of its fossils come from the Miocene–Pliocene Ogallala Formation or Quaternary sediments, but Permian and Triassic rocks have also yielded fossils. The fossil records of the other units are generally isolated occurrences or from cultural contexts. PECO features both, including a Permian vertebrate site and collections of local marine invertebrate fossils made by people who lived at Pecos Pueblo and associated sites. If non-network units that are geographically within the SOPN are considered, SAFE has the most diverse fossil record in the area, although this comes with the additional caveat that the exact locations of fossil discoveries along the trail are not certain. Therefore, it is perhaps more accurate to describe the fossils as historically associated with the Santa Fe Trail rather than on the national historical trail itself. The route(s) of the trail itself also shifted over time. The majority of the fossils from on or near the trail are Pennsylvanian and Permian marine invertebrates and Cretaceous plants. SAFE's fossil record is of particular interest because of the historical association with many well-known geologists of the middle 19th century, and its use in the geologic expeditions to the Southwest. It has the oldest report of fossils from a NPS unit geographically within the SOPN (at least 1856). Additionally, SAFE is one of only two NPS units within the SOPN known to be associated with type specimens; as many as 56 species of fossil organisms were named from specimens found on or near the trail. Together, the fossils of the SOPN provide a diverse series of geologic "snapshots" illustrating the organisms that have inhabited the region for nearly 500 million years.

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Dedication

We dedicate the Southern Plains (SOPN) Inventory and Monitoring Network Paleontological Resource Inventory and Monitoring report to Patrick Malone, Assistant Regional Director, Natural Resources, Intermountain Region of the National Park Service. Patrick has been a strong advocate and supporter for paleontological resource management, protection and research in the parks of the Intermountain Region.



Introduction

Paleontological resources, or fossils, are any remains of past life preserved in geologic context. There are two main types of fossils: body fossils and trace fossils. Body fossils are the physical remains of an actual organism (shells, bones, teeth, plant leaves, etc.), while trace fossils (burrows, coprolites, footprints, trackways, etc.) preserve evidence of an organism's activity or behavior. Fossils are non-renewable natural resources that possess scientific, educational, and interpretive value. In the National Park Service (NPS) there are three contextual categories of fossils: in situ (fossils found in sediment or rock layers), in museum collections, or in association with cultural resources (archeological resources, historic structures or building stone, historic documents, and ethnographic legends or stories). This report addresses fossils occurring in all of these contexts.

The establishment of baseline paleontological resource data is essential for the appropriate management of fossils found within National Park System units. Although at least 259 units have been identified with paleontological resources, only a few parks have adequate baseline paleontological resource data.

In conjunction with the NPS Geologic Resources Division (GRD) and the NPS Inventory and Monitoring (I&M) Program, paleontological resource inventories have been initiated in dozens of parks and are further described in the Methodology and Inventory Strategies section of this report. This report presents paleontological resource inventory and monitoring data compiled for the parks of the Southern Plains I&M Network (SOPN).

The Southern Plains Network includes eleven NPS areas in a roughly diamond-shaped geographic area including western Kansas, eastern Colorado, northwestern New Mexico, north-central Texas, and most of Oklahoma. These parks, as shown in Figure 1, include: Alibates Flint Quarries National Monument (ALFL), Bent's Old Fort National Historic Site (BEOL), Capulin Volcano National Monument (CAVO), Chickasaw National Recreation Area (CHIC), Fort Larned National Historic Site (FOLS), Fort Union National Historic Site (FOUN), Lake Meredith National Recreation Area (LAMR), Lyndon B. Johnson National Historical Park (LYJO), Pecos National Historical Park (PECO), Sand Creek Massacre National Historic Site (SAND), and Washita Battlefield National Historic Site (WABA). The majority of the units encompass between 280 ha (700 acres) and 650 ha (1,600 acres), with the smallest being WABA at 127.56 ha (315.20 acres), and the largest being LAMR at 18,201.80 ha (44,977.63 acres). Most of the units commemorate events or locations from the frontier period of American history (BEOL, FOLS, FOUN, PECO, SAND, and WABA). There are also two reservoir-centered recreation areas (CHIC and LAMR), an ancient archeological site (ALFL), and an extinct volcano (CAVO). A handful of non-I&M units are also geographically situated within the SOPN, including several historic trails that pass through some part of the network. Although it is beyond the scope of this document to provide a detailed discussion of the trails, one of them, Santa Fe National Historic Trail (SAFE), is briefly discussed because of the historic significance of fossils collected or reported from sites on or near the original trail. Another non-I&M unit, Nicodemus National Historic Site (NICO), has good potential for preserving fossils in building stone, although further evaluation is needed.

The majority of the fossils known from the SOPN parks come from CHIC and LAMR. Folding, faulting, and tilting of a diverse Paleozoic marine sequence has exposed a variety of rocks and fossils at the surface in CHIC. LAMR's fossil record is strongest in the relatively recent past of the Neogene, represented by a variety of terrestrial fossils from sites scattered around the recreation area. PECO also has a rare combination of Permian vertebrates and an abundance of other fossils from archeological contexts. The earliest scientific reports of fossils from the network were made by geologists who traveled on the Santa Fe Trail during the 1850s.

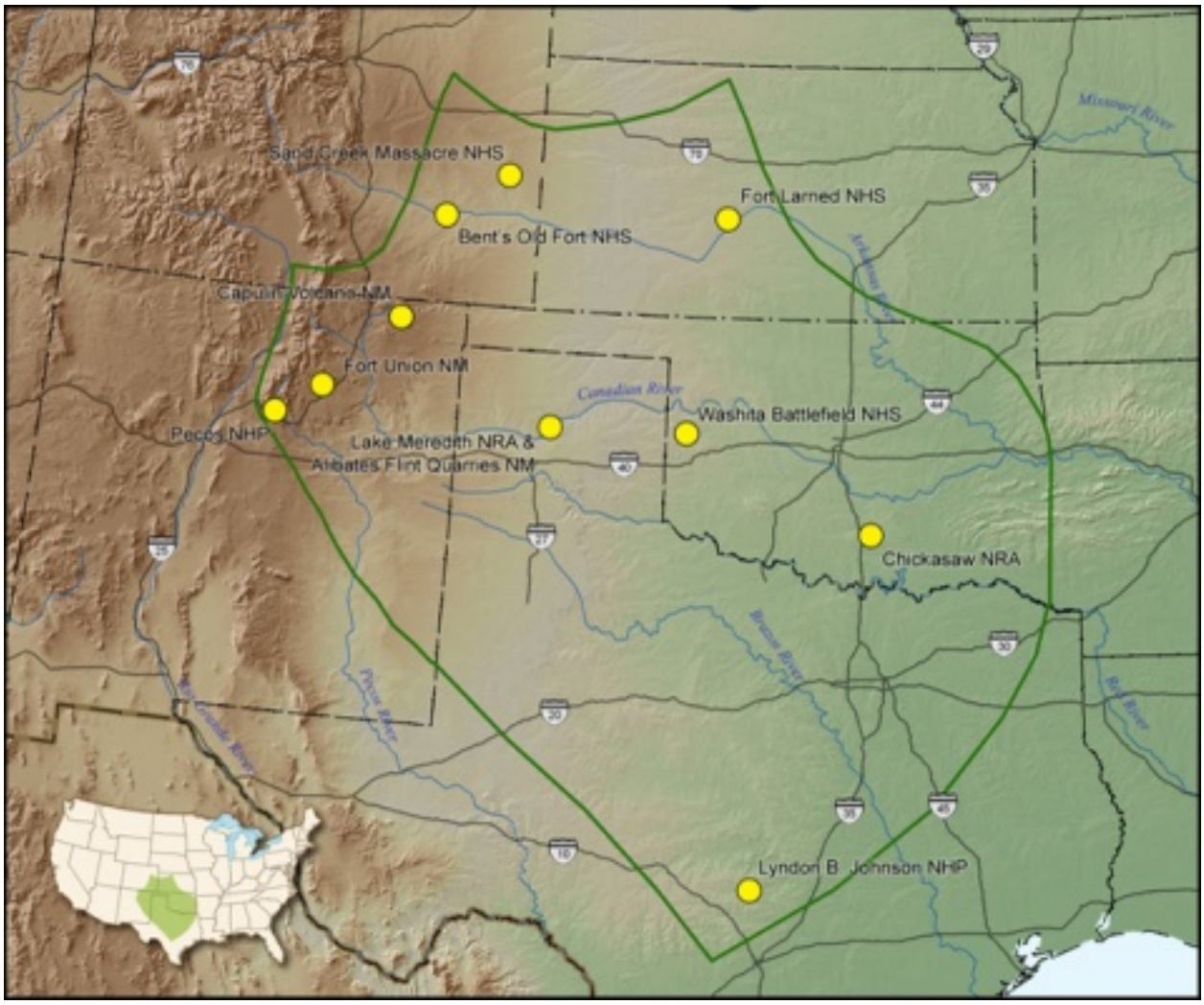


Figure 1. Map of Southern Plains Network parks (NPS map).

SOPN Geological Background

The geologic history of the SOPN (discussed in greater detail in the individual park summaries that follow) goes back as far as the Paleoproterozoic, but most of the parks have geologic histories beginning in the Permian or Cretaceous (see the Appendix for a geologic time scale). The Permian, Cretaceous, and Quaternary are the best represented geologic time periods in the network parks. The Permian rocks include a combination of coastal terrestrial and shallow-marine rocks, while the

Cretaceous rocks were generally deposited in shallow to moderately deep waters of a continental sea, and the Quaternary deposits usually show the influence of rivers.

The SOPN is near the southwestern extremity of the North American craton (the ancient core of the continent), and because of this peripheral location, the ancient bedrock here has been subjected to several episodes of deformation. One of these, around 1.2 billion years ago, metamorphosed the rocks of the Llano Uplift northwest of LYJO. Another event, around 550 to 525 Ma (million years ago), created a large rift valley in what is now Oklahoma. This rift, known as the Southern Oklahoma Aulacogen ("aulacogen" is the term for a failed rift), became a major depositional basin for approximately 200 million years, and partially explains why CHIC has such a long Paleozoic geologic record. A subsidiary basin from this event, the Anadarko Basin, influenced the geology of AFLM. During the Pennsylvanian, between about 323 and 298 Ma, North America and South America collided along the southern margin of North America as the supercontinent Pangea assembled, forcing up mountain ranges in the southern United States. Some of these mountain ranges, such as the Amarillo Mountains of the Texas Panhandle, the Llano Uplift of central Texas, the Wichita Mountains of southwestern Oklahoma, the Arbuckle Mountains of south-central Oklahoma, and several uplifts in northern New Mexico and southern Colorado, influenced the geology of SOPN units. After Pangea broke up during the Triassic and Jurassic, and the geography of the North American plate had been refashioned, the southern margin of the United States was no longer near a plate boundary, and no additional continental collisions have occurred.

The oldest rocks exposed in a SOPN unit are Paleoproterozoic granites and gneisses in the Cañoncito unit of PECO, which are over 1.6 billion years old. The next oldest are the rocks of the Wilberns Formation in LYJO, which were deposited during the late Cambrian, about 490 Ma. Thus, there is a gap of at least 1.1 billion years in SOPN geology, although rocks in the vicinity of the parks fill in part of the gap, as described in part above. The Cambrian rocks of LYJO are part of a series of marine and coastal rocks deposited during marine transgression-regression (advance-retreat) cycles. To the north, in south-central Oklahoma, another series of marine rocks was being deposited in the CHIC area.

Before the deposition of the oldest rocks of CHIC and LYJO, in the earlier Cambrian, a continental rift opened in southern North America. In a continental rift, typically three arms develop, radiating from a central point. Two of the arms go to completion, while the third fails, leaving behind a deep faulted basin. In the case of south-central Oklahoma, the failed rift became the Southern Oklahoma Aulacogen. The aulacogen served as a depositional basin for many tens of millions of years. Numerous depositional cycles occurred in the basin, in some cases due to fluctuations of sea level, and in other cases due to the basin filling followed by basin subsidence. Over a dozen formations were deposited in and around the basin between the Middle Ordovician and the Late Mississippian, as seen at CHIC and in the vicinity. Most were deposited under a shallow tropical sea, and show evidence of abundant life, dominated by various forms of sessile filter-feeding invertebrates. There are also some rocks from extremely shallow settings or deeper, oxygen-poor water, with fewer fossils. By the Late Mississippian, the southern landmass Gondwana was approaching the southern and eastern margin of North America. This culminated in a series of mountain-building events,

affecting areas from Oklahoma and Texas to southeastern Canada. The formations deposited at CHIC from the Late Mississippian to the Late Pennsylvanian show the impact of the collision, going from coastal to alluvial deposition as the Arbuckle Mountains rose and eroded.

Outcrops in a park other than CHIC which date to between the Ordovician and Permian are found only in PECO, as the Middle–Late Pennsylvanian Alamitos Formation (about 310 to 300 Ma), but during the Permian PECO is joined by AFLM and WABA. The late Paleozoic rocks of PECO were deposited between about 310 and 265 Ma, representing many millions of years near the margin of a shallow sea. As sea level and climate fluctuated, deposition shifted between fluvial, eolian, and shallow-marine settings and processes. Marine invertebrates were common during some of the depositional episodes, and their fossils were occasionally collected from near PECO and brought to Pecos Pueblo by native people. At other times, land vertebrates such as large amphibians and early mammal relatives ("mammal-like reptiles") inhabited the area. To the east, around the Texas Panhandle and into western Oklahoma, slightly younger rocks from around 250 Ma record shallow-marine and coastal-terrestrial deposition under an arid, harsh climate, with few traces of life. Deposition persisted in the AFLM and PECO areas into the Triassic, where similar fluvial and floodplain formations were deposited around 225 to 210 Ma. Although only a few fossils have been found in these formations in the parks, equivalent rocks are very productive to the northwest and west in places like Petrified Forest National Park.

The time between about 210 and 120 Ma is not represented within any of the parks of the SOPN, although the Santa Fe National Historic Trail (SAFE) probably crosses Jurassic rocks in the Oklahoma Panhandle. The middle Cretaceous has a good geologic presence in the SOPN: BEOL, FOLS, FOUN, LYJO, and SAND all include or are near Cretaceous outcrops, or have Cretaceous rocks in the shallow subsurface. In addition, SAFE crosses Cretaceous rocks, and the non-network unit Nicodemus National Historic Site (NICO) features buildings constructed of Cretaceous stone. The Cretaceous rocks of the SOPN are associated with the Western Interior Seaway, a vast continental sea that covered much of the central United States at various times between about 115 and 70 Ma. Sea level was unusually high during this time because of a combination of young buoyant oceanic crust raising the floors of the new Atlantic ocean basin, and a greenhouse climate phase. On the west side of the Seaway were geologically young mountain ranges and volcanoes, which occasionally spewed ash into the continental sea, later to decompose to bentonite. Evidence of the Seaway is found in many NPS units of the central third of the United States. The final retreat of the Seaway resulted from falling sea levels and geologic uplifts in the western United States, in particular the Laramide Orogeny (mountain building event). The Laramide Orogeny began the process of forming the modern Rocky Mountains, and also raised much of western North America to elevations far above sea level.

The oldest rocks related to the Seaway in the SOPN are the Hensel Sand and Glen Rose Formation of LYJO. Because of their proximity to the Gulf of Mexico, they are somewhat different from the Cretaceous rocks of the other SOPN units, but they are comparable. The Seaway formations in the parks to the north and west of LYJO are part of a common sequence beginning with a transition from coastal plain to coastal deposition (often identified as the Dakota Formation or Group) leading into

shallow marine and eventually deeper marine deposition. Over time, the Seaway underwent cycles of expansion and retreat, which influenced the types of rocks that were deposited and the types of organisms that were present.

The latest Cretaceous and much of the Cenozoic are not represented by surficial exposures in SOPN parks. The SOPN was not geologically quiet during this time, though. Volcanoes were active in the Austin area toward the end of the Cretaceous, about 80 Ma. Farther west, the appearance of the Santa Fe Rift about 26 Ma not only created a network of faults and basins in central New Mexico and southern Colorado, but also spurred volcanic activity along an ancient Precambrian structural weakness known as the Jemez Lineament. Several volcanic fields have formed along the Lineament. Among the notable eruptions are those that formed Valles Caldera at 1.61 and 1.22 Ma. At a smaller scale, the eruption that produced Capulin Volcano (CAVO) around 60,000 years ago was also part of a volcanic field associated with the Jemez Lineament. The Ogallala Formation, exposed in AFLM, along the Santa Fe Trail, and near WABA, was deposited between about 13 and 5 Ma during some of this volcanic activity, as evidenced by the quantity of volcanically-derived sediments. This formation, noted as an aquifer, is present in much of the Plains of the United States, and preserves fossils from a variety of mammals, such as canids, “beardogs”, nimravids (false sabre-toothed “cats”), elephant relatives, rhinos, horses, and a variety of small extinct artiodactyls. During the deposition of this formation, major rivers of the SOPN, like the Canadian and Pecos, began to attain their modern configurations.

Quaternary (2.58 Ma to the present) deposition is represented throughout the SOPN parks, usually associated with a river. The shifting of river courses makes many of the parks likely candidates for Quaternary pollen studies. To date most pollen studies have been focused on the past two centuries, but could be extended further back in time. Glacial ice did not reach the SOPN, and the lack of a coast means that glacial sea level changes are also not represented in the network. Instead, the parks were affected indirectly by climate changes. Climate seems to have generally been cooler and moister during significant parts of the Quaternary; the continental ice sheets to the north appear to have forced the Jet Stream farther south, bringing with it more moisture. Grasslands supported bison, horses, and mammoths; fossils of mammoths and an extinct bison species have been found at AFLM, and mammoth tusk material has been found at BEOL. Evidence indicates that humans arrived in the SOPN by the end of the Pleistocene, 11,700 years ago. In fact, some of the most famous ancient Paleoindian sites are within the SOPN. The Clovis culture is named for a site in eastern New Mexico, and the Folsom culture was named for a site a few km or mi northwest of CAVO. People have known of the fossils in the SOPN for thousands of years, as shown by the hundreds of fossils recovered from rubbish heaps at Pecos Pueblo in PECO. The systematic study of fossils from this region began during the 1850s, with the great western railroad surveys, and has continued sporadically since then.

Collectively, the paleontological resources of the SOPN park units contribute to a greater understanding of the history of life on earth. Continued paleontological resource inventories will serve to expand this ever-widening base of paleontological knowledge represented throughout the

NPS. Although at least 259 parks have already been identified as containing paleontological resources, much of what is to be known about the history of life on earth remains to be discovered.

Report Organization and Methodology

This report summarizes the paleontological resources of park units in the Southern Plains Inventory & Monitoring Network (SOPN). The report consolidates baseline paleontological resource data for each network park to support management operations, planning, and science-informed decision-making as required by NPS management policies and the Paleontological Resources Preservation Act (2009). This section of the report details the organization of the report and summarizes how the report was written.

Each network report includes an executive summary, introduction with geologic background, methodology chapter (this chapter), description of resource management strategies, and individual park narratives, which are described below. Some network reports include information for non-network parks, those that are not officially part of the Inventory and Monitoring Network, but are within the geographic boundaries of the network. Such parks were included in instances where paleontological resources were documented. For more information regarding different paleontological resource inventory strategies, refer to the chapter on Paleontological Resource Management.

This 2015 Southern Plains Network Paleontological Resource Inventory and Monitoring report represents a substantial update of the previous SOPN paleontology summary completed by Koch and Santucci (2003). The methodology section below describes the changes between the original report and this document.

Organization of the Park Narratives

Each park narrative contains the following sections.

Geologic Background

The Geologic Background section contains basic geographic information for the park and lists pertinent geology and paleontology references. A brief geologic history is included to provide context for the fossils discovered within or near the park.

Sources of Paleontological Resources

The Sources of Paleontological Resources section reviews each fossil-bearing rock unit within the park. The history of paleontological resource field work in the park is summarized. A brief geologic description is included as well as the scope and significance of paleontological resources known to occur within the park. This section is organized stratigraphically from oldest rock unit to youngest.

Potential Sources of Paleontological Resources

The rock units listed in the Potential Sources section are units mapped within the park that potentially contain fossils. Although fossils have not been previously documented from those units within the park, fossils have been discovered within those units at localities outside of the park. In some cases, the lack of documented fossils within a particular park or a specific geologic unit in a park may

simply be due to the fact that field inventories for fossils have never been undertaken in the park. As with the Sources section, the geologic units are listed stratigraphically from oldest to youngest.

Park Collections

The Park Collections section summarizes museum collections of fossils associated with the park. Such collections may be housed within the park or in external museum or university repositories. Fossil collections maintained by the park may include specimens discovered both from within and outside the park. It is important to recognize that the park's museum Scope of Collections may include fossils from localities outside of the park boundaries. Regional museums and other outside repositories may curate fossils collected within the park prior to or subsequent to the park's establishment as a unit of the National Park Service. Both scenarios are included in the report. The Smithsonian Institution National Museum of Natural History maintains significant collections of National Park Service fossils. The U.S. Geological Survey maintains collections and archives associated with paleontological resources from many NPS areas.

Cultural Resource Contexts

Resource stewardship strategies and management plans typically address paleontological resources that are known to occur within the rocks of the park. Fossils may also occur in a variety of cultural resource contexts, including: in association with archeological resources, ethnographic stories and legends, prehistoric and historic structures, or other documented historical occurrences. Fossils may be found as tools, jewelry, spiritual or ceremonial objects, or other cultural objects in archeological sites. A few ethnographic stories and legends told by American Indians and "mountain men" of the American West incorporate fossils. Building stones occasionally contain fossils. In addition, archives, journals, memoirs, and photographs include other historical accounts of fossils in NPS areas. Kenworthy and Santucci (2006) summarizes such occurrences and provides examples of fossils associated with cultural resources.

Paleontological Resource Management, Preliminary Recommendations

In addition to geology and paleontology content, the authors suggest "next steps" for paleontological resource management and stewardship at each park. The recommendations are based on discussion with park staff and other geologists or paleontologists, or as part of broader NPS paleontological resource management strategies. These strategies are summarized in the next chapter. Parks may choose to address the recommendations based upon available staff time, training, and budget. Contact the NPS Geologic Resources Division for technical assistance or further guidance.

References Cited and Additional References

Each park narrative has a bibliography that is divided into two sections. References mentioned in the park narrative are included in the References Cited section. References discovered during the data-mining process that maybe of secondary value or interest are listed in the Additional References section. Although these publications were not included in the narrative, they are relevant to the park's geology or paleontology and commonly contain additional detail beyond the scope of the narrative.

Data Sets

The Data Sets section includes a list of research projects, museum collections, NPS Geologic Resources Inventory Program-produced geologic map data, archives, or other files and information relevant to the paleontology of a particular park.

Figures, Photographs, and Graphics

The first network-based paleontological resource summaries (completed between 2002 and 2011) did not include figures, photographs, or other graphics aside from the report cover and a network map. This second generation of Inventory & Monitoring Network-based paleontological resource inventory reports includes basic geologic maps, stratigraphic columns, paleontological resource summary tables, and photographs for each park when available. Many of the geologic maps are adapted from the NPS Geologic Resources Inventory (GRI) map data for each park. These data are available in GIS format and support accompanying GRI reports, all of which are available from the GRI publications page: http://www.nature.nps.gov/geology/inventory/gre_publications.cfm. The stratigraphic columns illustrates a compiled section of all the rock units mapped in the park along with rock unit name, age, map symbol, thickness, and lithology. Also new to the second generation network-based reports is a summary table listing all the fossiliferous geologic units within the park, fossils collected within the park and the inferred depositional environment. Photographs of park fossils are inserted where appropriate.

Report Methodology

Inventory & Monitoring Network-based paleontological resource inventories compile baseline paleontological resource data for each of the parks within a particular network, and as such, require considerable research and data mining. To minimize costs, field work is not normally conducted as part of the report preparation process. However, field inventory data is incorporated when field work has been accomplished within a park. This section details the research methodology and report preparation, review, publication, and distribution for network-based paleontological inventories.

Between 2002 and 2011, network-based inventories were completed for all of the 32 I&M networks. In 2001, the Northern Colorado Plateau Network technical committee supported a modest funding proposal to develop a prototype paleontological resource inventory for the network. Koch and Santucci (2002) represented the first attempt at compiling baseline paleontological resource data at a network level. That report laid the foundation upon which similar work would be completed for each of the I&M Networks in the National Park System. Between 2002 and 2006, 13 network reports were completed using small amounts of funds provided from each network. Funding from the NPS I&M Program was designated to systematically complete the remaining 19 reports between 2006 and 2011.

This second-generation Southern Plains Network Paleontological Resource Inventory Report represents a substantial revision of the original report, completed in 2003 (Koch and Santucci 2003). This updated network-based paleontological resource inventory report represents a new template and format for future revisions to other network summaries.

Research

One of the most important components of any paleontological resource inventory is an intensive literature search and data mining. The American Geological Institute's GeoRef is the leading database for geology references, indexing more than 3.3 million references to North American geology dating back to the 1660s. To compile the appropriate literature base for this report, the authors conducted intensive GeoRef searches for general and park-specific publications.

Additional databases or information catalogs include the NPS Integrated Resource Management Applications (IRMA) portal (https://irma.nps.gov/app/portal/home), the U.S. Geological Survey (USGS) library system (http://library.usgs.gov/) and publications warehouse (http://pubs.er.usgs.gov/), and Google Scholar (http://scholar.google.com/), as well as museum, university, and other institutional libraries and archives.

The literature search also includes unpublished material, or "gray literature," from park files, museum archives, local newspapers, field notes, and other sources. An important sources for NPS archives related to the SOPN is the Western Archeological and Conservation Center (WACC). In addition to literature searches, interviews with park staff, university faculty, geologists from the USGS and state geological surveys, and even local amateur geologists or paleontologists can often yield unpublished information regarding park paleontological resources. These interviews frequently result in capturing data that might otherwise be undocumented and potentially lost or unrecognized.

One category of "gray literature" deserves further mention. For over a century, paleontologists of the U.S. Geological Survey would identify and make informal reports on fossils sent to the survey by other geologists, for example to establish the relative age of a formation or to help correlate beds. The system was eventually formalized as a two-part process including a form sent by the transmitting geologist and a reply by the survey geologist. The files are known as E&R reports ("Examine and Report on Referred Fossils"). These files often describe fossil localities that are now within NPS units, some of which have never appeared in a formal publication. In addition, they include information about historical activities in park areas, and can provide clues about other work in the same area. Extensive access to the original files was granted to the NPS by the USGS in 2014 (Santucci et al. 2014).

Report authors develop a comprehensive list of geologic units within each park by consulting published geologic maps and other sources. Geologic maps show the types of rocks and the associated geological formations within a park area. These maps alone can often suggest the potential for paleontological resources to occur within a park. The NPS GRI Program is producing standardized digital geologic map data (GIS) for all I&M Program parks. When available, the updated network-based paleontological resource inventory reports adapt GRI map data for each of the parks.

The nomenclature for geologic formations evolves over time and can differ based upon different geological interpretations. To maximize consistency with other NPS geology products, this report generally followed the geologic nomenclature used in GRI maps and report when they were available. The USGS maintains the National Geologic Map Database (NGMDB), which includes a

searchable lexicon of valid geologic formation names (http://ngmdb.usgs.gov/Geolex/geolex_home.html). This lexicon provides a basic summary for each formation, summarizes current and past usage of the various formation names found in the literature, and provides an annotated bibliography for each formation.

Narrative

Information from these various sources is compiled into a narrative report for each park. The narrative is organized according to the scheme detailed earlier in this section.

Review

The park narratives and compiled report are extensively peer reviewed by professional geologists or paleontologists, as well as NPS staff from each park and the NPS Geologic Resources Division. Upon completion of a compiled, draft report, network staff have the opportunity to provide review. Network staff also determine if the previous technical review was adequate for publication.

Publication and Distribution

The peer-reviewed, network-approved reports are currently published in the NPS Natural Resource Report (NRR) series. Previously, network-level inventories were included in the similar Natural Resource Technical Report series (NRTR), which was merged with the NRR series January 1, 2015. A description of these series can be found at http://www.nature.nps.gov/publications/nrpm/. To minimize production costs, hard copies are not generally produced. The reports are distributed in PDF format to park and network staff and available to other NPS staff via the Integrated Resource Management Applications portal. Report reviewers and paleontologists working in the parks may also receive copies. The reports are not intended for, or distributed to, the general public due to the sensitive nature of paleontological resource locality information.

References Cited

Kenworthy, J. P. and V. L. Santucci. 2006. A preliminary inventory of NPS paleontological resources found in cultural resource contexts, part 1: General overview. Pages 70–76 *in* S. G. Lucas, J. A. Spielmann, P. M. Hester, J. P. Kenworthy, and V. L. Santucci, editors. America's antiquities: 100 years of managing fossils on federal lands. New Mexico Museum of Natural History and Science, Albuquerque, New Mexico. Bulletin 34. Available at: http://www.nature.nps.gov/geology/paleontology/pub/fossil_conference_7/9%20Kenworthy.pdf (accessed February 2015).

Koch, A. L. and V. L. Santucci. 2003. Paleontological resource inventory and monitoring: Southern Plains Network. TIC# D-107. National Park Service, Denver, Colorado.

Santucci, V. L., J. M. Ghist, and R. B. Blodgett. 2014. Inventory of U.S. Geological Survey paleontology collections to identify fossil localities in National Park Service areas. Proceedings of the 10th Conference on Fossil Resources. Dakoterra 6:215–218.

Inventory and Monitoring Strategies and Resource Management Guidance

Paleontological Resource Inventory Strategies

In order to better document fossil occurrences and to provide baseline paleontological resource data to NPS areas, the NPS GRD and the NPS I&M Program have established three paleontological resource inventory strategies. These strategies include: comprehensive park-specific inventories, Service-wide thematic inventories, and I&M Network-based summaries.

Comprehensive Park-Specific Surveys

Comprehensive park-specific surveys identify all known paleontological resources within a single NPS unit. A team of specialists from within the NPS and from educational institutions and cooperators work with the targeted park to identify and address all aspects of its paleontological resources. The surveys commonly include sections addressing: park geology, paleontological resources inventory (species list and other compilations), localities, museum collections and curation, interpretation, management and protection, and recommendations. Paleontological resource training for park staff is an important component of many comprehensive park paleontological resource inventories.

Park-specific comprehensive paleontological resource inventories have been completed for Amistad National Recreation Area (Visaggi et al. 2009), Arches National Park (Swanson et al. 2005; Madsen et al. 2012), Bighorn Canyon National Recreation Area (Santucci et al. 1999; Boudreau et al. 2014), Chesapeake and Ohio Canal National Historical Park (Clites and Santucci 2010), Death Valley National Park (Nyborg and Santucci 1999), Glacier Bay National Park and Preserve (Blodgett et al. 2012), Golden Gate National Recreation Area (Henkel et al. 2015), Mississippi National River and Recreation Area (Tweet 2014), Santa Monica Mountains National Recreation Area (Koch et al. 2004), Walnut Canyon National Monument (Santucci and Santucci 2001), Yellowstone National Park (Santucci 1998, the first park to have such a survey completed), and Zion National Park (DeBlieux et al. 2005). Similar paleontological resource inventories are currently underway at Big Bend National Park, Chaco Culture National Historical Park, Grand Canyon National Park, Lake Mead National Recreation Area, and Mesa Verde National Park.

Service-wide Thematic Inventories

Service-wide thematic paleontological resource inventories compile data regarding specific types of paleontological resources that occur in parks throughout the NPS. These reports offer brief summaries of each occurrence of a particular type or category of fossils documented within a particular park. These reports are based primarily on literature review and communication with park staff and professional geologists and paleontologists.

The first thematic paleontological resource inventory identified 19 NPS units that preserve fossil vertebrate tracks (Santucci et al. 1998). Subsequent discoveries have increased the number of parks identified with fossil vertebrate tracks to 25 and warranted an updated publication (Santucci et al. 2006). Another thematic inventory identified paleontological resources associated with NPS caves in 35 parks (Santucci et al. 2001). Service-wide thematic inventories have also been initiated for fossil

fish (Hunt et al. 2006), Cenozoic fossil vertebrate tracks and burrows (Santucci et al. 2014a), fossil coprolites (Hunt et al. 2012), fossil packrat middens (Tweet et al. 2012), Mesozoic mammals and other therapsids (Tweet et al. 2015), and fossils found in cultural resource contexts (Kenworthy and Santucci 2006). Smaller-scale inventories have documented the paleontological resources of NPS units in Utah (Santucci 2000) and fossil plants from the National Capital Region (Santucci et al. 2014b). Two thematic paleontological resource inventory projects are currently underway: an inventory of paleontological resources associated with NPS coastal and shoreline parks, and an inventory for trilobite fossils from NPS areas. Additionally, an inventory of USGS paleontological localities within NPS units is a long-term project currently in progress (Santucci et al. 2014c).

Inventory and Monitoring Network-Based Summaries

Network-based paleontological resource inventories compile baseline paleontological resource data for each of the parks within a particular I&M Network. Between 2002 and 2011, network-based inventories were completed for all 32 I&M Networks. This report represents an overhaul and substantial revision of the SOPN report, the sixth I&M Network reported completed originally and the fifth network update completed to date. An update of the original Mojave Desert Network Paleontological Resource Inventory Report (Santucci et al. 2004) is the next update planned, for 2015. For more information on the content of network-based summaries and how they are completed, refer to the Report Organization and Methodology chapter. Citations for the completed reports are listed in the References Cited section. A comprehensive summary report is currently being developed to present an overview and highlights of the 10-year effort to document fossils throughout the NPS using the network-based strategy. Four Servicewide paleontological resource summary reports are planned, which are referred to collectively as the NPS Paleontology Synthesis Project. The NPS Paleontology Synthesis Project (NPS-PSP) includes reports that present data based on geologic time, taxonomy, museum collections and fossil type specimens. See Santucci et al. (2012) for a brief overview.

The network-based paleontological resource summaries may also include discussion of non-I&M parks that are geographically within a given network, to ensure that information is not overlooked. The majority of non-I&M parks protect a specific cultural or historic location or resources, and encompass small areas. However, these parks sometimes have significant paleontological resources that should be incorporated into the NPS paleontological resource inventory evaluations. Paleontological resources are associated with many non-I&M parks, and include such notable specimens as fossils discovered on the Lewis and Clark expedition, one of the first dinosaur skeletons reported from the Western Hemisphere, and a mastodon tooth fragment that may have been owned by Benjamin Franklin. In addition, some fossil-yielding parks have been added to the NPS after the I&M program was established in the late 1990s, which would have fit the criteria for inclusion had they existed previously. Examples include Tule Springs Fossil Beds National Monument and Valles Caldera National Preserve. There was some consideration of including Valles Caldera National Preserve in this report, but geographically it fits better with the Southern Colorado Plateau Network. Finally, there are many scenic and historic rivers and trails, most of which are not in the I&M program, but many of which are either known to yield fossils or have high potential. These units have generally been omitted, because they often do not pertain to just one network, and

because of the challenges inherent in dealing with these long, narrow corridors. It is hoped to address them eventually in a dedicated document. One example, Santa Fe National Historic Trail, is briefly discussed in this document because of its historically notable fossil record and close association with several SOPN units.

During the period in which final review for this SOPN Paleontological Resource Inventory Report was being conducted, national media was reporting on the possible designation of the Waco Mammoth Site as a new unit of the NPS. Although it would be premature to include the Waco Mammoth Site in this summary, the reference to this possible future NPS fossil park is included because the site is located within the geographic area for the SOPN.

Paleontological Resource Monitoring Strategies

Following the compilation of baseline paleontological resource inventories, monitoring of fossil localities represents the next phase in paleontological resource management. Santucci and Koch (2003) presented a preliminary strategy for monitoring paleontological resources and identified natural and human-related impacts to fossils. Santucci et al. (2009) presented a more comprehensive strategy for paleontological resource monitoring that identified natural and human-related stressors upon paleontological resources, described five vital signs, and provided examples of study design and case studies. The five vital signs include: (1) erosion, geologic factors; (2) erosion, climatic factors; (3) catastrophic geohazards; (4) hydrology/bathymetry; and (5) human access/public use. The vital signs discussions provide detailed recommendations for resource managers, incorporating expertise, personnel, and equipment needed, approximate cost, and labor intensity. Santucci et al. (2009) is one chapter in the Geological Monitoring manual that provides guidance for monitoring various geologic resources and processes. The manual (Young and Norby 2009) was published by the NPS Geologic Resources Division and Geological Society of America.

During 2009, Glen Canyon National Recreation Area (GLCA) was selected as the prototype paleontological resource monitoring park for the NPS. A number of considerations relative to the paleontological resources at GLCA, including the large number of fossil localities along the shorelines of Lake Powell impacted by frequent fluctuations in lake water levels, present excellent opportunities for paleontological resource monitoring (Kirkland et al. 2011). Paleontological resource monitoring has been established in several other NPS areas, including Arches National Park, Capitol Reef National Park, George Washington Birthplace National Monument, Point Reyes National Seashore, and Zion National Park.

Paleontological Resource Management Legislation and Guidance

I&M Network reports such as this are meant to provide network parks with sound baseline paleontological resource data that can stimulate future research, interpretation, education, or resource management projects. Science-based management of resources identified through these inventories is mandated by many NPS policies including the newly enacted Paleontological Resource Preservation Act of 2009 (PRPA).

2009 Paleontological Resource Preservation Act

The Paleontological Resource Preservation Act (P.L. 111-11; "PRPA") was signed into law on March 30, 2009 as Subtitle D of the Omnibus Public Lands Act of 2009 (16 U.S.C. 470aaa–470aaa-11). PRPA will serve as explicit authority for the management, protection and interpretation of paleontological resources in parks. The Department of the Interior PRPA regulations are currently (May 2015) being finalized by the National Park Service, Bureau of Land Management, Bureau of Reclamation, and the U.S. Fish and Wildlife Service. PRPA specifically provides the NPS with the following mandates to enhance paleontological resources stewardship:

- §6302 calls for the management and protection of paleontological resources using scientific principles and expertise. The NPS should develop plans for inventory, monitoring, and the scientific and educational use of paleontological resources. Planning should emphasize interagency coordination and collaboration and where possible include non-federal partners, the scientific community, and the public.
- §6303 calls for the establishment of education programs to increase public awareness about the significance of paleontological resources.
- §6304 calls for the development of a specific permit for the collection of NPS paleontological resources. The new legislation and other existing authorities clarify and reaffirm issues of property ownership, accountability, access and confidentiality of locality information associated with the management of NPS paleontological resources.
- §6305 calls for the curation of NPS paleontological resources, along with any associated data or records, in approved repositories.
- §6306 provides clarity regarding prohibited acts involving paleontological resources and specifies criminal penalties associated with these prohibited acts.
- §6307, along with other existing authorities, enables the NPS to seek civil penalties and restitution for the violation of any prohibited activities involving paleontological resources.
- §6308 provides the NPS a confidentiality provision with an exemption from the disclosure of any information associated with the nature and specific location of NPS paleontological resources.
- §6310 directs the Secretaries of the Interior and Agriculture to issue regulations appropriate to carry out the Act.

NPS Management Policies

In addition to the PRPA, several other authorities influence the management of NPS paleontological resources. The 2006 National Park Service Management Policies (§1.4.6) stipulates that paleontological resources are considered park resources and values that are subject to the "no impairment" standard set forth by the NPS Organic Act in 1916. Basic guidelines for management of paleontological resources are found in sections 4.8.2 and 4.8.2.1 of the 2006 NPS Management Policies (http://www.nps.gov/policy/MP2006.pdf).

Other Resources

Paleontological resource management issues were the subject of a Report of the Secretary of the Interior in May 2000, viewable online at http://www.blm.gov/heritage/docum/fossilrpt.pdf. That report was prepared in response to a Congressional request for an assessment of the need for a unified federal policy on the collection, storage and preservation of fossils and for standards that would maximize the availability of fossils for scientific study.

The Paleontological Resources Management section of Natural Resource Management Reference Manual 77 provides guidance and additional information regarding the implementation and continuation of paleontological resource management programs (http://www.nature.nps.gov/rm77/paleo.cfm).

As described above, Santucci et al. (2009) provided guidance for paleontological resource monitoring.

As of the date of publication for this report, the NPS manages more than 571,000 catalogued fossil specimens in collections across the country. Many thousands more specimens await cataloging. For information regarding fossils in museum collections, refer to the NPS Museum management handbook, particularly Part I, Appendix U (http://www.nps.gov/museum/publications/handbook.html).

Education and Outreach Opportunities

Fossils occupy an enduring place in the hearts and mind of the public, presenting excellent opportunities for education and outreach. These opportunities support provisions in the Paleontological Resources Preservation Act (above) as well as the NPS natural resource stewardship mission. The NPS Geologic Resources Division coordinates two fossil-related education and outreach opportunities with a national scope: National Fossil Day and the Junior Paleontologist program. National Fossil Day is a celebration organized to promote public awareness and stewardship of fossils, as well as to foster a greater appreciation of their scientific and educational value. Learn more at the NFD website: http://nature.nps.gov/geology/nationalfossilday/index.cfm. The Junior Paleontologist program (part of the Junior Ranger program) provides opportunities for children to explore the ways that paleontologists work, learn about earth's history, and protect fossils and the rocks in which they are found. For more information, visit the Junior Paleontologist program webpage: http://nature.nps.gov/geology/nationalfossilday/jrpaleo.cfm. Contact the Geologic Resources Division for information on how to participate in either program.

In conclusion, our knowledge of the fossil record is only as good as our previous field season. The potential for new paleontological discoveries is proportionally related to our understanding as managers and stewards of this non-renewable evidence of life from the past. We believe that the baseline information provided in these reports and the resulting increased understanding of paleontological resources will inevitably result in paving the way for future fossil discoveries in NPS areas.

References Cited

Blodgett, R. B., V. L. Santucci, and L. Sharman. 2012. An inventory of paleontological resources from Glacier Bay National Park and Preserve, Alaska. Pages 43–47 *in* S. Weber, editor. Rethinking protected areas in a changing world: proceedings of the 2011 George Wright Society Biennial Conference on Parks, Protected Areas, and Cultural Sites. The George Wright Society, Hancock, Michigan.

Boudreau, D. B., V. L. Santucci, and T. Connors. 2014. Bighorn Canyon National Recreation Area: Paleontological resources inventory. Natural Resource Report NPS/BICA/NRR—2014/885. National Park Service, Fort Collins, Colorado.

Clites, E. C., and V. L. Santucci. 2010. Preliminary paleontological resource field survey: Chesapeake and Ohio Canal National Historical Park. Natural Resource Report NPS/NRPC/NRR—2010/197. National Park Service, Fort Collins, Colorado.

DeBlieux, D. D., J. A. Smith, J. L. McGuire, J. I. Kirkland, and V. L. Santucci. 2005. Zion National Park paleontological survey. Utah Geological Survey, Salt Lake City, Utah.

Henkel, C. J., W. P. Elder, V. L. Santucci, and E. C. Clites. 2015. Golden Gate National Recreation Area: Paleontological resource inventory. Natural Resource Report NPS/GOGA/NRR—2015/915. National Park Service, Fort Collins, Colorado.

Hunt, R. K., V. L. Santucci, and J. P. Kenworthy. 2006. A preliminary inventory of fossil fish from NPS units. Pages 63–69 *in* S. G. Lucas, J. A. Spielmann, P. M. Hester, J. P. Kenworthy, and V. L. Santucci, editors. America's antiquities: 100 years of managing fossils on federal lands. New Mexico Museum of Natural History and Science, Albuquerque, New Mexico. Bulletin 34. Available at http://nature.nps.gov/geology/paleontology/pub/fossil_conference_7/8%20Hunt%202.pdf (accessed February 2015).

Kenworthy, J. P., and V. L. Santucci. 2006. A preliminary inventory of NPS paleontological resources found in cultural resource contexts, part 1: General overview. Pages 70–76 *in* S. G. Lucas, J. A. Spielmann, P. M. Hester, J. P. Kenworthy, and V. L. Santucci, editors. America's antiquities: 100 years of managing fossils on federal lands. New Mexico Museum of Natural History and Science, Albuquerque, New Mexico. Bulletin 34. Available at http://nature.nps.gov/geology/paleontology/pub/fossil_conference_7/9%20Kenworthy.pdf (accessed February 2015).

Kirkland, J. I., S. K. Madsen, D. D. DeBlieux, and V. L. Santucci. 2011. Establishing a paleontological monitoring test site at Glen Canyon National Recreation Area. Geology Studies 49(A):51–60.

Koch, A. L. and V. L. Santucci. 2003. Paleontological resource inventory and monitoring: Southern Plains Network. TIC# D-107. National Park Service, Denver, Colorado.

Koch, A. L., V. L. Santucci, and T. R. Weasma. 2004. Santa Monica Mountains National Recreation Area paleontological survey. NPS Geologic Resources Division, Denver, Colorado. Technical Report NPS/NRGRD/GRDTR—04/01. Available at http://nature.nps.gov/geology/paleontology/surveys.cfm (accessed February 2015).

Madsen, S. K., J. I. Kirkland, D. D. DeBlieux, V. L. Santucci, P. Inkenbrandt, and J. Tweet. 2012. Paleontological resources inventory and monitoring at Arches National Park, Utah. Utah Geological Survey Contract Deliverable.

Nyborg, T. G., and V. L. Santucci. 1999. The Death Valley National Park paleontological survey. National Park Service, Geologic Resources Division, Denver, Colorado. Technical Report NPS/NRGRD/GRDTR—99/01. Available at http://nature.nps.gov/geology/paleontology/surveys.cfm (accessed February 2015).

Santucci. V. L. 1998. The Yellowstone paleontological survey. Yellowstone Center for Resources, National Park Service, Yellowstone National Park, Wyoming. Report YCR-NR-98-1. Available at http://nature.nps.gov/geology/paleontology/surveys.cfm (accessed February 2015).

Santucci, V. L. 2000. A survey of paleontological resources from the national parks and monuments in Utah. Pages 535–556 *in* D. A. Sprinkel, P. B. Anderson, and T. C. Chidsey, Jr., editors. Geology of Utah's parks and monuments. Utah Geological Association, Salt Lake City, Utah. Publication 28.

Santucci, V. L., and A. L. Koch. 2003. Paleontological resource monitoring strategies for the National Park Service. Park Science 22(1):22–25. Available at http://www.nature.nps.gov/parkscience/index.cfm?ArticleID=16 (accessed February 2015).

Santucci, V. L., and V. L. Santucci, Jr. 1999. An inventory of paleontological resources from Walnut Canyon National Monument, Arizona. Pages 188–120 *in* V. L. Santucci and L. McClelland, editors. Paleontological research volume 4. Technical Report NPS/NRGRD/GRDTR-99/03. National Park Service, Geologic Resources Division, Lakewood, Colorado. Available at http://nature.nps.gov/geology/paleontology/pub/grd4/nsp_paleo_vol4.pdf (accessed February 2015).

Santucci, V. L., A. P. Hunt, and M. G. Lockley. 1998. Fossil vertebrate tracks in National Park Service areas. Dakoterra 5:107–114.

Santucci, V. L., D. Hays, J. Staebler, and M. Milstein. 1999. A preliminary assessment of paleontological resources at Bighorn Canyon National Recreation Area, Montana and Wyoming. Pages 18–22 *in* V. L. Santucci and L. McClelland, editors. Paleontological Research Volume 4. Technical Report NPS/NRGRD/GRDTR-99/03. National Park Service, Geologic Resources Division, Lakewood, Colorado. Available at http://nature.nps.gov/geology/paleontology/pub/grd4/nsp_paleo_vol4.pdf (accessed February 2015).

Santucci, V. L., J. Kenworthy, and R. Kerbo. 2001. An inventory of paleontological resources associated with National Park Service caves. NPS Geologic Resources Division, Denver. Technical Report NPS/NRGRD/GRDTR-01/02. TIC# D-2231. Available at http://nature.nps.gov/geology/paleontology/pub/cavepaleo.pdf (accessed February 2015).

Santucci, V. L., A. L. Koch, and J. P. Kenworthy. 2004. Paleontological resource inventory and monitoring: Mojave Desert Network. TIC# D-305. National Park Service, Denver, Colorado.

Santucci, V. L., A. P. Hunt, T. Nyborg, and J. P. Kenworthy. 2006. Additional fossil vertebrate tracks in National Park Service areas. Pages 152–158 *in* S. G. Lucas, J. A. Spielmann, P. M. Hester, J. P. Kenworthy, and V. L. Santucci, editors. America's antiquities: 100 years of managing fossils on federal lands. New Mexico Museum of Natural History and Science, Albuquerque, New Mexico. Bulletin 34. Available at http://nature.nps.gov/geology/paleontology/pub/fossil_conference_7/21%20Santucci%20et%20al..pdf (accessed February 2015).

Santucci, V. L., J. P. Kenworthy, and A. L. Mims. 2009. Monitoring in situ paleontological resources. Pages 189–204 *in* R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. Available at http://nature.nps.gov/geology/monitoring/paleo.cfm (accessed February 2015).

Santucci, V. L., J. S. Tweet and J. P. Kenworthy. 2012. Paleoblitz: uncovering the fossil record of the national parks. Park Science 29(1):29–32.

Santucci, V. L., J. S. Tweet, D. Bustos, T. Nyborg, and A. P. Hunt. 2014a. An inventory of Cenozoic fossil vertebrate tracks and burrows in National Park Service areas. Pages 469–488 in M. G. Lockley S. G. Lucas, editors. Fossil footprints of western North America. New Mexico Museum of Natural History and Science, Albuquerque, New Mexico. Bulletin 62.

Santucci, V. L., C. Knight, and M. Antonioni. 2014b. Fossil plants from the National Park Service areas of the National Capital Region. Dakoterra 6:181–190.

Santucci, V. L., J. M. Ghist, and R. B. Blodgett. 2014c. Inventory of U.S. Geological Survey paleontology collections to identify fossil localities in National Park Service Areas. Dakoterra 6:215–218.

Swanson, B. A., V. L. Santucci, S. K. Madsen, A. S. Elder, and J. P. Kenworthy. 2005. Arches National Park paleontological survey. NPS Geologic Resources Division, Denver, Colorado. Technical Report NPS/NRGRD/GRDTR—05/01.

Tweet, J. S. 2014. Paleontology of Mississippi National River and Recreation Area. Natural Resource Report NPS/MISS/NRR—2014/888. National Park Service, Fort Collins, Colorado.

Tweet, J. S., V. L. Santucci, and A. P. Hunt. 2012. An inventory of packrat (*Neotoma* spp.) middens in National Park Service areas. Pages 355–368 *in* A. P. Hunt, J. Milàn, S. G. Lucas, and J. A. Spielmann, editors. Vertebrate coprolites. New Mexico Museum of Natural History and Science,

Albuquerque, New Mexico. Bulletin 57. Available at http://www.nature.nps.gov/Geology/paleontology/Publications/surveys/thematic/TWEET_SANTUCCI_HUNT_2012_NPS_PACKRAT_MIDDENS.pdf (accessed February 2015).

Tweet, J. S., and V. L. Santucci. 2015. An inventory of Mesozoic mammals and non-mammalian therapsids in National Park Service areas. Pages 297–302 *in* R. M. Sullivan and S. G. Lucas, editors. Fossil Record 4. New Mexico Museum of Natural History and Science, Albuquerque, New Mexico. Bulletin 68.

Visaggi, C. C., J. G. Johnson, A. S. Johnson, J. P. Kenworthy, and V. L. Santucci. 2009. Paleontological resource survey: Amistad National Recreation Area. Natural Resource Report NPS/NRPC/GRD/NRR—2009/133. National Park Service, Fort Collins, Colorado.

Young, R., and L. Norby, editors. 2009. Geological monitoring. Geological Society of America, Boulder, Colorado. Available at http://nature.nps.gov/geology/monitoring/index.cfm (accessed February 2015).

Citations for I&M Network-Based Summaries

Citations are listed alphabetically by network

Appalachian Highlands Network (APHN)

Santucci, V. L., R. T. P. McKenna, J. P. Kenworthy, and T. Connors. 2008. Paleontological resource inventory and monitoring: Appalachian Highlands Network. Natural Resource Technical Report NPS/NRPC/NRTR—2008/080. National Park Service, Fort Collins, Colorado.

Arctic Network (ARCN)

Elder, W., V. L. Santucci, J. P. Kenworthy, R. B. Blodgett, and R. T. P. McKenna. 2009. Paleontological resource inventory and monitoring: Arctic Network. Natural Resource Technical Report NPS/NRPC/NRTR—2009/276. National Park Service, Fort Collins, Colorado.

Central Alaska Network (CAKN)

Santucci, V. L., R. B. Blodgett, W. P. Elder, J. S. Tweet, and J. P. Kenworthy. 2011. Paleontological resource inventory and monitoring: Central Alaska Network. Natural Resource Technical Report NPS/NRSS/NRTR—2011/510. National Park Service, Fort Collins, Colorado.

Chihuahuan Desert Network (CHDN)

Santucci, V. L., J. P. Kenworthy, and C. C. Visaggi. 2007. Paleontological resource inventory and monitoring: Chihuahuan Desert Network. National Park Service TIC# D-500.

Cumberland Piedmont Network (CUPN)

Hunt-Foster, R., J. P. Kenworthy, V. L. Santucci, T. Connors, and T. L. Thornberry-Ehrlich. 2009. Paleontological resource inventory and monitoring: Cumberland Piedmont Network. Natural Resource Technical Report NPS/NRPC/NRTR—2009/235. National Park Service, Fort Collins, Colorado.

Eastern Rivers and Mountains Network (ERMN)

Koch, A. L. and V. L. Santucci. 2004. Paleontological resource inventory and monitoring: Eastern Rivers and Mountains Network. TIC# D-265. National Park Service, Denver, Colorado.

Great Lakes Network (GLKN)

Hunt, R. K., J. P. Kenworthy, and V. L. Santucci. 2008. Paleontological resource inventory and monitoring: Great Lakes Network. Natural Resource Technical Report NPS/NRPC/NRTR—2008/120. TIC# D-65. National Park Service, Fort Collins, Colorado.

Greater Yellowstone Network (GRYN)

[Original Report] Koch, A. L. and V. L. Santucci. 2003. Paleontological resource inventory and monitoring: Greater Yellowstone Network. TIC# D-1025. National Park Service, Denver, Colorado.

[Updated Report] Tweet, J. S., V. L. Santucci, and T. Connors. 2013. Paleontological resource inventory and monitoring—Greater Yellowstone Network. Natural Resource Technical Report NPS/NRR—2013/794. National Park Service, Fort Collins, Colorado.

Gulf Coast Network (GULN)

Kenworthy, J. P., V. L. Santucci, and C. C. Visaggi. 2007. Paleontological resource inventory and monitoring: Gulf Coast Network. TIC# D-750. National Park Service, Denver, Colorado.

Heartland Network (HTLN)

Hunt, R. K., J. P. Kenworthy, and V. L. Santucci. 2008. Paleontological resource inventory and monitoring: Heartland Network. Natural Resource Technical Report NPS/NRPC/NRTR—2008/132. TIC# D-66. National Park Service, Fort Collins, Colorado.

Klamath Network (KLMN)

Santucci, V. L. and J. P. Kenworthy. 2009. Paleontological resource inventory and monitoring: Klamath Network. Natural Resource Technical Report NPS/NRPC/NRTR—2009/208. TIC# D-22. National Park Service, Fort Collins, Colorado.

Mediterranean Coast Network (MEDN)

[Original Report] Koch, A. L. and V. L. Santucci. 2003. Paleontological resource inventory and monitoring: Mediterranean Coast Network. TIC# D-177. National Park Service, Denver, Colorado.

[Updated Report] Tweet, J. S., V. L. Santucci, and T. Connors. 2012. Paleontological resource inventory and monitoring: Mediterranean Coast Network. Natural Resource Technical Report NPS/MEDN/NRTR—2012/640. National Park Service, Fort Collins, Colorado

Mid-Atlantic Network (MIDN)

Kenworthy, J. P., C. C. Visaggi, and V. L. Santucci. 2006. Paleontological resource inventory and monitoring: Mid-Atlantic Network. TIC# D-800. National Park Service, Denver, Colorado.

Mojave Desert Network (MODN)

Santucci, V. L., A. L. Koch, and J. P. Kenworthy. 2004. Paleontological resource inventory and monitoring: Mojave Desert Network. TIC# D-305. National Park Service, Denver, Colorado.

Northeast Coastal and Barrier Network (NCBN)

[Original Report] Kenworthy, J. P. and V. L. Santucci. 2003. Paleontological resource inventory and monitoring: Northeast Coastal and Barrier Network. TIC# D-340. National Park Service, Denver, Colorado.

[Updated Report] Tweet, J. S., V. L. Santucci, and T. Connors. 2014. Paleontological resource inventory and monitoring: Northeast Coastal and Barrier Network. Natural Resource Technical Report NPS/NCBN/NRTR—2014/897. National Park Service, Fort Collins, Colorado.

North Coast and Cascades Network (NCCN)

Fay, L. C., J. P. Kenworthy, and V. L. Santucci. 2009. Paleontological resource inventory and monitoring: North Coast and Cascades Network. Natural Resource Technical Report NPS/NRPC/NRTR—2009/250. National Park Service, Fort Collins, Colorado.

Northern Colorado Plateau Network (NCPN)

[Original Report] Koch, A. L. and V. L. Santucci. 2002. Paleontological resource inventory and monitoring: Northern Colorado Plateau Network. TIC# D-206. National Park Service, Denver, Colorado.

[Updated Report] Tweet, J. S., V. L. Santucci, T. Connors, and J. P. Kenworthy. 2012. Paleontological resource inventory and monitoring: Northern Colorado Plateau Network. Natural Resource Technical Report NPS/NCPN/NRTR—2012/585. National Park Service, Fort Collins, Colorado.

National Capital Region Network (NCRN)

Kenworthy, J. P. and V. L. Santucci. 2004. Paleontological resource inventory and monitoring: National Capital Region. TIC# D-289. National Park Service, Denver, Colorado.

Northeast Temperate Network (NETN)

Tweet, J., V. L. Santucci, and J. P. Kenworthy. 2010. Paleontological resource inventory and monitoring: Northeast Temperate Network. Natural Resource Technical Report NPS/NRPC/NRTR—2010/326. TIC# 962/102111. National Park Service, Fort Collins, Colorado.

Northern Great Plains Network (NGPN)

Tweet, J. S., V. L. Santucci, and J. P. Kenworthy. 2011. Paleontological resource inventory and monitoring: Northern Great Plains Network. Natural Resource Technical Report NPS/NRPC/NRTR—2011/437. National Park Service, Fort Collins, Colorado.

Pacific Islands Network (PACN)

Hunt, R. K., V. L. Santucci and J. P. Kenworthy. 2007. Paleontological resource inventory and monitoring: Pacific Islands Network. TIC# D-24. National Park Service, Denver, Colorado.

Rocky Mountain Network (ROMN)

Koch, A. L., J. P. Kenworthy, and V. L. Santucci. 2004. Paleontological resource inventory and monitoring: Rocky Mountain Network. TIC# D-436. National Park Service, Denver, Colorado.

Southern Colorado Plateau Network (SCPN)

Tweet, J., V. L. Santucci, J. P. Kenworthy, and A. L. Mims. 2009. Paleontological resource inventory and monitoring: Southern Colorado Plateau Network. Natural Resource Technical Report NPS/NRPC/NRTR—2009/245. TIC# D-59. National Park Service, Fort Collins, Colorado.

Southeast Alaska Network (SEAN)

Santucci, V. L. and J. P. Kenworthy. 2008. Paleontological resource inventory and monitoring: Southeast Alaska Network. Natural Resource Technical Report NPS/NRPC/NRTR—2008/108. TIC# D-155. National Park Service, Fort Collins, Colorado.

Southeast Coast Network (SECN)

Tweet, J., V. L. Santucci, and J. P. Kenworthy. 2009. Paleontological resource inventory and monitoring: Southeast Coast Network. Natural Resource Technical Report NPS/NRPC/NRTR—2009/197. TIC# D-89. National Park Service, Fort Collins, Colorado.

San Francisco Bay Area Network (SFAN)

Elder, W. P., T. Nyborg, J. P. Kenworthy, and V. L. Santucci. 2008. Paleontological resource inventory and monitoring: San Francisco Bay Area Network. Natural Resource Technical Report NPS/NRPC/NRTR—2008/078. TIC# D-20. National Park Service, Fort Collins, Colorado.

South Florida-Caribbean Network (SFCN)

Toscano, M. A. , J. P. Kenworthy, and V. L. Santucci. 2010. Paleontological resource inventory and monitoring: South Florida / Caribbean Network. Natural Resource Technical Report NPS/NRPC/NRTR—2010/335. National Park Service, Fort Collins, Colorado.

Sierra Nevada Network (SIEN)

Santucci, V. L. and J. P. Kenworthy. 2007. Paleontological resource inventory and monitoring: Sierra Nevada Network. Natural Resource Technical Report NPS/NRPC/NRTR—2007/053. TIC # D-21. National Park Service, Fort Collins, Colorado.

Sonoran Desert Network (SODN)

Tweet, J., V. L. Santucci, and J. P. Kenworthy. 2008. Paleontological resource inventory and monitoring: Sonoran Desert Network. Natural Resource Technical Report NPS/NRPC/NRTR—2008/130. TIC# D-58. National Park Service, Fort Collins, Colorado.

Southern Plains Network (SOPN)

[Original Report] Koch, A. L. and V. L. Santucci. 2003. Paleontological resource inventory and monitoring: Southern Plains Network. TIC# D-107. National Park Service, Denver, Colorado.

[Updated Report] [this document]

Southwest Alaska Network (SWAN)

Kenworthy, J. P. and V. L. Santucci. 2003. Paleontological resource inventory and monitoring: Southwest Alaska Network. TIC# D-93. National Park Service, Denver, Colorado.

Upper Columbia Basin Network (UCBN)

Kenworthy, J. P., V. L. Santucci, M. McNerney, and K. Snell. 2005. Paleontological resource inventory and monitoring: Upper Columbia Basin Network. TIC# D-259. National Park Service, Denver, Colorado.

General SOPN Information

Southern Plains I&M Network: http://science.nature.nps.gov/im/units/SOPN/index.cfm

Geological Survey Websites

American Geological Institute: http://www.agiweb.org/

Geological Society of America: http://www.geosociety.org/

Colorado Geological Survey: http://coloradogeologicalsurvey.org/

Kansas Geological Survey: http://www.kgs.ku.edu/

New Mexico Bureau of Geology & Mineral Resources: https://geoinfo.nmt.edu

Oklahoma Geological Survey: http://www.ogs.ou.edu/homepage.php

Bureau of Economic Geology, University of Texas at Austin: http://www.beg.utexas.edu/

U.S. Geological Survey: http://www.usgs.gov/

Library Catalogs

Smithsonian Institution Research Information System: http://www.siris.si.edu/

U.S. Geological Survey Library: http://library.usgs.gov/

WorldCat.org: http://www.worldcat.org/

Museums

National Park Service Museum Collections: http://museum.nps.gov/ParkIndex.aspx

American Museum of Natural History: http://www.amnh.org/

Denver Museum of Nature & Science: http://www.dmns.org/

Museum of Comparative Zoology (Harvard University): http://www.mcz.harvard.edu/

Museum of the Earth (Paleontological Research Institution): http://www.museumoftheearth.org/

New Mexico Museum of Natural History & Science: http://www.nmnaturalhistory.org/

Panhandle–Plains Historical Museum: http://www.panhandleplains.org/pages/home.asp

Perot Museum of Natural History: http://www.perotmuseum.org/

Sam Noble Museum of Natural History (University of Oklahoma): http://www.snomnh.ou.edu/

Smithsonian National Museum of Natural History Dept. of Paleobiology: http://paleobiology.si.edu/

Sternberg Museum of Natural History (Fort Hays State University): http://sternberg.fhsu.edu/

Texas Memorial Museum (University of Texas at Austin):
http://www.utexas.edu/tmm/exhibits/index.html

University of California Museum of Paleontology: http://www.ucmp.berkeley.edu/

University of Colorado Museum of Natural History: http://cumuseum.colorado.edu/

University of Kansas Natural History Museum: http://naturalhistory.ku.edu/

Other Websites of Interest for SOPN Geology
Abilene Geological Society: http://www.abilenegeo.org/

Dallas Geological Society: http://dgs.org/

The Digital Archaeological Record: http://core.tdar.org/

Kansas Geological Society: http://www.kgslibrary.com/

New Mexico Geological Society: https://nmgs.nmt.edu/

Oceans of Kansas Paleontology: http://oceansofkansas.com/

Oklahoma City Geological Society: https://www.ocgs.org/

Paleontological Institute (University of Kansas): http://paleo.ku.edu/

Panhandle Geological Society: http://panhandlegeologicalsociety.org/

Pleistocene Vertebrates of Southwestern USA and Northwestern Mexico:
http://www.utep.edu/leb/pleistNM/

Tulsa Geological Society: http://www.tulsageology.org/

Resource Management/Legislation Documents
Paleontological Resources Preservation Act (PRPA):
http://www.nature.nps.gov/geology/nationalfossilday/prpa_text.cfm

NPS 2006 Management Policies (§1.4; Park Management):
http://www.nps.gov/policy/mp/chapter1.htm

NPS 2006 Management Policies (§4.8.2.1; Paleontological Resources): http://www.nps.gov/policy/mp/chapter4.htm

NPS 1998 Omnibus Management Act (paleontological resource summary): http://www.nature.nps.gov/geology/paleontology/paleo_5_1/index.htm

NPS Natural Resource Management Reference Manual #77 (paleontology section): http://www.nature.nps.gov/rm77/paleo.cfm

Assessment of Fossil Management on Federal & Indian Lands: http://www.nature.nps.gov/geology/paleontology/Publications/FOSSIL%20REPORT%20TO%20CONGRESS.pdf

National Park Service Paleontology Program Sites

National Fossil Day: http://nature.nps.gov/geology/nationalfossilday/

NPS Geologic Resources Division: http://www.nature.nps.gov/geology/

NPS GRD Geologic Resource Inventory Products (scoping summaries, GRI reports, digital geologic maps): http://www.nature.nps.gov/geology/inventory/gre_publications.cfm

NPS Paleontology Program: http://www.nature.nps.gov/geology/paleontology/

NPS Park Paleontology Newsletter (published 1999-2004): http://www.nature.nps.gov/geology/paleontology/newsletter.cfm

I&M Network paleontological resource summary project website and PDFs of all reports (InsideNPS): http://inside.nps.gov/waso/custommenu.cfm?lv=4&prg=753&id=4518

NPS Technical Information Center (Denver, repository for technical (TIC) documents): http://etic.nps.gov/

Other Geology/Paleontology Tools

Bates, R. L. and J. A. Jackson, editors. American Geological Institute dictionary of geological terms (3rd edition). Bantam Doubleday Dell Publishing Group, New York.

Biodiversity Heritage Library (many journal series, especially pre-1923): http://www.biodiversitylibrary.org/

Internet Archive (for both publications and online addresses that have lapsed): https://archive.org/

NeoMap (Neogene Mammal Mapping Portal): http://www.ucmp.berkeley.edu/neomap/

Neotoma (Quaternary fossil database): http://www.neotomadb.org/

NOAA Paleoclimatology: http://www.ncdc.noaa.gov/data-access/paleoclimatology-data

Paleobiology Database (search for fossil taxonomy, localities, or geologic formations): http://fossilworks.org/bridge.pl?

Paleontology Portal (general fossil info based on geographic location or geologic time): http://www.paleoportal.org/

Fossils in US National Parks (Paleontology Portal): http://www.paleoportal.org/nps/

University of California–Berkeley Museum of Paleontology online paleontology exhibits: http://www.ucmp.berkeley.edu/

U.S. Geological Survey digital state geology maps: http://mrdata.usgs.gov/geology/state/

U.S. Geological Survey Geology in the Parks Glossary: http://geomaps.wr.usgs.gov/parks/misc/glossarya.html

U.S. Geological Survey Paleontological Terms Glossary: http://geology.er.usgs.gov/paleo/glossary.shtml

U.S. Geological Survey National Geologic Map Database (NGMDB): http://ngmdb.usgs.gov/ngmdb/ngmdb_home.html

U.S. Geological Survey Geologic Names Lexicon (GEOLEX; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/search

U.S. Geological Survey Geographic Names Information System (GNIS; search for place names and geographic features, and plot them on topographic maps or aerial photos): http://gnis.usgs.gov/

U.S. Geological Survey GeoPDFs (download searchable PDFs of any topographic map in the United States): http://store.usgs.gov (click on “Map Locator”).

U.S. Geological Survey Publications Warehouse (many USGS publications are available online): http://pubs.er.usgs.gov/

U.S. Geological Survey, description of physiographic provinces: https://web.archive.org/web/20130815000000*/http://tapestry.usgs.gov/Default.html

Alibates Flint Quarries National Monument and Lake Meredith National Recreation Area

Alibates Flint Quarries National Monument (ALFL) and Lake Meredith National Recreation Area (LAMR) are adjoining National Park Service (NPS) units in the Texas Panhandle. ALFL protects an area near the Canadian River where people quarried flint from the Alibates Dolomite for thousands of years (AFLM Figure 1). The flint was prized for making projectile points, knives, and other tools, and was traded over a wide area of the southern High Plains. ALFL was authorized as Alibates Flint Quarries and Texas Panhandle Pueblo Culture National Monument on August 21, 1965. It was given its present name November 10, 1978, and had a boundary change at the same time. ALFL encompasses 529.31 ha (1,307.97 acres), all but 118.06 ha (291.74 acres) of which are federal.

LAMR was established to administer Lake Meredith and its immediate surroundings. Lake Meredith is a man-made reservoir on the Canadian River created by Sanford Dam. The recreation area has been used for boating, fishing, hiking, and other outdoor recreational activities, although water-based activities have been curtailed by recent low lake levels. LAMR began as Sanford National Recreation Area on March 15, 1965. At that time it was administered in cooperation with the Bureau of Reclamation. The present name was applied October 16, 1972, and the recreation area was redesignated November 28, 1990. LAMR encompasses 18,201.80 ha (44,977.63 acres), all of which are federal.

The summaries for ALFL and LAMR are combined in this report because the two units are administered together, share a boundary (AFLM Figure 2), and perhaps most significantly contain the same bedrock geology. References to ALFL or LAMR indicate the individual NPS units. AFLM indicates the two together, or their general area.



AFLM Figure 1. The downcutting of the Canadian River through the AFLM area (left) has exposed the Alibates Dolomite, which yields the prized flint (right) (AFLM/NPS).

Geologic Background

AFLM is located in Hutchinson, Moore, and Potter counties, in the central Texas Panhandle. The small communities of Borger, Fritch, and Sanford are all within a few km or mi of the two park units. The nearest large city is Amarillo, Texas; central Amarillo is about 28 km (17 mi) south of the nearest part of AFLM. The geology of the Panhandle is of great interest because of its status as an oil-producing region. This, combined with the archeological interest in Alibates flint, the building of Sanford Dam, and the occasional small earthquakes in the area, have resulted in a number of publications that document the geology and paleontology of AFLM and the immediate vicinity. These include: Gould (1920); Patton (1923); Sellards (1937, 1939); Bryan (1950); Shaeffer (1958, 1963); Green and Kelley (1960); Bock and Crane (1963); Eck and Redfield (1963a, 1963b, 1965); Horn (1963); Duffield (1964, 1970); Shurbet (1969); Bowers and Reaser (1974); Bowers (1975); Lynn (1975); Anderson (1977); Sansom and Shurbet (1981, 1983); Wilson (1988); Dalquest and Schultz (1992); Wyckoff (1993); Butler (2001); Hunt (2000); Hunt and Santucci (2001); Santucci et al. (2001); Koch and Santucci (2003a, 2003b); KellerLynn (2011); and Quigg et al. (2011). The NPS Geologic Resources Division coordinated a Geologic Resource Inventory workshop for AFLM in May 2011 (KellerLynn 2011), and produced a digital geologic map in 2011 (NPS 2011). Previous paleontologic resource inventories and summaries were prepared by Hunt and Santucci (2001) and Koch and Santucci (2003a, 2003b).

AFLM has bedrock outcrops dating to the late Permian, Late Triassic, and late Cenozoic, giving a somewhat disjointed survey of local geologic history (see Appendix A for a geologic time scale). Igneous rocks are encountered over 600 m (2,000 ft) below the surface (Patton 1923). These rocks represent the ancient basement of the Texas Panhandle, which is rhyolitic and dates to 1,400 to 1,350 Ma (million years ago) (Thomas et al. 1984). This is significantly older than the oldest exposed bedrock of AFLM, which was deposited approximately 260 Ma.

The Paleozoic bedrock of the Panhandle features several basins separated by positive features (structural arches, not to be confused with the much smaller erosional arches of places like Arches National Park) (Nicholson 1960; Johnson 1978; McGillis and Presley 1981). The presence of multiple basins and arches in the Panhandle region partially accounts for the complicated geologic nomenclature, because the various formations are not always traceable across the features, and were sometimes deposited over different durations of time and under different conditions in the different basins. AFLM itself is located over an arch at its southern end, while its northern end is within the southwestern part of the Anadarko Basin. To the northwest of AFLM is the Dalquest Basin, and to the south is the Palo Duro Basin. These structures formed as early as the Mississippian, and filled and subsided at different rates (Nicholson 1960).

An epicontinental sea submerged the Panhandle during the Permian (Nicholson 1960). Deposition occurred in a relatively narrow area flanked by land on the west and east (Johnson 1978). The Permian rocks of the area represent a number of transgression-regression cycles (marine encroachment and retreat) that produced sequences of carbonates, redbeds, and evaporite minerals like gypsum and halite (salt). Rocks exposed in AFLM were probably deposited on low-relief intertidal to supratidal areas, by strongly saline waters under an arid climate. The upper Permian

rocks of AFLM (the Whitehorse Sandstone–Alibates Dolomite–Quartermaster Formation sequence) were deposited during an overall regression, the last of the Permian, with the coast retreating to the southwest (McGillis and Presley 1981). Following this regression, the Panhandle was above sea level for an extended period of time. This terrestrial episode is represented in AFLM by the Upper Triassic Tecovas and Trujillo formations, which were deposited by rivers flowing from the east to the west (Hunt et al. 2001). These two formations were deposited by about 220 Ma, and the next formation exposed at AFLM, the Ogallala Formation, was not deposited until about 12 Ma. Thus, over 200 million years of geologic history is missing at AFLM, due to erosion and non-deposition. There is indirect evidence of another marine episode that occurred during the Cretaceous around 100 Ma, in the form of fossil bivalves that were eroded from Cretaceous rocks and redeposited in younger rocks and sediments (Patton 1923; Hunt and Santucci 2001).

The Ogallala Formation of approximately 12 to 5 Ma is of great importance as an aquifer. This sandy formation was initially deposited by rivers in paleovalleys cut into the eroding bedrock. At some point, the ancestral Canadian and Pecos river systems appear to have captured most of the drainage, and deposition shifted to wind-driven (eolian) (Gustavson and Winkler 1989). The basic setting of the Ogallala Formation is thought to have been grassy floodplains traversed by east-flowing streams (Schultz 1990a). Volcanic eruptions to the west and northwest occasionally covered the land with ash (Cepeda 2001). The general time frame of the Ogallala Formation included a number of large-scale events with important implications for life. For example, the growth of the Antarctic ice sheet accelerated from 15 Ma, the Panamanian Straits closed between about 13 and 2 Ma, and the Mediterranean Sea desiccated and refilled multiple times between 6 and 5 Ma (Passey et al. 2002). On the Great Plains, C4 grasses became the dominant vegetation (Passey et al. 2002; McInerney et al. 2011; Strömberg and McInerney 2011). Neighboring areas of the Panhandle include a variety of post-Ogallala Formation geologic units not found at AFLM, which is more directly associated with the Canadian River. These formations primarily represent eolian and lake deposits (Gustavson et al. 1991).

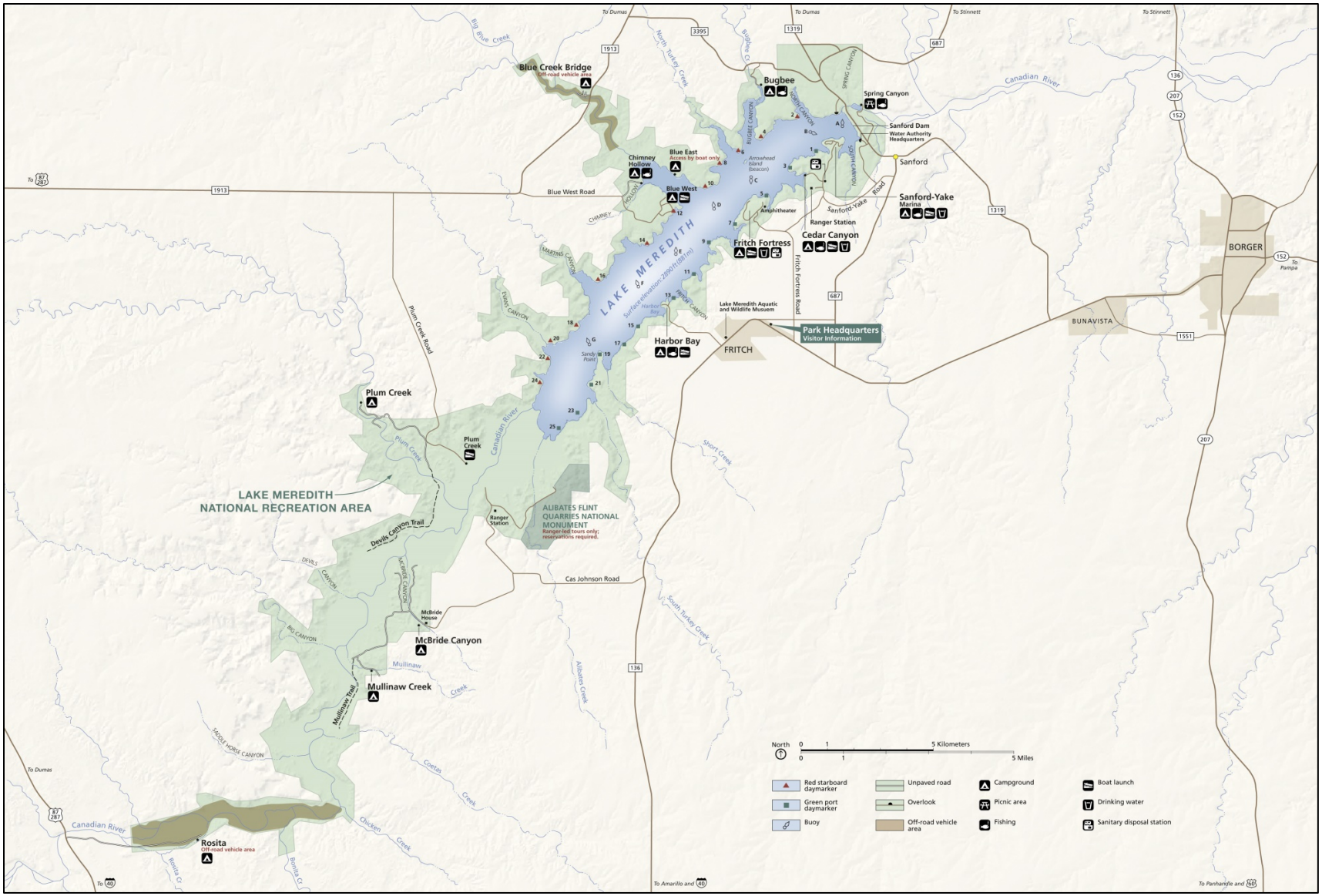
Dissolution of the evaporites in the Permian formations has influenced topography and drainage for millions of years in the Panhandle. Localized dissolution produces voids that can fill with sediments. In some cases, later erosion removes the rock surrounding these filled voids, leaving behind the fill. This results in a structure called a chimney, for its distinctive shape. Examples can be seen at Fritch Fortress and Sanford-Yake Marina (Butler 2001). If dissolution occurs near the surface, a sinkhole can form, which can trap animals and potentially become a source of fossils (Schultz 1990a). Broader dissolution can lead to lakes (Gustavson et al. 1991), although it is probable that most of the Panhandle lakes formed in deflation basins (Anderson and Kirkland 1969). Leaching and alteration of younger rocks probably produced the conditions that resulted in some of the Alibates Dolomite of ALFL becoming chert, and thus eventually being quarried (Bowers 1975).

Humans have been present in the Panhandle for thousands of years. Use of Alibates flint by people of the Clovis and Folsom cultures (Quigg et al. 2011) shows that people have visited the ALFL quarries since about the end of the Pleistocene, around 11,700 years ago. The best-known precontact

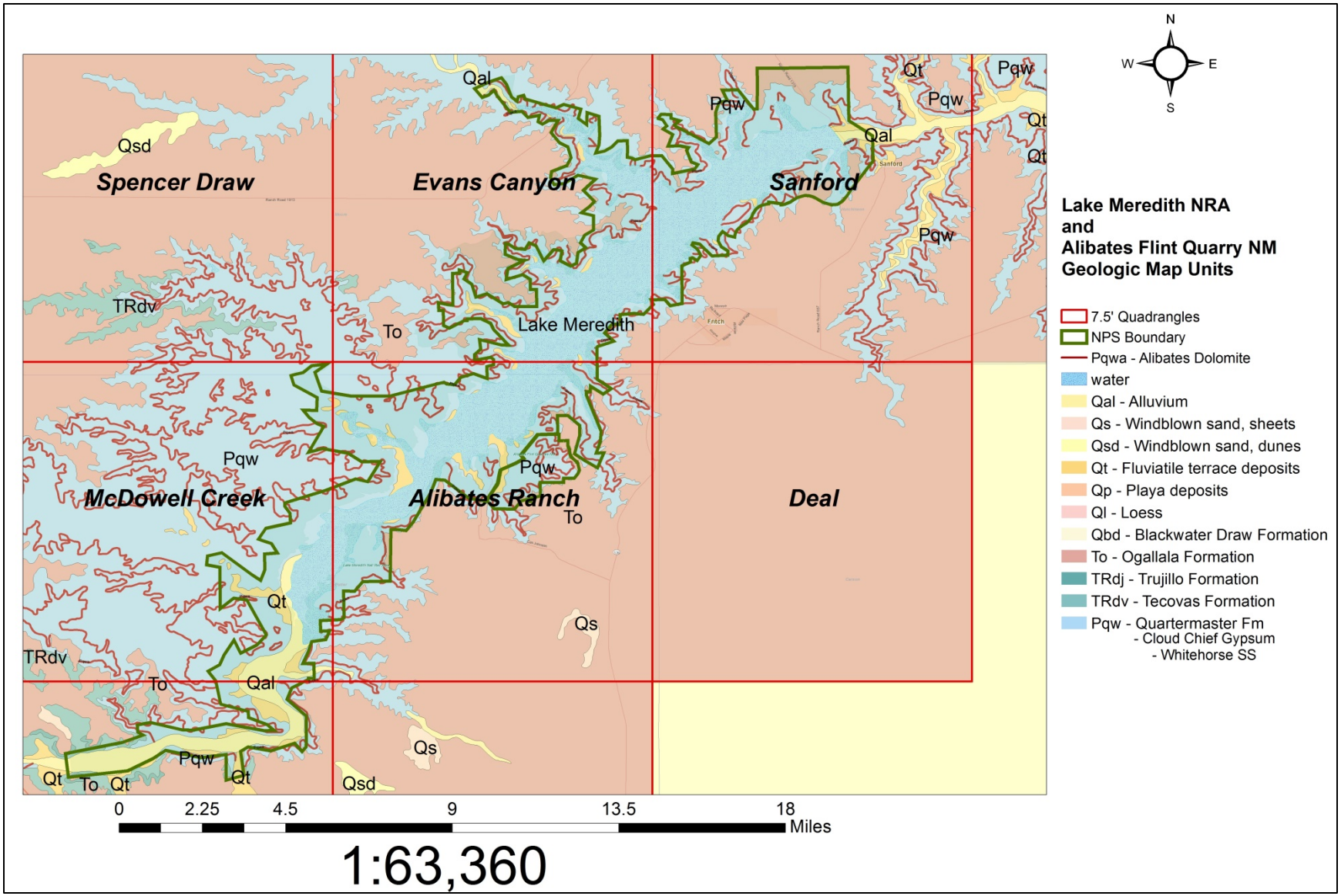
inhabitants of the area are probably the people of the Panhandle Culture, who inhabited the area from about 1200 to 1450 AD (Baerreis and Bryson 1966; Gunnerson 1987).

Several geologic formations are exposed within ALFL and LAMR (AFLM Figure 3). From oldest to youngest, they include: Permian units interpreted here as the Whitehorse Sandstone, Alibates Dolomite, and Quartermaster Formation; the Tecovas and Trujillo formations of the Upper Triassic Dockum Group; the Ogallala Formation (Miocene–Pliocene); and Quaternary sediments (Pleistocene–Holocene) (NPS 2011). Of these formations, the Alibates, Tecovas, and Ogallala formations and the Quaternary sediments are fossiliferous within ALFL or LAMR, and the others have some potential for fossil discovery (AFLM Figure 4, Table 1). Low water levels at other NPS reservoir sites, such as Lake Powell in Glen Canyon National Recreation Area, have exposed fossil sites, but this is less likely for Lake Meredith because the formerly submerged rocks are relatively unfossiliferous.

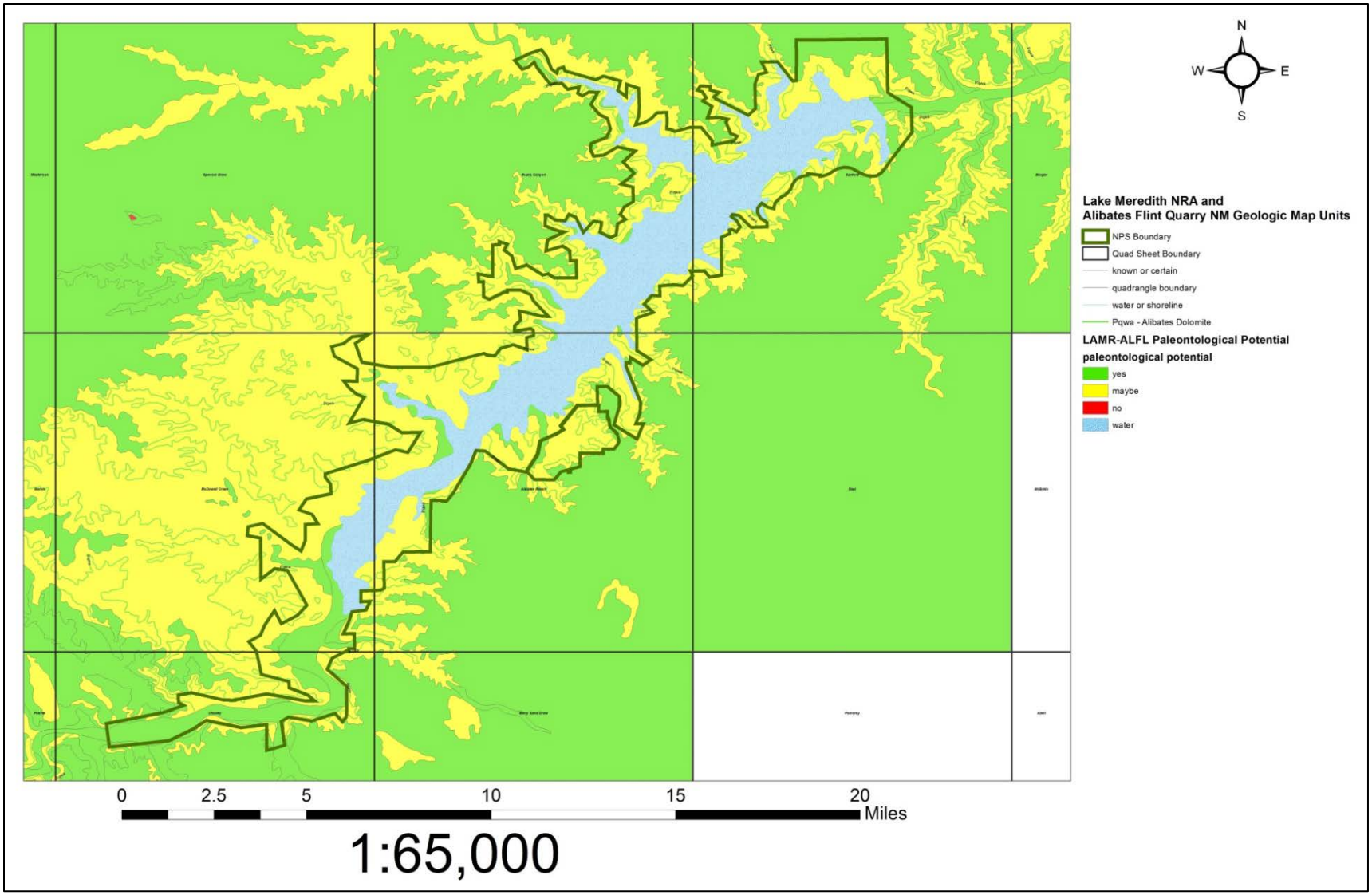
The nomenclature of Permian rocks in the Texas Panhandle has a long and confusing history, and the AFLM area is additionally complex because it encompasses multiple structural regions. Bowers (1975) noted this complexity and opted to use the tripartite division above. Hunt and Santucci (2001) referred to the Quartermaster Formation as the Dewey Lake Formation and included a fourth unit at the base of the column, the Cloud Chief Gypsum, for a prominent gypsum bed. This report does not follow that usage because the Cloud Chief Gypsum is supposed to be above the Whitehorse Sandstone. In some cases it is used as the upper member of the Whitehorse Sandstone (Roth et al. 1941), and in other cases the Alibates Dolomite is itself described as a member of the Cloud Chief Gypsum (Eck and Redfield 1963a,1965), but the Cloud Chief Gypsum has not been described as below any part of the Whitehorse Sandstone.



AFLM Figure 2. Geography of AFLM (NPS). Lake Meredith is presently smaller than depicted.



AFLM Figure 3. Schematic geologic map of AFLM. Lake Meredith presently is smaller than depicted. Map graphic adapted from digital geologic map data available at the following URL: https://irma.nps.gov/App/Reference/Profile/2176370.



AFLM Figure 4. Paleontological potential map of AFLM, showing the distribution of geologic units where fossils have been found and may be found. Lake Meredith presently is smaller than depicted. Map graphic adapted from digital geologic map data available at the following URL: https://irma.nps.gov/App/Reference/Profile/2176370.

AFLM Table 1. Summary of AFLM stratigraphy, fossils, and depositional settings in descending order of age, from youngest to oldest. Details and references can be found in the text.

Formation (*=only in LAMR)	Age	Fossils (LAMR except where noted as ALFL)	Depositional Environment
Quaternary sediments	Pleistocene–Holocene	Middle Pleistocene plant debris and invertebrate burrows; gastropods, a mammoth humerus, a *Bison latifrons* skull, a bison rib fragment (Pleistocene); rodent burrow with charcoal (Pleistocene or Holocene); reworked petrified wood and Cretaceous bivalves (*Texigryphaea*); Numerous late Holocene (Panhandle Aspect or Culture, approximately 1200–1450 AD) archeological sites have been described from ALFL and LAMR. Although quite recent, they include the following: ALFL: bones of turtles, snakes, owls, hawks, ducks, geese, swans, grouse, corvids, rodents, rabbits, canids, bobcats, badgers, deer, pronghorn, cows, and bison LAMR: bony fish, frogs/toads, turtles, snakes, ducks, perching birds, moles, rodents, rabbits, dogs, badgers, deer, pronghorns, and bison	Primarily fluvial and terrace deposits
Ogallala Formation	Middle Miocene–Early Pliocene	Bones of turtles and other vertebrates (ALFL), a proboscidean tooth, and a bonebed with unspecified remains; possibly also root casts, grass anthoecia, *Celtis* endocarps, gastropods, insect burrows, fish impressions, vertebrate material, and reworked Cretaceous bivalves and fossiliferous limestone (provenance unclear)	Fluvial to eolian over time
*Trujillo Formation	Late Triassic	None to date; fragmentary vertebrate fossils are most likely	Fluvial–floodplain
*Tecovas Formation	Late Triassic	Petrified wood; possibly also fragmentary amphibian and reptile fossils (provenance unclear)	Fluvial–floodplain
Quartermaster Formation	late Permian–Early Triassic?	None to date; fossils are generally rare in this formation	Restricted marine to arid continental
Alibates Dolomite	late? Permian	Stromatolites are present on the trail to the ALFL quarries, but it is not stated if they are in ALFL or LAMR	Intertidal to supratidal
Whitehorse Sandstone	late? Permian	None to date; fossils are generally rare in this formation	Restricted marine to arid continental

Sources of Paleontological Resources

The fossils of ALFL and LAMR present opportunities for education, interpretation, and continued or future scientific research in the park areas.

Alibates Dolomite (upper? Permian)

The Alibates Dolomite is typically composed of two beds of dolomite or gypsum separated by red shale (Johnson 1978). In AFLM and the immediate area, all three divisions were originally present, but the upper dolomite bed has often been removed by erosion. The dolomite beds are typically massive white crystalline dolomite with some chert, and fine wavy laminations can be seen on weathered surfaces. The lower bed is close to 3 m (9 ft) thick, and the upper bed is less than 1 m (2 ft) thick. The intervening bed is slightly more than 1 m (4 ft) of red shale and sandstone (Warren

1943). The lower dolomite bed makes a prominent ridge, and the thinner upper bed makes a lesser ridge (Eck and Redfield 1963a). Bowers (1975) treated the three divisions as distinct but informal members. The formation is sometimes correlated to the Day Creek Dolomite (Clifton 1926), a formation named from rocks in southern Kansas.

The Alibates Dolomite is interpreted as having been deposited in saline coastal environments, above or within tidal levels. The overall setting was probably like a modern sabkha, or salt flat. The middle section, lacking dolomite, is more terrestrial than the two dolomite beds, and probably was deposited during a brief marine regression (Bowers 1975). The formation offers little to establish its age, but the overlying Quartermaster Formation includes an ash bed dated to approximately 252 Ma (Tabor et al. 2011), so the Alibates Dolomite must be at least somewhat older. The contacts with the underlying Whitehorse Sandstone and overlying Quartermaster Formation are probably unconformable (Bowers 1975).

The Alibates Dolomite is most noted for its high-quality flint, which was quarried from chert within what is now ALFL. Alibates flint was used by early Paleoindian groups, such as the Clovis and Folsom cultures, and was still being quarried as recently as 500 years ago (Quigg et al. 2011). The quarries today are shallow pits. At least 731 such pits in four or five clusters have been recognized in ALFL, along an outcrop about 1.2 km (0.7 mi) long on the south side of a valley (Quigg et al. 2011). Silicification of the Alibates Dolomite to chert is sporadic, and only two to three percent of the formation is chert. Chert is found in small beads, nodular or pod-like masses, and massive sheets. Beads and nodules are widely distributed, but sheets are found only at ALFL and the Devil's Canyon–Cactus Flats area. In these areas, the thin upper dolomite has been replaced by chert, perhaps over an area as great as 50 km^2 (20 mi^2). The silicification is a secondary feature, and may still be occurring. Most of it is probably due to infiltration of silica from overlying formations, perhaps calichification in the overlying Ogallala Formation that released silica (Bowers 1975). The flint from the ALFL area is regarded as the highest quality. The flint comes in a variety of colors, but most recognized Alibates flint artifacts are red. This may be due to quality, the color preference of the knappers, or the search image of archeologists (Shaeffer 1958). Flint from other local sources (the Dockum Group and reworked cobbles in the Ogallala Formation) can be confused with Alibates flint (Green and Kelley 1960), but at least some of the sources can be distinguished by geochemistry (Quigg et al. 2011). Artifacts of Alibates flint have been reported in several neighboring states, which has led to the interpretation of the flint as a trade object. However, workable cobbles of chert can be found in the Canadian River valley well into western Oklahoma, so some of the distant finds may actually represent locally-sourced eroded cobbles (Wyckoff 1993).

The only fossils reported from the Alibates Dolomite to date are layered microbial mat features such as stromatolites (McGillis and Presley 1981). KellerLynn (2011) reported the presence of stromatolites in the Alibates Dolomite along the trail to the flint quarries; it is not specified whether these were found in ALFL or LAMR, but these trace fossils are likely to be found over wide areas.

Dockum Group: Tecovas Formation (Upper Triassic)

The Tecovas Formation is composed primarily of variegated shale in the AFLM region (Gould 1920; Patton 1923). In Potter County, the Tecovas Formation is about 45 to 60 m (150 to 200 ft) thick, and

composed of varicolored shale and soft gray sandstone. It is thinner or absent in the northeast, where AFLM is located (Patton 1923). Of the two NPS units surrounding Lake Meredith, the Tecovas Formation is only exposed in LAMR, where it is found in the Rosita Flats area at the southwestern end of the recreation area (NPS 2011). The terminology of the Dockum Group has been complicated by long-running mapping and nomenclatural conflicts between geologists in New Mexico and Texas (Lehman 1994; Long and Murry 1995). Depending on the author and citation, the Tecovas Formation may be considered a formation in the Dockum Group, a member in the Dockum Formation, a formation in the Chinle Group, and/or the same or roughly equivalent to the Garita Creek Formation in New Mexico.

A few decades ago the Tecovas and overlying Trujillo formations were interpreted as having been deposited in large lakes, but they are now interpreted as fluvial and alluvial. Drainage flowed from highlands to the south and east to an ocean basin near present-day Nevada (Hunt et al. 2001). The Tecovas Formation is Late Triassic in age (Long and Murry 1995). References to the Carnian part of the Late Triassic (about 235 to 228 Ma) predate a shift in dating; the Tecovas Formation would now be considered within the Norian (about 228 to 208.5 Ma) (Parker 2008). The contact with the Trujillo Formation is generally conformable (Patton 1923).

Petrified wood has been reported from the Tecovas Formation of LAMR (W. Phillips in Hunt and Santucci 2001). Wilson (1988) reported that fossil logs as much as 4 m (13 ft) long and 1 m (3 ft) in diameter were present on the southwest rim of Corral Creek in this formation. Corral Creek, which joins the Canadian River near the far southwestern end of LAMR, is partially within and outside of the recreation area, so it is unclear if these occurrences are within the recreation area. Similarly, Wilson (1988) also reported amphibian and reptile bone fragments from unspecified localities in the LAMR area. Because petrified logs and bone fragments are widely distributed in the Tecovas Formation, it probably is most useful for management to assume that such fossils will eventually be found.

Over its entire depositional area, the Tecovas Formation has yielded a diverse fossil assemblage. Plants are represented by lignite (Patton 1923), spores and pollen, leaf and cuticle fragments, conifer needles, petrified wood (Dunay and Fisher 1979), seeds (Ash 2011), and a few macroscopic fossils identifiable to genera, including the ferns *Clathopteris* and *Phlebopteris*, the cycadeoid *Otozamites*, and possible gnetophyte *Dinophyton* (Dunay and Fisher 1979). Invertebrates are represented by bivalves, gastropods (snails; these once identified as “spirorbid worms”), ostracodes (“seed shrimp”) (Lucas and Luo 1993), and conchostracans (“clam shrimp”) (Kietzke and Lucas 1991). Vertebrates reported from the formation include cartilaginous fish, ray-finned fish, lungfish, metoposaurs (giant extinct amphibians), cynodonts (near-mammals), the near-mammal or early true mammal *Adelobasileus*, extinct lizard-like procolophonids, *Colognathus* (an enigmatic reptile, possibly a procolophonid), extinct herbivorous lizard-like trilophosaurids, sphenodontians (represented today by the tuatara), rhynchosaurs (extinct reptile vaguely resembling a beaked pig crossed with a lizard), extinct crocodile-like phytosaurs, extinct armored herbivorous aetosaurs, rauisuchians (extinct carnivorous reptiles related to crocodilians but appearing somewhat like carnivorous dinosaurs), early crocodile relatives, the dinosaur-mimic *Shuvosaurus* (identified as *Chatterjea*), possible

pterosaurs (extinct flying reptiles), early dinosaurs, and several types of reptiles of uncertain relationships (including forms like *Tecovasaurus*, then thought to be an ornithischian dinosaur) (Long and Murry 1995; Heckert 2004). Finally, trace fossils include possible root casts or burrows (Patton 1923) and vertebrate coprolites (fossil feces) (Heckert 2004). The nearest major finds come from the Rotten Hill/Sierrita de la Cruz Creek area, about 32 km (20 mi) east-southeast of the southwest of LAMR. Metoposaur fossils are particularly abundant. Other groups represented include chondrichthyans, ray-finned fish, sphenodontians, rhynchosaurs, trilophosaurids, phytosaurs, aetosaurs, rauisuchians, and early crocodile relatives (Long and Murry 1995). The best-known fossil sites in the formation are in the Kalgary area of Crosby County, about 240 km (150 mi) south of AFLM (Murry 1989; Long and Murry 1995; Heckert 2004).

The above identifications take into account recent reclassifications, and so will differ with some identifications in the original sources. Because there are many poorly known but clearly distinctive fossil organisms found in the Upper Triassic rocks of North America, identifications often change as additional fossils are discovered and studied, and no doubt some of the above will need to be revised in the future.

Ogallala Formation (Middle Miocene–Lower Pliocene)

The Ogallala Formation (or Group, in some areas) is a widespread sedimentary rock formation deposited during the late Cenozoic from the Dakotas to Texas. In the AFLM area, the formation is conglomeratic and light brown to buff in color, with caliche in some areas; its sand can infiltrate underlying formations (Bowers 1975). Working in Potter County, Patton (1923) divided the post-Triassic, pre-Quaternary beds currently identified as the Ogallala Formation into an overlying Coetas Formation and underlying Potter Formation. The Coetas Formation was 30 to 60 m (100 to 200 ft) thick and composed of slightly consolidated sand with thin beds of limestone near the top. The underlying Potter Formation was 20 to 30 m (70 to 100) of better-consolidated sand and gravel. The Coetas Formation was noted for including abundant vertebrate fossils (Patton 1923). These two terms have generally fallen out of use, or been deemed members or facies of the Ogallala Formation (Schultz 1990a), although Wilson (1988) reused them, with the addition of the informal LX Member. Wilson's scheme divides the Ogallala Formation of the AFLM area into four units, in ascending order the Potter Creek, LX, Coetas, and unnamed upper members. The Potter Creek Member is composed of conglomerate and conglomeratic sandstone, as much as 130 m (430 ft) thick. The LX Member is about 33.5 m (110 ft) of sandstone and silty sandstone. The Coetas Member is about 21.5 m (70.5 ft) of flaggy or sandy limestone and thinly laminated mudstone and siltstone. Finally, the upper member is up to 75 m (250 ft) of sandstone, gravel, and calcrete. This member is capped by up to 10 m (30 ft) of calcrete (Wilson 1988). Much of this thickness is probably not present at AFLM: erosion has removed much of the Ogallala Formation near Lake Meredith (Eck and Redfield 1963a). The unnamed upper member perhaps correlates in part to Patton (1923)'s undifferentiated Quaternary, because of the presence of a caliche bed in both.

Interpretations of the sedimentology of the Ogallala Formation have shifted several times. Initially, the Ogallala Formation was thought to be lacustrine in origin. Later, it was interpreted as fluvial-built alluvial fans, then valley alluviation (Frye and Leonard 1959). More recently, it has been interpreted

as a combination of fluvial deposits at the base, in pre-existing valleys, followed by eolian deposition (Gustavson and Winkler 1989). Diversion of the drainage is thought to have occurred with the appearance of the ancestral Canadian and Pecos rivers (Gustavson and Winkler 1989). Periodically, major volcanic eruptions to the west and northwest would blanket the landscape with ash (Cepeda 2001). The climate is thought to have been subhumid to subtropical initially, followed by cooling and drying. Depositional environments in the Panhandle region include stream channels, floodplains, overbank swamps, and oxbows. East-flowing meandering and braided streams crossed grassy floodplains dotted with marshes and ponds (Schultz 1990a).

The Ogallala Formation of the Panhandle region was deposited during the Miocene and Pliocene. Mammal fossils indicate that it spans the Clarendonian (12.5–9 Ma) and Hemphillian (9–4.7 Ma) North American Land Mammal Ages (NALMAs). In fact, these two NALMAs were named from Ogallala Formation fossil faunas found in the Panhandle (Schultz 1990a). Volcanic ash beds provide more direct age constraints via radiometric dating. In Potter County, there is an ash bed dated to 9.5 Ma along the east bank of West Amarillo Creek, which joins the Canadian River just upstream of LAMR (Cepeda and Perkins 2006). The Ogallala Formation's upper contact with Quaternary sediments is unconformable (Patton 1923).

Hunt and Santucci (2001) reported six fossil occurrences in the AFLM area, three which can be definitely attributed to the NPS lands, and three which have more general localities. The three occurrences definitely within one of the two parks are as follows: a now-lost proboscidean (elephants and relatives) tooth, identified informally as from a mastodon but probably from a gomphothere, was recovered from Cedar Canyon near the eastern end of LAMR during the placing of a restroom pipe; a site with turtle remains and other in situ bones from the southern end of ALFL, reported to the authors by W. Phillips; and a bonebed with unspecified fossils from the Turkey Creek area of LAMR, reported by W. Phillips. The other three occurrences were all reported in Wilson (1988). These occurrences lack detailed locality information and cannot be attributed to either ALFL or LAMR at this time; they are most comparable to the generalized descriptions of formations on geologic maps. In the Potter Creek Member, Wilson noted the presence of bone scraps and reworked Cretaceous bivalves (perhaps *Texigryphaea*) and limestone. In his "LX Member", Wilson noted the presence of root casts, silicified grass anthoecia, *Celtis* (hackberry) endocarps, and insect burrows, with vertebrate remains in the upper 6 to 7 m (20 to 23 ft). Finally, in the Coetas Member, he reported the presence of gastropod molds, imprints of two fish, and vertebrate fossils of Clarendonian age in the thin flaggy upper beds.

An assemblage of Clarendonian fossils has been collected just outside the boundaries of AFLM. This collection has been designated the Coetas Creek local fauna. The earliest reference to these fossils is in Patton (1923), who reported horse teeth in "Coetas Formation" limestone in section 10, G. & M. Block 20, on the west side of Coetas Creek, apparently just outside of LAMR. Several institutions have collected fossils from this area. The University of California Museum of Paleontology collected in the area (Bivins Ranch, V-3103) during the early 1930s, and was followed in the late 1930s by the Frick Laboratory (American Museum of Natural History). West Texas State University collected from this area more recently. The assemblage is mostly undescribed, but includes turtles, tortoises,

shore birds, felids, canids, gomphotheres, horses, rhinoceroses, peccaries, pronghorns, oreodonts (extinct sheep-like camel relatives), and camels (Schultz 1990a). Patton (1923) noted that although fossils were abundant in the "Coetas Formation" of Potter County, they were usually poorly preserved fragments that were difficult to remove. *Celtis* endocarps were also common, although they might be younger specimens buried in burrows dug into the older rocks. The "Potter Formation" included reworked Cretaceous bivalves, but no fossils that represent organisms that lived during the deposition of the sediments (Patton 1923).

Panhandle vertebrate fossils are important for paleontologists studying the Ogallala Formation and Cenozoic life in North America. Notable Ogallala Formation fossil sites are found throughout the Texas Panhandle and adjacent areas of Oklahoma (Schultz 1990a). At family levels, the Clarendonian and Hemphillian faunas are similar, but the genera and species differ. Clarendonian faunas in the Panhandle area include mollusks, gars, toads, turtles, tortoises, snakes, crocodilians, geese, shore birds, rodents, nimravids (false sabre-toothed "cats"), felids, canids, amphicyonids (beardogs), mustelids (weasels and allies), gomphotheres, horses, rhinoceroses, peccaries, a variety of small extinct artiodactyls (such as dromomerycids and protoceratids), moschids (musk deer), pronghorns, oreodonts, and camels (Schultz 1990a). Hemphillian faunas in the Panhandle include gars (Schultz 1990a), salamanders, frogs and toads, tortoises, lizards, snakes (Holman 1973), crocodilians, hawks, ducks, sloths, shrews, moles, rodents, rabbits, bats, nimravids, felids, canids, ursids, procyonids, mustelids, gomphotheres, horses, rhinoceroses, peccaries, a variety of small extinct artiodactyls (such as dromomerycids and gelocids), pronghorns, and camels (Schultz 1990a). Other categories of fossils are also represented in the Ogallala Formation of the Panhandle. Plants are represented by petrified wood (Lee et al. 1975), forbs, grasses (Thomasson 1990), box elder, ash, hackberry, persimmon, sycamore, cottonwood, willow, elm, cattails, and sedges (Schultz 1990a). Trace fossils include root casts, insect burrows (Wilson 1988), avian, felid, canid, ursid, proboscidean, and camelid tracks (Lucas and Schultz 2007). In addition, some beds are diatomaceous (rich in the silica "shells" of diatom "algae") (Schultz 1990a), and reworked Cretaceous bivalves are sometimes found (Patton 1923; Wilson 1988).

Quaternary rocks and sediments (Pleistocene–Holocene)

The Quaternary sediments of AFLM are primarily terrace deposits and alluvium (NPS 2011). These units have produced a variety of paleontological resources, including fossils of extinct Pleistocene megafauna such as mammoths and extinct bison species, and numerous bones from archeological sites. Hunt and Santucci (2001) reported five Pleistocene sites within LAMR, yielding a variety of paleontological resources:

- The only site to have received significant attention in the literature is a locality on the north side of Lake Meredith, east of the boat ramp near Plum Creek, in an inset terrace. In the 1970s, a partial skull of a bison was found here (Anderson 1977; Dalquest and Schultz 1992). The skull (WTSU [West Texas State University] unnumbered) is now in the collections of the Panhandle–Plains Historical Museum in Canyon, Texas. It is interpreted as the skull of a female *Bison latifrons*, an extinct species of giant Pleistocene bison. Complete female skulls of *B. latifrons* are rare; only one other may be known (McDonald 1981). Further

investigation of the site by Anderson (1977) uncovered gastropods, a bison rib fragment, and a rodent burrow with charcoal, the latter potentially a Holocene excavation into the Pleistocene sediment. The bones came from a 2 m (7 ft) thick layer of fine sand and gravel. The gastropods and burrow were found in a lower layer of fine sand, with a 1.5 m (5 ft) thick layer of coarse sand and gravel between the two fossiliferous sands (Anderson 1977).

- A fossil described as a mammoth humerus (upper arm bone) was found and removed from a site in LAMR just west of the ALFL–LAMR boundary. The discovery site is in a cliff of alluvium adjacent to an oil well, part of an inset terrace. The bone was in a 6.5 m (21 ft) thick coarse pebbly sandstone. Above this layer is 2 m (7 ft) of reddish brown conglomerate and below it is 1 m (3 ft) of brown poorly sorted conglomerate. Both conglomerates contained petrified wood and fragments of the "middle" Cretaceous bivalve *Texigryphaea*, reworked from older rocks.

- Along South Canyon on the south side of LAMR, an ash bed produced by an eruption of the Yellowstone caldera can be seen as a 3 m (10 ft) white bed. This ash, identified as the Lava Creek B ash, which erupted about 640,000 years ago (Lanphere et al. 2002), contains plant debris and burrows (apparently crayfish burrows). The shape of the deposit resembles a pond, and there is the potential that it contains common pond fossils such as leaves, pollen, ostracodes, and diatoms. Should such fossils be present, they would be of interest for paleoclimatological and paleoecological studies.

- Pleistocene gravels near the Ogallala Formation proboscidean site mentioned in the Ogallala Formation section contained petrified wood and *Texigryphaea* fragments.

- A chimney at the Eagle's Nest in LAMR, just west of ALFL, yielded a piece of petrified wood. The chimneys of the park areas are potential candidates to yield additional fossils.

The Panhandle is dotted with Quaternary fossil sites. Many of them are found in eolian sediments (Blackwater Draw Formation) and lacustrine deposits (Blanco Formation, Tahoka Formation, etc.) (Gustavson et al. 1991; Hovorka 1995) that have not been found within AFLM (NPS 2011). Although not yet known from the NPS areas, they do shed light on other fossils that may be found in AFLM, as well as the recent prehistoric landscape of the vicinity. Lake deposits have produced green algae, mosses, spores of spikemosses and the gnetale *Ephedra*, conifer pollen, angiosperm pollen and body fossils, bivalves, gastropods, ostracodes, insects, ray-finned fish (Anderson and Kirkland 1969), frogs, salamanders, turtles, snakes (Stephens 1960), lizards (Kasper and Parmley 1988), loons and other water birds, turkeys, wading birds (Johnson and Savage 1955), and various mammals. The mammals that inhabited the region during the late Pliocene and Pleistocene included glyptodonts, sloths, insectivores, rodents, rabbits, bats, bears, bone-crushing and less specialized dogs, hyenas, machairodont (sabre-toothed) and less specialized felids, mustelids, raccoons, proboscideans, horses, peccaries, pronghorns, camels, deer, and bison (Johnson and Savage 1955; Stephens 1960; Schultz 1990b).

Two notable Pleistocene sites have been found just outside of AFLM, as reported by Dalquest and Schultz (1992); their fossils are known as the Sanford-Big Creek and Merchant Ranch local faunas. The Sanford-Big Creek Local Fauna was found at "a roadcut on the north side of Farm-to-Market Road 687, 0.8 km west of Big Creek, approximately 3.2 km north of the town of Sanford in Section 39, Blk. 41, H and TC RR Co. Survey" (Hunt and Santucci 2001). This site has produced at least 12 species of gastropods, fish, frogs, snakes, four species of rodents, coyotes, foxes, horses, camel, and deer (Dalquest and Schultz 1992). The Merchant Ranch Local Fauna was found "120 m south of Farm-to-Market Road 687 in the banks of a tributary of Big Creek, 1.6 km north of the Canadian River, 3.2 km north of Sanford in Section 39, Blk. 46, H and TC RR Co. Survey" (Hunt and Santucci 2001). This site has produced fossils of three rodent species and a horse, and a partial mammoth skeleton (Dalquest and Schultz 1992).

In addition to the Pleistocene sites, there are several Panhandle Aspect (1200 to 1450 AD) archeological sites in AFLM that include remains of contemporaneous fauna (Duffield 1964, 1970; Hunt and Santucci 2001). Because of their recent occurrence, they would usually be omitted in a discussion of paleontology, but are included here as evidence of past life. The sites include:

- Alibates 28, on the edge of the bluffs overlooking Alibates Creek Canyon within ALFL, was excavated from 1938 to 1941 by Works Progress Administration workers. This site included remains of turtles, snakes, owls, hawks, ducks, geese, swans, grouse, corvids, rodents, rabbits, canids, bobcats, badgers, deer, pronghorn, cows, and bison.

- Sanford Ruin, on the promontory that now forms the south end of Sanford Dam within LAMR, was excavated in 1953 by the Panhandle–Plains Historical Museum. Remains of frogs and/or toads, turtles, rodents, rabbit, possible deer, pronghorn, and bison were found here.

- The Roper Site, west-northwest of Sanford on the south side of South Canyon within LAMR, was excavated in 1957 by the Panhandle–Plains Historical Museum and the Norpan Archeological Society. Remains of birds, turtles, moles, rodents, rabbits, deer, pronghorn, and bison were found here.

- Pickett Ruin, on the east side of the promontory now on the south end of Sanford Dam within LAMR, was excavated in 1958 by the Panhandle–Plains Historical Museum and the Norpan Archeological Society. Remains of turtles, pronghorn, and bison were found here.

- The Medford Ranch site, on the west fork of Spring Canyon within LAMR, was excavated in 1961 as part of the Texas Archeological Salvage Project, a joint University of Texas–National Park Service project to salvage sites in the area affected by the proposed Sanford reservoir. Remains of turtles, birds, rodent, rabbit, deer, pronghorn, and bison were found here.

- The Spring Canyon site, on the east side of Spring Canyon within LAMR, was also excavated in 1961 by the Texas Archeological Salvage Project. Remains of bony fish, turtles,

snake, duck, perching birds, rodents, rabbits, dog, badger, deer, pronghorn, and bison were found here.

Potential Sources of Paleontological Resources

Fossils have not yet been documented from the following rock units within ALFL or LAMR. However, they are known to preserve fossils elsewhere, and future field investigations within the park areas may result in the discovery of fossils from one or more of these units.

Whitehorse Sandstone (upper? Permian)

The Whitehorse Sandstone is a slope-forming red bed unit. Generally only a few meters are exposed in AFLM, but more than 45 m (150 ft) can be seen at Harbor Bay (Bowers 1975). It is composed of a mix of lithologies, including sandstone, shale, sandy shale, gypsum beds, and fossiliferous sandstone beds (Clifton 1930). At AFLM, it is mostly red to brown mudstone and silty sandstone, with some meter-scale beds of white gypsum and more resistant red sandstone. Near the contact with the overlying Alibates Formation, it can become gypsum- or lime-rich, and the uppermost 10 to 50 cm (4 to 20 in) are commonly green and gray mudstone (Bowers 1975). Two of the gypsum beds are sometimes identified as the Saddlehorse Member (Eck and Redfield 1963a). As noted by Bowers (1975) and Hunt and Santucci (2001), the terminology can be quite confusing, and in the interests of space, relevance, and clarity, a detailed investigation of the nomenclature is omitted. Occasionally the Whitehorse Sandstone is known as the Salado-Tansill Formation (McGillis and Presley 1981), and it can be mistaken for the Quartermaster Formation (Clifton 1926; Bowers 1975). Other investigators have raised the Whitehorse to a group and included the Quartermaster and Alibates formations as members (Nicholson 1960).

The Whitehorse Sandstone was deposited in marine to arid continental settings (Clifton 1926). The depositional conditions are inferred to have been harsh to life, given the quantities of gypsum, anhydrite, and salt, which point to sustained periods of evaporation (Newell 1940). It is regarded as a Permian formation, although as with the Alibates Dolomite there is little internal evidence to provide a more narrow range of dates.

Overall, the Whitehorse Sandstone is poorly fossiliferous, and is not known to be fossiliferous in AFLM. Fossils of marine invertebrates are present in the upper part of the formation, in so-called “channel sands” or “shoestring sands”, confined lenses or bodies of cross-bedded sandy dolomite or dolomitic sandstone. The assemblages are dominated by molds of bivalves and gastropods, with smaller numbers of bryozoans (“moss animals”), brachiopods (“lamp shells”), rostroconchs (extinct bivalve-like mollusks), scaphopods (“tusk shells”), and microconchids (probably something like a coiled tube worm; these originally described as spirorbids). The sand bodies were originally interpreted as channel fills of drowned stream valleys with transported fossils, but are more likely offshore barrier bars. It is possible that lagoonal areas behind the bars were more hospitable to life, with freshwater input from the land mitigating the otherwise strongly saline waters (Newell 1940).

Quartermaster Formation (upper Permian–Lower Triassic?)

The Quartermaster Formation is another redbed unit. In the AFLM area, it is quite similar to the Whitehorse Sandstone. The thickest section in the area is at Bugbee Creek, where about 7 m (23 ft)

are present. At this site it is composed of maroon mudstone and silty sandstone (Bowers 1975). As with the other Permian formations, the nomenclature of the Quartermaster interval has frequently changed. The rocks are also sometimes called the Doxey Shale (Johnson 1978) or Dewey Lake Formation (McGillis and Presley 1981; Hunt and Santucci 2001). At one time, the rocks were called the Pierce Canyon redbeds, until it became clear that the actual Pierce Canyon redbeds were Pliocene and Pleistocene in age (Lucas and Anderson 1994).

Because of its similarity to the Whitehorse Sandstone, the Quartermaster Formation was probably deposited in similar settings under similar conditions. However, there historically has been difficulty arriving at a consensus. Most interpretations converge on arid and evaporitic settings, along the lines of restricted hypersaline water bodies and shorelines with fluvial and deltaic input (Fracasso and Kolker 1985). Recent interpretations have emphasized terrestrial processes, such as meandering channels (Tabor et al. 2011) and floodplains (Kirchholtes et al. 2013). There is also a volcanic ash component (Kirchholtes et al. 2013). The Quartermaster Formation was deposited near the end of the Permian, and probably spans the Permian–Triassic boundary. Ash in the lower Quartermaster Formation has been dated to 252.2 ± 0.6 Ma and 252.3 ± 0.6 Ma (Tabor et al. 2011), more or less the same as the modern date for the end of the Permian (252.2 Ma). The contact with the overlying Tecovas Formation is unconformable (Patton 1923).

Few fossils have been reported from the Quartermaster Formation, and none are known from AFLM. Fossils include petrified wood and phytoliths (Looy et al. 2011), bivalves and gastropods in a thin dolomite bed near the base of the formation, and invertebrate burrows in shales below (Roth et al. 1941). The mollusks are similar to those of the Whitehorse Sandstone (Roth et al. 1941). Patton (1923) reported some possible burrows in Potter County, but no other fossils.

Dockum Group: Trujillo Formation (Upper Triassic)

The Trujillo Formation is similar to the underlying Tecovas Formation but is more coarse overall. In Potter County, the Trujillo Formation is primarily composed of sandstone and conglomerate, and is 6 to 8 m (20 to 25 ft) thick. As with the Tecovas Formation, it is thinner or absent in the northeast part of the county (Patton 1923). South of the AFLM area, it often appears as two or three ledges of conglomeratic sandstone separated by beds of dark red shale (Gould 1920), but closer to the NPS areas only one ledge is usually present, due either to consolidation or pre-Ogallala erosion (Patton 1923). For AFLM, the Trujillo Formation is only exposed in a few valleys in the Rosita Flats area, at the southwestern end of LAMR (NPS 2011).

Like the Tecovas Formation, the Trujillo Formation is dominantly fluvial in origin. There are also rocks deposited in floodplains and lakes (Lucas and Spielmann 2010). It is Late Triassic in age (Long and Murry 1995). The contact with the overlying Ogallala Formation is unconformable (Patton 1923).

No fossils have yet been reported from the Trujillo Formation at LAMR, and overall the formation is not as fossiliferous as the underlying Tecovas Formation. Plants are represented by spores and pollen, conifer needles, petrified wood (Dunay and Fisher 1979), the enigmatic angiosperm-like plant *Sanmiguelia* (Ash 1976), the ferns *Phlebopteris* and *Todites*, the horsetail *Neocalamites*, and the

cycadeoid *Otozamites* (Lucas and Spielmann 2010). Some plants have been affected by the tree fungus *Polyporites* (Hunt 2001). Invertebrates are represented by bivalves (Hunt 2001). Vertebrates include ray-finned fish, coelacanths, metoposaurs, the trilophosaurs *Spinosuchus* and *Trilophosaurus*, phytosaurs, rauisuchians, aetosaurs, various indeterminate reptiles (including some similar to dinosaurs), and vertebrate coprolites (Hunt 2001; Heckert et al. 2006). The nearest major fossil sites are south of Amarillo, in the Palo Duro Canyon system (Murry 1989; Long and Murry 1995; Hunt 2001).

Park Collections

Hunt and Santucci (2001) noted that many vertebrate specimens found in archeological contexts, principally bison bones, are in the collections of LAMR. The Panhandle–Plains Historical Museum, part of West Texas A&M University (formerly West Texas State University) in Canyon, Texas, houses both Pleistocene and Holocene material from AFLM, most notably the *Bison latifrons* skull (Hunt and Santucci 2001).

Cultural Resources Connections

In addition to the examples of faunal remains at archeological sites discussed under "Quaternary rocks and sediments", the dolomite beds of the Alibates Dolomite are probably at least in part microbial in origin (the "cryptalgalaminite" of Bowers [1975]), which would imply that at least some portion of the flint is distantly derived from fossils, an interesting potential cultural–paleontological connection. It is not unusual to find artifacts made from fossiliferous material or directly from fossils. Fossiliferous flint has been used for artifacts elsewhere, such as the Knife River Flint, derived from silicified peat (Hoganson and Murphy 2003). In the Southwest, petrified wood from the Chinle Formation (broadly equivalent in age to the Dockum Group) was often used for artifacts; the majority of parks in the neighboring Southern Colorado Plateau Network have examples (Tweet et al. 2009). It may be of interest to find if there is some way to establish how much, if any, of the Alibates flint derives from ~250-million-year-old microbial mats. Kenworthy and Santucci (2006) presented an overview and cited selected examples of National Park Service fossils found in cultural resource contexts.

Paleontological Resource Management, Preliminary Recommendations

- Staff should be encouraged to observe exposed rocks and sedimentary deposits for fossil material while conducting their usual duties. To promote this, staff should also receive guidance regarding how to recognize common local fossils. When opportunities arise to observe paleontological resources in the field and take part in paleontological field studies with trained paleontologists, staff should take advantage of them, if funding and time permit.

- Staff should photodocument and monitor any occurrences of paleontological resources that may be observed in situ. Fossils and their associated geologic context (surrounding rock) should be documented but left in place unless they are subject to imminent degradation by artificially accelerated natural processes or direct human impacts. A Geologic Resource Monitoring Manual by the Geological Society of America and NPS Geologic Resources Division includes a section on paleontological resource monitoring (Santucci et al. 2009). Santucci and Koch (2003) present information on paleontologic resource monitoring.

Santucci et al. (2001) discuss paleontological management with regard to oil and gas production at AFLM.

- Fossils found in a cultural context should be documented like other fossils, but will also require the input of an archeologist or a cultural resource specialist. Any fossil which has a cultural context may be culturally sensitive as well (e.g., subject to NAGPRA) and should be regarded as such until otherwise established. The Geologic Resources Division can coordinate additional documentation/research of such material.

- Contact the NPS Geologic Resources Division for technical assistance with paleontological resource management issues.

References Cited

Anderson, B. A. 1977. Overview of bison remains from the Plum Creek area, Lake Meredith Recreation Area, Texas. Southwest Cultural Resources Center, Santa Fe, New Mexico. Unpublished report on file at Lake Meredith National Recreation Area.

Anderson, R. Y., and D. W. Kirkland, editors. 1969. Paleoecology of an early Pleistocene lake on the High Plains of Texas. Geological Society of America, Boulder, Colorado. Memoir 113.

Ash, S. R. 1976. Occurrence of the controversial plant fossil *Sanmiguelia* in the upper Triassic of Texas. Journal of Paleontology 50(5):799–804.

Ash, S. R. 2011. Anomalous occurrence of the Gondwanan winged seed *Fraxinopsis* in a new Late Triassic (Norian) flora from West Texas, USA. Review of Palaeobotany and Palynology 166(1–2):94–106.

Baerreis, D. A., and R. A. Bryson. 1966. Dating the Panhandle aspect cultures. Bulletin of the Oklahoma Anthropological Society 14:105–116.

Bock, R. W., and C. O. Crane. 1963. Design and construction of Sanford Dam. Pages 46–53 *in* Alibates Flint Quarries, Alibates Indian ruin, Santa Fe Trail, Sanford Dam, field trip, September 14, 1963. Panhandle Geological Society, Amarillo, Texas.

Bowers, R. L. 1975. Petrography and petrogenesis of the Alibates dolomite and chert (Permian) northern Panhandle of Texas. Thesis. University of Texas at Arlington, Arlington, Texas.

Bowers, R. L., and D. F. Reaser. 1974. Local chert occurrence in Alibates Dolomite, Alibates National Monument and vicinity, northern Panhandle of Texas. Abstracts with Programs - Geological Society of America 6(2):96–97.

Bryan, K. 1950. Flint quarries—the sources of tools and, at the same time, the factories of the American Indian, with a consideration of the theory of the “blank” and some of the technique of flint utilization. Papers of the Peabody Museum, Harvard University 17(3).

Butler, E. 2001. Lake Meredith National Recreation Area. Fritch, Texas.

Cepeda, J. C. 2001. A 10 Ma silicic fallout tuff in the Texas Panhandle: comparisons with the Pearlette Ash. Abstracts with Programs - Geological Society of America 33(6):397.

Cepeda, J. C., and M. E. Perkins. 2006. A 10 million year old ash deposit in the Ogallala Formation of the Texas Panhandle. Texas Journal of Science 58(1):3–12.

Clifton, R. L. 1926. Stratigraphy of the Whitehorse sandstone: formation extends from Clarke County, Kansas, through Oklahoma and into Panhandle area of Texas. Oil & Gas Journal 25(2):70–74.

Clifton, R. L. 1930. Permian structure and stratigraphy of northwestern Oklahoma and adjacent areas. Bulletin of the American Association of Petroleum Geologists 14(2):161–173.

Dalquest, W. W., and G. E. Schultz. 1992. Ice Age mammals of northwestern Texas. Midwestern State University Press, Wichita Falls, Texas.

Duffield, L. F. 1964. Three Panhandle Aspect sites at Sanford Reservoir, Hutchinson County, Texas. Bulletin of the Texas Archeological Society 35:19–81.

Duffield, L. F. 1970. Some Panhandle Aspect sites: their vertebrates and paleoecology. Dissertation. University of Wisconsin, Madison, Wisconsin.

Dunay, R. E., and M. J. Fisher. 1979. Palynology of the Dockum Group (Upper Triassic), Texas, U.S.A. Review of Palaeobotany and Palynology 28(1):61–92.

Eck, W., and R. C. Redfield. 1963a. Geology of Sanford Dam, Borger, Texas. Pages 54–57 *in* Alibates Flint Quarries, Alibates Indian ruin, Santa Fe Trail, Sanford Dam, field trip, September 14, 1963. Panhandle Geological Society, Amarillo, Texas.

Eck, W. J., and R. C. Redfield. 1963b. Geology of Sanford Damsite, Borger, Texas. Page 143 *in* Abstracts for 1962. Geological Society of America, Boulder, Colorado. Special Paper 73.

Eck, W., and R. C. Redfield. 1965. Engineering geology problems at Sanford Dam, Borger, Texas. Bulletin of the Association of Engineering Geologists 2(1):15–25.

Fracasso, M. A., and A. Kolker. 1985. Late Permian volcanic ash beds in the Quartermaster–Dewey Lake formations, Texas Panhandle. West Texas Geological Society Bulletin 24(6):5–10.

Frye, J. C., and A. B. Leonard. 1959. Correlation of the Ogallala Formation (Neogene) in western Texas with type localities in Nebraska. Bureau of Economic Geology, University of Texas at Austin, Austin, Texas. Report of Investigations 39.

Gould, C. N. 1920. Preliminary notes on the geology and structure of the Amarillo region. Bulletin of the American Association of Petroleum Geologists 4(3):269–275.

Green, F. E., and J. H. Kelley. 1960. Comments on Alibates flint. American Antiquity 25(3):413–414.

Gunnerson, J. H. 1987. Archaeology of the High Plains. United States Forest Service, Denver, Colorado.

Gustavson, T. C., and D. A. Winkler. 1988. Depositional facies of the Miocene–Pliocene Ogallala Formation, northwestern Texas and eastern New Mexico. Geology 16(3):203–206.

Gustavson, T. C., R. W. Baumgardner, Jr., S. C. Caran, V. T. Holliday, H. H. Mehnert, J. M. O'Neill, and C. C. Reeves, Jr. 1991. Quaternary geology of the Southern Great Plains and an adjacent segment of the Rolling Plains. Pages 477–502 *in* R. B. Morrison, editor. Quaternary nonglacial geology, conterminous U.S. Geological Society of America, Boulder, Colorado. The geology of North America K-2.

Heckert, A. B. 2004. Late Triassic microvertebrates from the lower Chinle Group (Otischalkian-Adamanian, Carnian), southwestern U.S.A. New Mexico Museum of Natural History and Science Bulletin 27.

Heckert, A. B., S. G. Lucas, L. F. Rinehart, J. A. Spielmann, A. P. Hunt, and R. Kahle. 2006. Revision of the archosauromorph reptile *Trilophosaurus*, with a description of the first skull of *Trilophosaurus jacobsi*, from the Upper Triassic Chinle Group, West Texas, USA. Palaeontology 49(3):621–640.

Hoganson, J. W., and E. C. Murphy. 2003. Geology of the Lewis & Clark Trail in North Dakota. Mountain Press Publishing Company, Missoula, Montana.

Holman, J. A. 1973. A new Pliocene snake, genus *Elaphe*, from Oklahoma. Copeia 1973(3):574–580.

Horn, P. 1963. Geology and topography of Alibates Flint Quarries. Page 30 *in* Alibates Flint Quarries, Alibates Indian ruin, Santa Fe Trail, Sanford Dam, field trip, September 14, 1963. Panhandle Geological Society, Amarillo, Texas.

Hovorka, S. D. 1995. Quaternary evolution of playa lakes on the Southern High Plains: a case study from the Amarillo area, Texas. Bureau of Economic Geology, University of Texas at Austin, Austin, Texas. Report of Investigations 236.

Hunt, A. P. 2000. Preliminary assessment of the paleontological resources of Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument. Unpublished National Park Service report.

Hunt, A. P. 2001. Paleontology and age of the Upper Triassic Trujillo Formation, east-central New Mexico and West Texas. Pages 3–4 *in* S. G. Lucas and D. S. Ulmer-Scholle, editors. Geology of the Llano Estacado. New Mexico Geological Society, Socorro, New Mexico. Guidebook 52.

Hunt, A. P. and V. L. Santucci. 2001. Paleontological resources of Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument, west Texas. Pages 257–264 *in*

S. G. Lucas and D. S. Scholle, editors. Geology of the Llano Estacado. New Mexico Geological Society, Socorro, New Mexico. Guidebook 52.

Hunt, A. P., S. G. Lucas, and A. B. Heckert. 2001. Paleocurrents in the Trujillo Formation (Chinle Group: Upper Triassic), east-central New Mexico, and the myth of the Dockum Lake. Pages 22–23 *in* S. G. Lucas and D. S. Ulmer-Scholle, editors. Geology of the Llano Estacado. New Mexico Geological Society, Socorro, New Mexico. Guidebook 52.

Johnson, K. S. 1978. Stratigraphy and mineral resources of Guadalupian and Ochoan rocks in the Texas Panhandle and western Oklahoma. Pages 57–62 *in* G. S. Austin, compiler. Geology and mineral deposits of Ochoan rocks in Delaware Basin and adjacent areas. New Mexico Bureau of Geology & Mineral Resources, Socorro, New Mexico. Circular 159.

Johnston, C. S., and D. E. Savage. 1955. A survey of various Late Cenozoic vertebrate faunas of the Panhandle of Texas. Part I. Introduction, description of localities, preliminary faunal lists. University of California Publications in Geological Sciences 31:27–50.

Kasper, S., and D. Parmley. 1990. A late Pleistocene herpetofauna from the lower Texas Panhandle. Texas Journal of Science 42(3):289–294.

KellerLynn, K. 2011. Geologic resources inventory scoping summary: Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument, Texas. National Park Service, Geologic Resources Division, Denver, Colorado. Available at http://www.nature.nps.gov/geology/inventory/publications/reports/LAMR_ALFL_GRI_scoping_summary_2011-0919.pdf (accessed December 2014).

Kenworthy, J. P., and V. L. Santucci. 2006. A preliminary investigation of National Park Service paleontological resources in cultural resource contexts, Part 1: general overview. New Mexico Museum of Natural History and Science Bulletin 34:70–76. Available at http://nature.nps.gov/geology/paleontology/pub/fossil_conference_7/9%20Kenworthy.pdf (accessed December 2014).

Kietzke, K. K., and S. G. Lucas. 1991. Ostracoda from the Upper Triassic (Carnian) Tecovas Formation near Kalgary, Crosby County, Texas. Texas Journal of Science 43(2):191–197.

Kirchholtes, R. P. J., C. V. Looy, G. H. Mack, T. B. van Hoof, and N. J. Tabor. 2013. Paleozoic phytoliths: old microfossils, new tools. New Mexico Museum of Natural History and Science Bulletin 60:174.

Koch, A. L., and V. L. Santucci. 2003a. Alibates Flint Quarries National Monument. Pages 2–4 in A. L. Koch and V. L. Santucci. Paleontological resource inventory and monitoring: Southern Plains Network. TIC# D-107. National Park Service, Denver, Colorado.

Koch, A. L., and V. L. Santucci. 2003b. Lake Meredith National Recreation Area. Pages 16–18 in A. L. Koch and V. L. Santucci. Paleontological resource inventory and monitoring: Southern Plains Network. TIC# D-107. National Park Service, Denver, Colorado.

Lanphere, M. A., D. E. Champion, R. L. Christiansen, G. A. Izett, and J. D. Obradovich. 2002. Revised ages for tuffs of the Yellowstone Plateau volcanic field: assignment of the Huckleberry Ridge Tuff to a new geomagnetic polarity event. Geological Society of America Bulletin 114(5):559-568.

Lee, M. R., R. A. Gastaldo, and L. C. Matten. 1975. A preliminary report on petrified wood from the Ogallala Formation of northwest Oklahoma. Abstracts with Programs - Geological Society of America 7(2):182–183.

Lehman, T. M. 1994. The saga of the Dockum Group and the case of the Texas/New Mexico boundary fault. Pages 37–51 *in* J. Ahlen, J. Peterson, and A. L. Bowsher, editors. Geologic activities in the 90s: Southwest Section of AAPG 1994, Ruidoso, New Mexico, hosted by the Roswell Geological Society. New Mexico Bureau of Geology & Mineral Resources, Socorro, New Mexico. Bulletin 150.

Long, R. A., and P. A. Murry. 1995. Late Triassic (Carnian and Norian) tetrapods from the southwestern United States. New Mexico Museum of Natural History and Science Bulletin 4.

Looy, C. V., R. P. J. Kirchholtes, G. H. Mack, T. B. van Hoof, and N. J. Tabor. 2011. "Ochoan" Quartermaster Formation of North Texas, USA: Part III, First sign of plant life. Abstracts with Programs - Geological Society of America 43(5):383.

Lucas, S. G., and O. J. Anderson. 1994. Ochoan (Late Permian) stratigraphy and chronology, southeastern New Mexico and West Texas. Pages 29–36 *in* J. Ahlen, J. Peterson, and A. L. Bowsher, editors. Geologic activities in the 90s: Southwest Section of AAPG 1994, Ruidoso, New Mexico, hosted by the Roswell Geological Society. New Mexico Bureau of Geology & Mineral Resources, Socorro, New Mexico. Bulletin 150.

Lucas, S. G., and Luo Z. 1993. *Adelobasileus* from the Upper Triassic of West Texas: the oldest mammal. Journal of Vertebrate Paleontology 13(3):309–334.

Lucas, S. G., and G. E. Schultz. 2007. Miocene vertebrate footprints from the Texas Panhandle. New Mexico Museum of Natural History and Science Bulletin 42:177–183.

Lucas, S. G., and J. A. Spielmann. 2010. Exceptionally preserved paleoflora from the Upper Triassic Chinle Group, Santa Fe County, New Mexico. New Mexico Geology 32(2):66.

Lynn, A. R. 1975. Slope and shoreline modification at Lake Meredith in the Texas Panhandle. Thesis. West Texas University, Canyon, Texas.

McDonald, J. N. 1981. North American bison: their classification and evolution. University of California Press, Berkeley, California.

McGillis, K. A., and M. W. Presley. 1981. Tansill, Salado, and Alibates formations: Upper Permian evaporite/carbonate strata of the Texas Panhandle. Bureau of Economic Geology, University of Texas at Austin, Austin, Texas. Geological Circular 81-8.

McInerney, F. A., C. A. E. Strömberg, and J. W. C. White. 2011. The Neogene transition from C_3 to C_4 grasslands in North America: stable carbon isotope ratios of fossil phytoliths. Paleobiology 37(1):23–49.

Murry, P. A. 1989. Geology and paleontology of the Dockum Formation (Upper Triassic), west Texas and eastern New Mexico. Pages 102–144 *in* S. G. Lucas and A. P. Hunt, editors. Dawn of the age of dinosaurs in the American southwest. New Mexico Museum of Natural History, Albuquerque, New Mexico.

National Park Service (NPS), Geologic Resources Inventory Program. 2011. Unpublished Digital Geologic Map of Alibates Flint Quarries National Monument and Lake Meredith National Recreation Area and vicinity, Texas (NPS, GRD, GRI, ALFL, LAMR, AFLM digital map) adapted from Texas Water Development Board (2007) and University of Texas at Austin data. NPS Geologic Resources Inventory Program. Lakewood, Colorado. Geospatial Dataset-2176370. Available at https://irma.nps.gov/App/Reference/Profile/2176370 (accessed December 2014).

Newell, N. D. 1940. Invertebrate fauna of the late Permian Whitehorse sandstone. Geological Society of America Bulletin 51(2):261–335.

Nicholson, J. H. 1960. Geology of the Texas Panhandle. University of Texas at Austin, Austin, Texas. Publication 6017:51–64.

Parker, W. G., M. R. Stocker, and R. B. Irmis. 2008. A new desmatosuchine aetosaur (Archosauria, Suchia) from the Upper Triassic Tecovas Formation (Dockum Group) of Texas. Journal of Vertebrate Paleontology 28(3):692–701.

Passey, B. H., T. E. Cerling, M. E. Perkins, M. R. Voorhies, J. M. Harris, and S. T. Tucker. 2002. Environmental change in the Great Plains: an isotopic record from fossil horses. Journal of Geology 110(2):123–140.

Patton, L. T. 1923. The geology of Potter County. University of Texas Bulletin 2330.

Quigg, J. M., M. T. Boulanger, and M. D. Glascock. 2011. Geochemical characterization of Tecovas and Alibates source samples. Plains Anthropologist 56(219):121–141.

Roth, R. I., N. D. Newell, and B. H. Burma. 1941. Permian pelecypods in the lower Quartermaster Formation, Texas. Journal of Paleontology 15(3):312–317. Available at http://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1324&context=geosciencefacpub (accessed January 2015).

Sansom, J. W., Jr., and D. H. Shurbet. 1981. Microearthquake studies in Texas. Proceedings of the Annual Highway Geology Symposium 31:57–63.

Sansom, J. W., Jr., and D. H. Shurbet. 1983. Microearthquake studies in Texas. Bulletin of the Association of Engineering Geologists 20(3):267–269.

Santucci, V. L., and A. L. Koch. 2003. Paleontological resource monitoring strategies for the National Park Service. Park Science 22(1):22–25. Available at http://www.nature.nps.gov/ParkScience/archive/PDF/ParkScience22%281%29Fall2003.pdf (accessed January 2015).

Santucci, V. L., A. P. Hunt, and L. Norby, 2001. Oil/gas management planning and the protection of paleontological resources. Park Science 21(1):36–38. Available at http://www.nature.nps.gov/ParkScience/archive/PDF/ParkScience21%281%29FallWinter2001.pdf (accessed December 2014).

Santucci, V. L., J. P. Kenworthy, and A. L. Mims. 2009. Monitoring in situ paleontological resources. Pages 189–204 *in* R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado.

Schultz, G. E. 1990a. Clarendonian and Hemphillian vertebrate faunas from the Ogallala Formation (late Miocene-early Pliocene) of the Texas Panhandle and adjacent Oklahoma. Pages 56–97 *in* T. C. Gustavson, editor. Geologic framework and regional hydrology: Upper Cenozoic Blackwater Draw and Ogallala formations, Great Plains. Bureau of Economic Geology, University of Texas at Austin, Austin, Texas.

Schultz, G. E. 1990b. Stop 5: Blanco Local Fauna and the Blancan Land Mammal Age. Pages 44–51 *in* T. C. Gustavson, editor. Tertiary and Quaternary stratigraphy and vertebrate paleontology of parts of northwestern Texas and eastern New Mexico. Bureau of Economic Geology, University of Texas at Austin, Austin, Texas. Guidebook 24. Available at http://www.lib.utexas.edu/books/landscapes/detail.php?work_id=288461 (accessed December 2014).

Sellards, E. H. 1937. Borger (Texas) earthquake of June 19, 1936. Proceedings of the Geological Society of America for 1936:100.

Sellards, E. H. 1939. The Borger, Texas, earthquake of June 19, 1936. Bureau of Economic Geology, University of Texas at Austin, Austin, Texas. Publication 3945:699–704.

Shaeffer, J. B. 1958. The Alibates flint quarry, Texas. American Antiquity 24(2):189–191.

Shaeffer, J. B. 1963. The Alibates Flint Quarry, Texas. Pages 32–36 *in* Alibates Flint Quarries, Alibates Indian ruin, Santa Fe Trail, Sanford Dam, field trip, September 14, 1963. Panhandle Geological Society, Amarillo, Texas.

Shurbet, D. H. 1969. Increased seismicity in Texas. Texas Journal of Science 21(1):37–41.

Stephens, J. J. 1960. Stratigraphy and paleontology of a late Pleistocene basin, Harper County, Oklahoma. Geological Society of America Bulletin 71(11):1675–1702.

Strömberg, C. A. E., and F. A. McInerney. 2011. The Neogene transition from C_3 to C_4 grasslands in North America: assemblage analysis of fossil phytoliths. Paleobiology 37(1):50–71.

Tabor, N. J., T. S. Myers, G. H. Mack, C. V. Looy, P. R. Renne, R. Mundil, and J. W. Geissman. 2011. “Ochoan” Quartermaster Formation of north Texas, USA: Part I, Litho- and chemostratigraphy. Abstracts with Programs - Geological Society of America 43(5):383.

Thomas, J. J., R. D. Shuster, and M. E. Bickford. 1984. A terrane of 1,350- to 1,400-m.y.-old silicic volcanic and plutonic rocks in the buried Proterozoic of the Mid-Continent and in the Wet Mountains, Colorado. Geological Society of America Bulletin 95(10):1150–1157.

Thomasson, J. R. 1990. Fossil plants from the late Miocene Ogallala Formation of central North America: possible paleoenvironmental and biostratigraphic significance. Pages 99–114 *in* T. C. Gustavson, editor. Geologic framework and regional hydrology: Upper Cenozoic Blackwater Draw and Ogallala formations, Great Plains. Bureau of Economic Geology, University of Texas at Austin, Austin, Texas.

Tweet, J., V. L. Santucci, J. P. Kenworthy, and A. L. Mims. 2009. Paleontological resource inventory and monitoring: Southern Colorado Plateau Network. Natural Resource Technical Report NPS/NRPC/NRTR—2009/245. TIC# D-59. National Park Service, Fort Collins, Colorado.

Warren, L. E. 1943. Notes on dolomite in Potter and Moore counties, Texas. University of Texas at Austin, Austin, Texas. Publication 4301:259–264.

Wilson, G. A. 1988. The effects of subsurface dissolution of Permian salt on the deposition, stratigraphy and structure of the Ogallala Formation (Late Miocene age), northeast Potter County, Texas. Thesis. West Texas State University, Canyon, Texas.

Wyckoff, D. G. 1993. Gravel sources of knappable Alibates silicified dolomite. Geoarchaeology 8(1):35–58.

Additional References

Ash, S. R. 1972. Upper Triassic Dockum flora of eastern New Mexico and Texas. Pages 124–128 *in* V. C. Kelley and F. D. Trauger, editors. East-central New Mexico. New Mexico Geological Society, Socorro, New Mexico. Guidebook 23. Available at http://nmgs.nmt.edu/publications/guidebooks/downloads/23/23_p0124_p0128.pdf (accessed December 2014).

Baldridge, W. S. 2004. Geology of the American Southwest: a journey through two billion years of plate-tectonic history. Cambridge University Press, Cambridge, United Kingdom.

Czaplewski, N. J. 2008. Miocene vertebrates from Ogallala Formation sites in western Oklahoma. New Mexico Museum of Natural History and Science Bulletin 44:1–14.

Dalquest, W. W. 1983. Mammals of the Coffee Ranch local fauna, Hemphillian of Texas. Pearce-Sellards Series 38.

Dalquest, W. W., and D. B. Patrick. 1989. Small mammals from the early and medial Hemphillian of Texas, with descriptions of a new bat and gopher. Journal of Vertebrate Paleontology 9(1):78–88.

Dolliver, P. N. 1984. Cenozoic evolution of the Canadian River basin. Baylor Geological Studies Bulletin 42.

Elias, S. A. 1997. The Ice Age history of southwestern National Parks. Smithsonian Institution Press, Washington, D.C.

Ellwood, B. B. 1996. Geology and America's National Park areas. Prentice Hall, Upper Saddle River, New Jersey.

Graham, R. W. 1987. Late Quaternary mammalian faunas and paleoenvironments of the southwestern Plains of the United States. Pages 24–86 *in* R. W. Graham, H. A. Semken, Jr., and M. A. Graham, editors. Late Quaternary mammalian biogeography and environments of the Great Plains and prairies. Illinois State Museum, Springfield, Illinois. Scientific Papers 22.

Gregory, J. T. 1972. Vertebrate faunas of the Dockum Group, Triassic, eastern New Mexico and west Texas. Pages 120–123 *in* V. C. Kelley and F. D. Trauger, editors. East-central New Mexico. New Mexico Geological Society, Socorro, New Mexico. Guidebook 23. Available at http://nmgs.nmt.edu/publications/guidebooks/downloads/23/23_p0120_p0123.pdf (accessed December 2014).

Gustavson, T. C., editor. 1986. Geomorphology and Quaternary stratigraphy of the Rolling Plains, Texas Panhandle. Bureau of Economic Geology, University of Texas at Austin, Austin, Texas. Guidebook 22.

Hay, O. P. 1924. The Pleistocene of the middle region of North America and its vertebrated animals. Carnegie Institute of Washington Publication 322A. Available at https://archive.org/details/pleistoceneofmid00hayo (accessed January 2015).

Heckert, A. B. 2007. *Colognathus obscurus* Case, an unusual vertebrate index fossil of Adamanian (St. Johnsian: latest Carnian) time, from the Upper Triassic of the American Southwest. Abstracts with Programs - Geological Society of America 39(2):30.

Hesse, C. J. 1936. Lower Pliocene vertebrate fossils from the Ogallala Formation (Lavern zone) of Beaver County, Oklahoma. Carnegie Institution of Washington Publication 476:47–72.

Hesse, C. J. 1939. A Pliocene vertebrate fauna from Higgins, Lipscomb County, Texas. University of Texas at Austin, Austin, Texas. Publication 3945:671–698.

Holliday, V. T. 1997. Paleoindian geoarchaeology of the southern High Plains. University of Texas Press, Austin, Texas.

Holliday, V. T., C. V. Haynes, Jr., J. L. Hofman, and D. J. Meltzer. 1994. Geoarchaeology and geochronology of the Miami (Clovis) site, Southern High Plains of Texas. Quaternary Research 41(2):234–244.

Holliday, V. T., S. D. Hovorka, and T. C. Gustavson. 1996. Lithostratigraphy and geochronology of fills in small playa basins on the Southern High Plains, United States. Geological Society of America Bulletin 108(8):953–965.

Hoppe, K. A. 2004. Late Pleistocene mammoth herd structure, migration patterns, and Clovis hunting strategies inferred from isotopic analyses of multiple death assemblages. Paleobiology 30(1):129–145.

Kasper, S. 1992. Mammals from the late Pleistocene Carrol Creek local fauna, Donley Co., Texas. Southwestern Naturalist 37(1):54–64.

Katz, L. 1997. Late Pleistocene fauna at Blackwater Draw locality #1: an archaeological perspective. New Mexico Museum of Natural History and Science Bulletin 11:135–143.

Kolker, A., and M. A. Fracasso. 1985. K-Ar age of a volcanic ash bed in the Quartermaster and Dewey Lake formations (Late Permian), Texas Panhandle. Isochron/West 42:17–19.

Leonard, A. B. 1958. Two new fossil plants from the Pliocene of northwestern Texas. Kansas University Science Bulletin 38(2):1393–1403.

Leonard, A. B., and J. C. Frye. 1978. Paleontology of Ogallala Formation, northeastern New Mexico. New Mexico Bureau of Geology & Mineral Resources, Socorro, New Mexico. Circular 161.

Martz, J. W., and B. J. Small. 2006. *Tecovasuchus chatterjeei*, a new aetosaur (Archosauria, Stagonolepididae) from the Tecovas Formation (Carnian, Upper Triassic) of Texas. Journal of Vertebrate Paleontology 26(2):308–320.

Matthew, W. D., and R. A. Stirton. 1930. Equidae from the Pliocene of Texas. University of California Publications, Bulletin of the Department of Geological Sciences 19:349–396.

Mayor, A. 2005. Fossil legends of the first Americans. Princeton University Press, Princeton, New Jersey.

Morgan, G. S. 2008. Vertebrate fauna and geochronology of the Great American Biotic Interchange in North America. New Mexico Museum of Natural History and Science Bulletin 44:93–140.

Mutter, R. J., and A. B. Heckert. 2006. Re-investigation of enigmatic fish bones known as colobodontid/perleidid toothplates from the Upper Triassic Chinle Group (southwestern U.S.A.). New Mexico Museum of Natural History and Science Bulletin 37:530–542.

Olsen, S. J. 1971. Zooarchaeology: animal bones in archaeology and their interpretation. Addison-Wesley Publishing Company, New York City, New York.

Patton, L. T. 1925. Geology and the location of dams on the Canadian River, Texas. Economic Geology 20(5):464–469.

Reed, L. C., and O. M. Longnecker, Jr. 1932. The geology of Hemphill County, Texas. University of Texas Bulletin 3231.

Schultz, C. B., and J. M. Hillerud. 1977. The antiquity of *Bison latifrons* (Harlan) in the Great Plains of North America. Transactions of the Nebraska Academy of Sciences and Affiliated Societies 4:103–116.

Schultz, G E. 2010. Pleistocene (Irvingtonian, Cudahyan) vertebrates from the Texas Panhandle, and their geographic and paleoecologic significance. Quaternary International 217(1–2):195–224.

Schultz, G. E. 1972. Vertebrate paleontology of the southern High Plains. Pages 129–133 *in* V. C. Kelley and F. D. Trauger, editors. East-central New Mexico. New Mexico Geological Society, Socorro, New Mexico. Guidebook 23. Available at http://nmgs.nmt.edu/publications/guidebooks/downloads/23/23_p0129_p0133.pdf (accessed December 2014).

Schultz, G. E. 1977. Guidebook: field conference on Late Cenozoic biostratigraphy of the Texas Panhandle and adjacent Oklahoma. West Texas State University, Canyon, Texas. Special publication of the Killgore Research Center, Department of Geology and Anthropology 1:1–160.

Spielmann, J. A., S. G. Lucas, and P. Huber. 2013. New record of *Spinosuchus caseanus* (Archosauromorpha, Trilophosauridae) from the Late Triassic (Adamanian) of West Texas. New Mexico Museum of Natural History and Science Bulletin 61:573–576.

Studer, F. V. 1931. Some field notes and observations concerning Texas Panhandle ruins. Pages 131–141 *in* W. K. Moorehead. Archaeology of the Arkansas River Valley. Yale University Press, New Haven, Connecticut.

Williamson, T. E., and S. G. Lucas. 1996. Mammal footprints from the Miocene-Pliocene Ogallala Formation, eastern New Mexico. New Mexico Geology 18(1):1–5.

Data Sets

Alibates Flint Quarries National Monument Paleontological Archives
5/1985–present. (hard copy data; reports; electronic data; photographs; maps; publications).
Originated by Santucci, Vincent; status: Active.

Lake Meredith National Recreation Area Paleontological Archives
5/1985–present. (hard copy data; reports; electronic data; photographs; maps; publications).
Originated by Santucci, Vincent; status: Active.

Lake Meredith National Recreation Area Collections
1965–present. (museum specimens; associated specimen notes; collection records; maps; etc.).
Originated by LAMR staff; status: Active.

Alibates Flint Quarries National Monument and Lake Meredith National Recreation Area Digital Geologic Map

2011–present. (geologic map data; electronic files; GIS metadata; associated report). Originated by NPS-Geologic Resources Inventory staff; status: Active. Online. https://irma.nps.gov/App/Reference/Profile/2176370.

Panhandle–Plains Historical Museum
1950s–present. (museum specimens; associated specimen notes; collection records; maps; etc.). Originated by Panhandle–Plains Historical Museum staff; status: Active.

Bent's Old Fort National Historic Site

Bent's Old Ford National Historic Site (BEOL) was established to protect the site of an historic trading post that was in operation from 1833 to 1849. The fort was an important post for fur trade and was also a stop on the Santa Fe Trail (itself commemorated by the Santa Fe National Historic Trail). The fort was reconstructed on its original site in 1976 (BEOL Figure 1). BEOL was authorized June 3, 1960, and had a boundary change November 10, 1978. It encompasses 323.26 ha (798.80 acres), all but 25.58 ha (63.20 acres) of which are federal.



BEOL Figure 1. View of Bent's Old Fort from across the Arkansas River (BEOL/NPS).

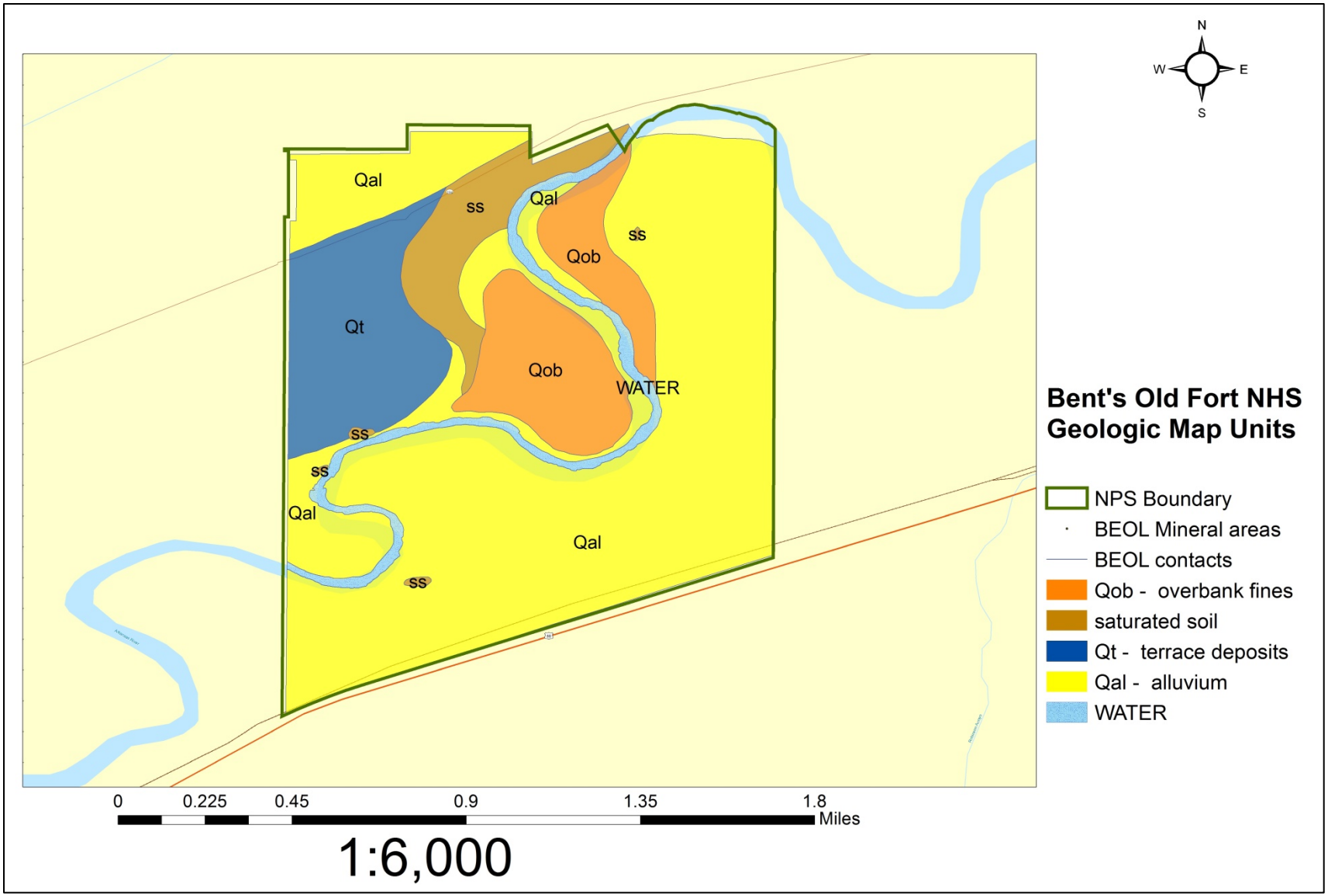
Geologic Background

BEOL is located in northeastern Otero County, in southeastern Colorado. The Arkansas River runs through the historic site in a meandering southwest to northeast course, with the fort on the north side of the river. BEOL is a little less than 10 km (6 mi) northeast of La Junta. This section of Colorado has few large cities; the nearest city with a population over 10,000 people is Pueblo, over 100 km (60 mi) to the west-northwest. Most of the surrounding terrain is relatively flat in topography, although the Arkansas drainage system has deeply eroded some areas, particularly along the Purgatoire River and its tributaries to the south. The Purgatoire River joins the Arkansas River about 20 km (12 mi) east of BEOL, between Las Animas and Fort Lyon. Publications that document the geology of BEOL and its surroundings include Darton (1906), Duce (1924), Weist et al. (1965), Swenson (1970), Moore (1973), Sharps (1976), Cobban et al. (1991), Moutoux and Cummings (1996), Linn (1999), Scott et al. (2001), Koch and Santucci (2003), and KellerLynn (2005). A geologic resources inventory report was prepared for the historic site in 2005 (KellerLynn 2005), and the NPS Geologic Resources Division produced a digital map of the historic site using Linn (1999). Koch and Santucci (2003) prepared the original paleontologic resource inventory and summary for BEOL.

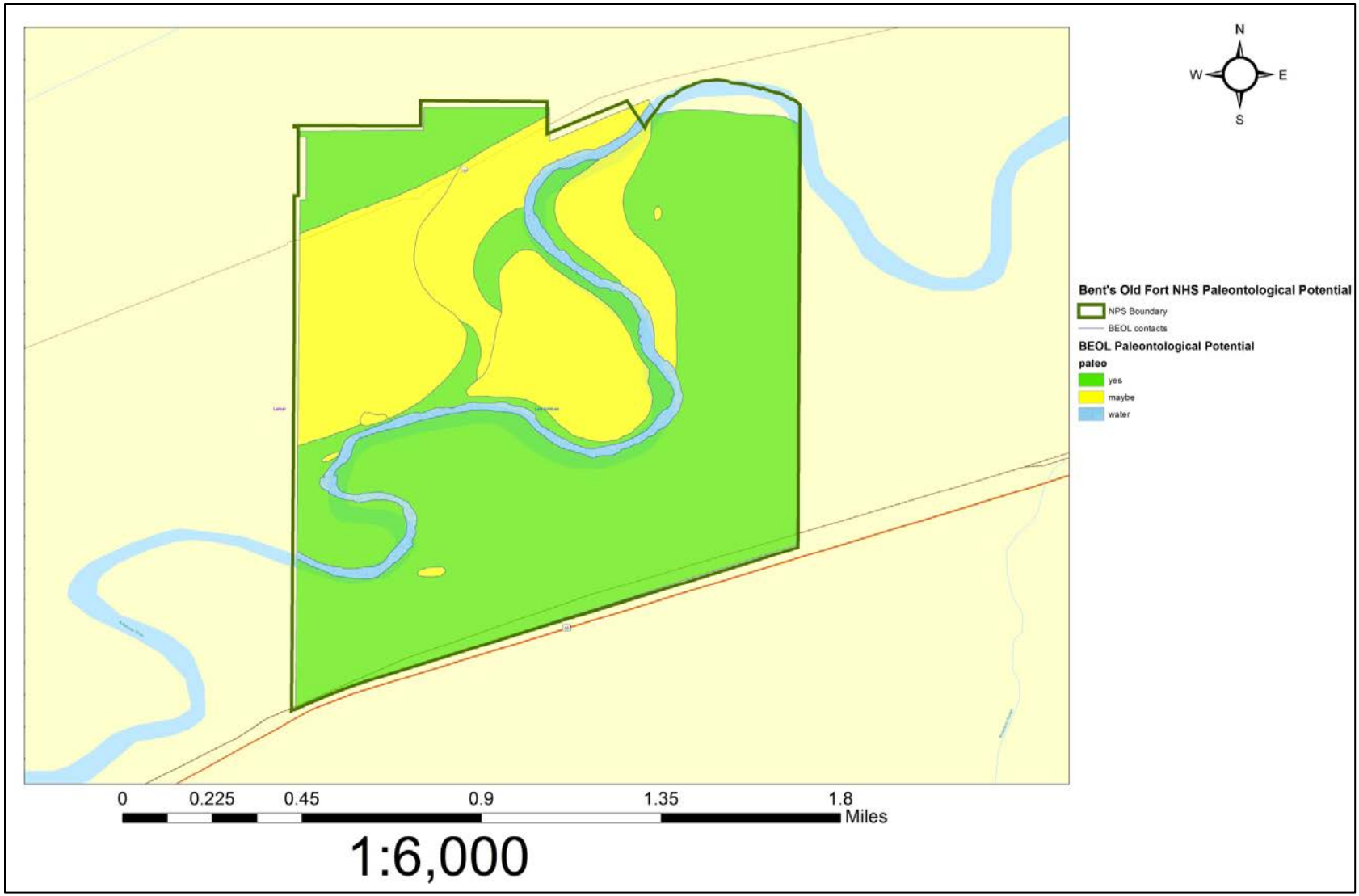
The rocks and sediments exposed at BEOL and the immediate vicinity record Upper Cretaceous marine deposition and Quaternary deposition associated with the Arkansas River drainage system (see Appendix A for a geologic time scale). Cretaceous rocks are exposed immediately outside of BEOL and form the shallow subsurface bedrock of the historic site. The rocks nearest to BEOL belong to the Greenhorn Limestone, with younger rocks of the Carlile Shale and Niobrara Formation found at slightly greater distances (Weist et al. 1965). These rocks were deposited in a shallow continental sea known as the Western Interior Seaway or Cretaceous Interior Seaway, which covered much of central North America from approximately 100 to 70 Ma (million years ago). At its greatest extent, the seaway extended from the Arctic to the Gulf of Mexico, bisecting North America (Elder and Kirkland 1993, 1994). Its advances (transgressions) and retreats (regressions) influenced the geology of numerous NPS units both within and outside of the Southern Plains Network (SOPN). Several major cycles of marine transgressions and regressions occurred (Kauffman et al. 1969; Scott et al. 1998), with smaller sea level rises and falls within them (Scott et al. 1998). Volcanoes to the west of the seaway introduced great quantities of ash, today preserved as bentonite layers (Hattin 1975a). Stratification of the seawater, limiting oxygen in the depths, appears to have occurred over the course of the cycles (Hattin 1975a; Kennedy et al. 1999; Da Gama et al. 2014). The cycles of transgressions and regressions ended after a mountain-building event toward the end of the Cretaceous, beginning roughly 75 Ma, uplifted the region far above sea level. This event, called the Laramide Orogeny, was the first step in the formation of the modern Rocky Mountains. Erosion wore down these peaks until tectonic activity resulted in renewed uplift during the past few million years (Sayre and Ort 2011).

There is little direct evidence for events that occurred in the vicinity of BEOL during the approximately 70 million years that separate the Cretaceous seaway and the Quaternary, which began about 2.6 Ma. The Arkansas River was present by the Quaternary, although its course has been steadily shifting. West of La Junta, the river has moved north, while between La Junta and Kansas it has moved south. Several terraces have formed along it, which are lithologically similar and differ only by elevation (Sharps 1969). The eolian (windblown) sands along the Arkansas River were first active about 8,000 years ago, early in the Holocene, and were reactivated more recently (Forman et al. 2004). The area is seismically quiet, although there is the large Cheraw Fault north of BEOL in northeastern Otero, southeastern Crowley, and southwestern Kiowa. It has occasionally been active since the late Pleistocene (Crone et al. 1997). Humans arrived in the region by about the end of the Pleistocene (Hofman 2001).

Quaternary deposits (Upper Pleistocene–Holocene) are mapped at the surface in BEOL (Weist et al. 1965; Linn 1999) (BEOL Figure 2). In addition, the Bridge Creek Limestone Member of the Greenhorn Formation (Upper Cretaceous) is mapped immediately south of BEOL, just on the other side of US 50 (Weist et al. 1965), and is sometimes exposed in the Arkansas River channel within BEOL when the river is dry (F. Pannebaker, BEOL, pers. comm., March 2015; B. Schumacher, U.S. Forest Service, pers. comm., March 2015). Both the Bridge Creek Limestone and the Quaternary deposits are fossiliferous in the historic site (BEOL Figure 3, Table 1).



BEOL Figure 2. Schematic geologic map of BEOL. Map graphic adapted from digital geologic map data available at the following URL: https://irma.nps.gov/App/Reference/Profile/1038951.



BEOL Figure 3. Paleontological potential map of BEOL, showing the distribution of geologic units where fossils have been found and may be found. Map graphic adapted from digital geologic map data available at the following URL: https://irma.nps.gov/App/Reference/Profile/1038951.

BEOL Table 1. Summary of BEOL stratigraphy, fossils, and depositional settings in descending order of age, from youngest to oldest. Details and references can be found in the text.

Formation	Age	Fossils Within BEOL	Depositional Environment
Quaternary sediments	Late Pleistocene–Holocene	Mammoth tusk fragments; latest Holocene phytoliths and pollen indicate the potential for older records	Fluvial and floodplain, associated with the Arkansas River
Greenhorn Limestone	Late Cretaceous	Bivalves	Marine

Sources of Paleontological Resources

The fossils of BEOL present opportunities for education, interpretation, and continued or future scientific research in the park.

Greenhorn Limestone (Upper Cretaceous)

The Bridge Creek Limestone Member of the Greenhorn Limestone is mapped immediately outside of BEOL, on the south side of US 50 (Weist et al. 1965). It is not mapped in BEOL (Linn 1999), but it can be exposed in the channel of the Arkansas River within BEOL when the river is dry (F. Pannebaker, pers. comm., 2015; B. Schumacher, U.S. Forest Service, pers. comm., March 2015). The Greenhorn Limestone is poorly exposed in the BEOL area. The Bridge Creek Limestone Member is the only unit that crops out in the immediate vicinity. In this area, it is composed of interbedded chalky limestone and lime-rich shale, with thin beds of bentonite and a local thin bed of limestone conglomerate. The limestone beds are hard, gray, and often fossiliferous, particularly in the upper part of the member. The beds are 3 to 31 cm (1 to 12 in) thick, separated by thicker intervals of shale. East of La Junta, the limestone beds form benches that are sometimes capped by Pleistocene terrace deposits. The Bridge Creek Limestone Member can be 9 to 26 m (30 to 85 ft) thick (Weist et al. 1965). In eastern Colorado, the Greenhorn Limestone consists of, in ascending order, the Lincoln Limestone Member, the Hartland Shale Member, and the Bridge Creek Limestone Member (Scott et al. 1998). Beds of the Greenhorn Limestone can be traced over hundreds of miles. This property shows that the Bridge Creek Limestone Member of eastern Colorado and far western Kansas is equivalent to the Pfeifer, Jetmore, and upper Hartland members of western and central Kansas (Hattin 1975a).

The Greenhorn Limestone is a shallow-marine formation, deposited under warm temperate waters with normal salinity and poor oxygenation near the sea floor. Water depth was greater than 18 to 24 m (60 to 80 ft) but considerably less than 180 m (600 ft). Generally the energy of deposition was not great, and decreased after an initial period of high energy (Lincoln Limestone Member). The maximum transgression occurred during deposition of the Bridge Creek Limestone (Jetmore and Pfeifer equivalents) (Hattin 1975a). The Bridge Creek Limestone Member displays cyclic bedding, which was first studied in rocks found in the Timpas unit of Comanche National Grassland, southwest of La Junta and BEOL (Miller 2013). The cyclic alternation of limestone and shale beds is attributed to orbital variations comparable to modern Milankovitch cycles (Courtinat 1993; Kennedy et al. 2005), with cycles perhaps 41,000 years long (Courtinat 1993; Scott et al. 1998). Cycles lower in the Greenhorn Limestone may be longer, on the order of 100,000 years (Scott et al. 1998). Based on its fossils (Hattin 1975a; Scott et al. 1998), deposition of the Greenhorn Limestone occurred

during the late Cenomanian and middle Turonian stages, beginning after 94.96 ± 0.50 Ma (ammonite *Plesiacanthus wyomingense* and bivalve *Inoceramus prefragilis*) and ending before 92.46 ± 0.58 Ma (ammonite *Collignoniceras woollgari* and bivalve *Mytiloides subhercynicus*) (Cobban et al. 2006), with the Bridge Creek Limestone Member having been deposited during the early and middle Turonian. The global stratotype, or reference section, for the Cenomanian–Turonian boundary is in fact within the Greenhorn Limestone at Pueblo Reservoir to the west (Kennedy et al. 2005). Because the transgression that produced the Greenhorn Limestone spread from west to east, the formation began deposition later and was deposited over a shorter time to the east (Hattin 1975a).

The Greenhorn Formation is fossiliferous within BEOL. Bruce Schumacher (pers. comm., March 2015) reported observing fossils of the bivalve *Inoceramus* (or *Mytiloides*) *labiatus* (BEOL Figure 4) in a small outcrop of the Bridge Creek Limestone Member in the active stream channel of the Arkansas River, on the north bank, during a visit approximately 2002. This outcrop is a small shelf of limestone about 6 m (20 ft) by 0.7 m (2 ft), and only a few cm/in above the water line (B. Schumacher, pers. comm., March 2015). Fran Pannebaker (pers. comm., March 2015) reported that the site was in an area approximately 360 m (1,200 ft) southwest of the fort itself, in the vicinity of the old gravel pit, and that it was only visible when there was no flow in the Arkansas River.



BEOL Figure 4. *Inoceramus* (or *Mytiloides*) *labiatus*, a common upper Greenhorn Limestone fossil from the Arkansas Valley (from Darton 1906).

The Bridge Creek Limestone Member is also fossiliferous in the immediate vicinity of BEOL. Cobban et al. (1991) described an occurrence of rudist bivalves, which are otherwise rare in the Greenhorn Limestone, from the uppermost Bridge Creek Limestone near BEOL. The discovery consists of at least 28 conjoined individuals of *Durania cornupastoris,* found at a roadcut on US 50 about 3 km (2 mi) southwest of the historic site. Inoceramid bivalves are more common in the area. Jackson Moore (pers. comm. to R. Scott, February 2000) reported that a geologist who investigated the 1964 mammoth discovery (Glenn Scott, USGS per Moore 1964) found inoceramids near the

historic site that allowed an identification of the formation. *Inoceramus* (or *Mytiloides*) *labiatus* is particularly abundant in the Greenhorn Limestone in Arkansas Valley (Darton 1906) (BEOL Figure 4). In addition, because a significant part of the formation is nannofossils, microfossils, and fragments of bivalve shells (Hattin 1975a), any given outcrop can be regarded as fossiliferous, although the fossil content would not necessarily be apparent to the naked eye.

The Greenhorn Formation is heavily fossiliferous, although the diversity of the macroscopic fossils is often limited (Hattin 1975a). Generally, the same types of fossils can be found throughout the formation, although genera and species differ, and vertebrate fossils are mostly found in the lower part of the formation (Hattin 1975a; Everhart and Bell 2009; Miller 2013), below the Bridge Creek Limestone Member. Microscopic fossils include nannofossils (extremely tiny fossils from marine phytoplankton) such as coccoliths (mineralized plates of plankton), foraminifera ("amoebas with shells"), algal calcispheres (Hattin 1975a), palynomorphs (organic microfossils) that may include foraminifera linings, dinoflagellates (single-celled organisms that move using one or more whip-like flagella), lignin and other plant materials, spores, pollen, fungi, and scolecodonts (worm jaws) (Courtinat 1993), and microscopic fecal pellets composed of coccoliths, possibly excreted by copepods or free-swimming tunicates (Hattin 1975b). A few plant fossils have been found, which likely drifted out to sea from the shore. The plant fossils include wood and logs, often with mollusk ("shipworm") borings. Filled borings left behind from decayed wood have also been found (Hattin 1975a). Invertebrate fossils are mostly limited to mollusks. Major groups include brachiopods (lamp shells), bivalves (mostly the thick-shelled inoceramids), ammonites, gastropods, barnacles, and echinoids (sea urchins) (Hattin 1975a). Rarer groups include corals (Hattin 1975a) and ostracodes (seed shrimp) (Hazel 1969). Invertebrates also produced burrows (Hattin 1975a) and bioturbation (nonspecific but heavy modification of sediment by organisms) (Kennedy et al. 2005). The invertebrate fauna is near the southern limit of the northern temperate assemblage. Generally, the bottom conditions were unfavorable to benthic fauna, although chalky limestones show burrowing, implying amelioration (Hattin 1975a).

The Greenhorn Limestone vertebrate assemblage includes chondrichthyans (including sharks, rays, and guitarfish), bony fish, the turtle *Desmatochelys*, diverse plesiosaurs (Arratia and Chorn 1998; Cicimurri 2001), the aquatic lizard *Coniasaurus*, early mosasaur relatives, pterosaurs (flying reptiles) (Cicimurri 2001), and toothed seabirds (Weishampel et al. 2004; Everhart and Bell 2009). Representatives of the three major Late Cretaceous plesiosaur groups have been found in this formation, including long-necked elasmosaurids (Everhart 2007), the pliosaurid *Polyptychodon* (Cicimurri 2001), and the polycotylid plesiosaurs *Dolichorhynchops* (Arratia and Chorn 1998) and *Pahasapasaurus* (Schumacher 2007; pliosaurids and polycotylids were superficially similar, both having short necks and large heads).

Quaternary rocks and sediments (upper Pleistocene–Holocene)

The Quaternary deposits of BEOL are composed of floodplain deposits near the Arkansas River and upper Pleistocene terrace deposits on the north side of the river (Moore 1973; Weist et al. 1996; Linn 1999). In at least some areas, there are about 3.6 m (12 ft) of latest Pleistocene sand and gravel overlying the Bridge Creek Limestone Member, and in turn overlain by clayey sand (Moore 1973).

Useful online paleontological resources for this area include the Neotoma paleoecology database (http://www.neotomadb.org/), and Faunmap, which is the vertebrate element of Neotoma (http://www.ucmp.berkeley.edu/faunmap/).

The Quaternary deposits of BEOL are fossiliferous. The most notable find is a fragmented mammoth tusk discovered September 12, 1964, in gravel at the borrow pit for the loop road. The discovery was accidental, with the specimen uncovered and somewhat damaged by heavy machinery. It was found atop limestone, and the fact that only a single tusk was found indicates that it was secondarily deposited, perhaps from a flood. It was excavated under the supervision of BEOL archeologist Jackson W. Moore, Jr. A USGS geologist, Glenn Scott, identified the limestone as the Bridge Creek Limestone Member, and indicated that the overlying tusk-bearing sediments were deposited between 11,000 and 8,000 years ago. The tusk is attributed to the Columbian mammoth (Moore 1964). In addition to Moore's 1964 tusk, a handful of other fragments from BEOL have been identified as fragments of mammoth tusks or teeth. These fossils were also recovered during Moore's work at the historic site, between 1963 and 1966. Two fragments were found in the laborer's quarters and one was found in the 1954 backfill in the military warehouse. They were not identified until 1992, and there is some question about their identification (N. Russell, BEOL, pers. comm. to V. L. Santucci, March 1999).

Moutoux and Cummings (1996) reported on four pollen and four phytolith (bits of silica found in some plants) samples from two sites in BEOL, from archeological sites attributed to the late Prehistoric (Ceramic) period. The great majority of the pollen represented angiosperms, but conifer and ephedra pollen was also present, as well as some clubmoss spores and fungal spores. A date of 730 ± 90 radiocarbon years before present (780 to 540 calibrated years before present) was obtained at one of the sites (Moutoux and Cummings 1996). (Note that radiocarbon dates are not the same as calendar dates, and must be calibrated to approximate calendar years. Dates can be calibrated using a calibration program such as Calib 7.1 [http://calib.qub.ac.uk/calib/] if error ranges are provided. "Present" in "before present" is 1950.) Although the samples are of relatively recent age, they are of paleontological interest because they show past environmental conditions at the historic site, and because they indicate the potential for older pollen records. Moore (1964) reported that sediment had been taken from the tusk excavation for pollen analysis, but no results appear to have been published.

These two types of records, isolated bones of large mammals and pollen-bearing sediments, represent typical types of fossils that can be found in Quaternary sediments of the southern Great Plains. There are few reports of Quaternary fossils within a 100 km (60 mi) radius of BEOL; for example, the maps of Hay (1924) or the Neotoma database show little for southeastern Colorado. Woodhull (1872) reported the discovery of two mammoth or mastodon teeth and a third bone (which disintegrated before identification) a few yards from the Arkansas River near Fort Lyon, about 28 km (17 mi) east-northeast of BEOL. The only other published reports close to the 100-km radius appear to be Holocene charcoal on the Cheraw Fault north of BEOL (Crone et al. 1997), and the McEndree Ranch site, just over 100 km (60 mi) southeast of BEOL. This is an Archaic-stage village site that was in use over 2,000 years ago, and has yielded charcoal and bones of birds, rodents, and bison (Shields

1980). In addition, bivalve and gastropod fossils have been found in alluvium in the canyons of the region (Duce 1924).

Park Collections

The mammoth remains are in park collections, under Archeology because they lack geologic context. They consist of 625 fragments in three lots, the majority (621) associated with Moore's tusk, and the rest being the specimens identified in 1992 (N. Russell, pers. comm. to V. L. Santucci, March 1999).

Cultural Resource Connections

No fossils have been reported from cultural resource contexts at BEOL, unless the late Holocene pollen and phytoliths recovered from archeological sites are considered both paleontological resources, and cultural because of provenance. Building stone is a common source of fossils in cultural contexts, and the fossiliferous Greenhorn Limestone is sometimes used for construction material (Hattin 1975a), but the primary building material at BEOL was adobe. Another common type of cultural association for this area is fossiliferous stone used for artifacts. For example, in the Southwest, petrified wood from the Upper Triassic Chinle Formation was often used for artifacts. The majority of parks in the neighboring Southern Colorado Plateau Network have examples (Tweet et al. 2009). Kenworthy and Santucci (2006) presented an overview and cited selected examples of National Park Service fossils found in cultural resource contexts.

Paleontological Resource Management, Preliminary Recommendations

- Staff from the historic site should be encouraged to observe exposed rocks and sedimentary deposits for fossil material while conducting their usual duties. To promote this, staff should also receive guidance regarding how to recognize common local fossils. When opportunities arise to observe paleontological resources in the field and take part in paleontological field studies with trained paleontologists, staff should take advantage of them, if funding and time permit.

- At a time when flow conditions permit, the fossiliferous Bridge Creek Limestone Member site southwest of the fort should be formally documented, and the vicinity scouted for additional outcrops.

- Staff should photodocument and monitor any occurrences of paleontological resources that may be observed in situ. Fossils and their associated geologic context (surrounding rock) should be documented but left in place unless they are subject to imminent degradation by artificially accelerated natural processes or direct human impacts. A Geologic Resource Monitoring Manual by the Geological Society of America and NPS Geologic Resources Division includes a section on paleontological resource monitoring (Santucci et al. 2009). Santucci and Koch (2003) present information on paleontologic resource monitoring.

- Fossils found in a cultural context should be documented like other fossils, but will also require the input of an archeologist or a cultural resource specialist. Any fossil which has a cultural context may be culturally sensitive as well (e.g., subject to NAGPRA) and should be

regarded as such until otherwise established. The Geologic Resources Division can coordinate additional documentation/research of such material.

- Contact the NPS Geologic Resources Division for technical assistance with paleontological resource management issues.

References Cited

Arratia, G,. and J. Chorn. 1998. A new primitive acanthomorph fish from the Greenhorn Formation (Late Cretaceous) of Nebraska. Journal of Vertebrate Paleontology 18(2):301–314.

Cicimurri, D. J. 2001. Cretaceous elasmobranchs of the Greenhorn Formation (middle Cenomanian-middle Turonian), western South Dakota. Pages 27–43 *in* V. L. Santucci, and L. McClelland, editors. Proceedings of the 6th fossil resource conference: 2001 a fossil odyssey. Technical Report - National Park Service, Geological Resource Division. Available at http://www.nature.nps.gov/geology/paleontology/pub/fossil_conference_6/cicimurri.htm (accessed January 2015).

Cobban, W. A., P. W. Skelton, and W. J. Kennedy. 1991. Occurrence of the rudistid *Durania cornupastoris* (Des Moulins, 1826) in the Upper Cretaceous Greenhorn Limestone in Colorado. Pages D1–D8 *in* W. J. Sando, editor. Shorter contributions to paleontology and stratigraphy. U.S. Geological Survey, Reston, Virginia. Bulletin 1985. Available at http://pubs.er.usgs.gov/publication/b1985 (accessed January 2015).

Cobban, W. A., I. Walaszczyk, J. D. Obradovich, and K. C. McKinney. 2006. A USGS zonal table for the Upper Cretaceous Middle Cenomanian-Maastrichtian of the Western Interior of the United States based on ammonites, inoceramids, and radiometric ages. U.S. Geological Survey, Reston, Virginia. Open-File Report 2006-1250. Available at http://pubs.usgs.gov/of/2006/1250/ (accessed January 2015).

Courtinat, B. 1993. The significance of palynofacies fluctuations in the Greenhorn Formation (Cenomanian-Turonian) of the Western Interior Basin, USA. Marine Micropaleontology 21(1–3):249–257.

Crone, A. J., M. N. Machette, L. Bradley, and S. A. Mahan. 1997. Late Quaternary surface faulting on the Cheraw Fault, southeastern Colorado. U.S. Geological Survey, Reston, Virginia. Miscellaneous Investigations Series 2591. Available at http://pubs.er.usgs.gov/publication/i2591 (accessed January 2015).

Da Gama, R. O. B. P., B. Lutz, P. Desjardins, M. Thompson, I. Prince, and I. Espejo. 2014. Integrated paleoenvironmental analysis of the Niobrara Formation: Cretaceous Western Interior Seaway, northern Colorado. Palaeogeography, Palaeoclimatology, Palaeoecology 413:66–80.

Darton, N. H. 1906. Geology and underground waters of the Arkansas Valley in eastern Colorado. U.S. Geological Survey, Washington, D.C. Professional Paper 52. Available at http://pubs.er.usgs.gov/publication/pp52 (accessed January 2015).

Duce, J. T. 1924. Geology of parts of Las Animas, Otero, and Bent counties. Colorado Geological Survey, Department of Natural Resources, Denver, Colorado. Bulletin 27(3):73–102.

Elder, W. P., and J. I. Kirkland. 1993. Cretaceous paleogeography of the Colorado Plateau and adjacent areas. Museum of Northern Arizona Bulletin 59:129–151.

Elder, W. P., and J. I. Kirkland. 1994. Cretaceous paleogeography of the southern Western Interior region. Pages 415–440 *in* M. V. Caputo, J. A. Peterson, and K. J. Franczyk, editors. Mesozoic System of the Rocky Mountain region, USA. Rocky Mountain Section, Society for Sedimentary Geology, Denver, Colorado.

Everhart, M. J. 2007. Use of archival photographs to rediscover the locality of the Holyrood elasmosaur (Ellsworth County, Kansas). Transactions of the Kansas Academy of Science 110(1–2):135–143.

Everhart, M. J., and A. Bell. 2009. A hesperornithiform limb bone from the basal Greenhorn Formation (Late Cretaceous, middle Cenomanian) of north central Kansas. Journal of Vertebrate Paleontology 29(3):952–956.

Forman, S. L., L. Marin, and J. Gomez. 2004. Eolian depositional records from southwestern Kansas and southeastern Colorado, a potential landscape response to droughts in the past 10,000 years. Abstracts with Programs - Geological Society of America 36(5):412.

Hattin, D. E. 1975a. Stratigraphy and depositional environment of Greenhorn Limestone (Upper Cretaceous) of Kansas. Kansas Geological Survey, Lawrence, Kansas. Bulletin 209. Available at http://www.kgs.ku.edu/Publications/Bulletins/209/index.html (accessed January 2015).

Hattin, D. E. 1975b. Petrology and origin of fecal pellets in upper Cretaceous strata of Kansas and Saskatchewan. Journal of Sedimentary Petrology 45(3):686–696.

Hay, O. P. 1924. The Pleistocene of the middle region of North America and its vertebrated animals. Carnegie Institute of Washington Publication 322A. Available at https://archive.org/details/pleistoceneofmid00hayo (accessed January 2015).

Hazel, J. E. 1969. *Cythereis eaglefordensis* Alexander, 1929: a guide fossil for deposits of latest Cenomanian age in the Western Interior and Gulf Coast regions of the United States. Pages D155–D158 *in* Geological Survey research 1969, Chapter D. U.S. Geological Survey, Washington, D.C. Professional Paper 650-D. Available at http://pubs.er.usgs.gov/usgspubs/pp/pp650D (accessed January 2015).

Hofman, J. L. 2001. Human occupations across the Pleistocene-Holocene transition on the Great Plains: geomorphic and regional patterns. Abstracts with Programs - Geological Society of America 33(6):287.

Kauffman, E. G., J. D. Powell, and D. E. Hattin. 1969. Cenomanian-Turonian facies across the Raton Basin. The Mountain Geologist 6(3):93–118.

KellerLynn, K. 2005. Bent's Old Fort National Historic Site: geologic resource evaluation report. Natural Resource Report NPS/NRPC/GRD/NRR—2005/005. National Park Service, Fort Collins, Colorado. Available at http://www.nature.nps.gov/geology/inventory/publications/reports/beol_gre_rpt_view.pdf (accessed January 2015).

Kennedy, W. J., W. A. Cobban, W. P. Elder, and J. I. Kirkland. 1999. Lower Turonian (Upper Cretaceous) *Watinoceras devonense* Zone ammonite fauna in Colorado, USA. Cretaceous Research 20(5):629–639.

Kennedy, W. J., I. Walaszczyk, and W. A. Cobban. 2005. The global boundary stratotype section and point for the base of the Turonian stage of the Cretaceous: Pueblo, Colorado, U. S. A. Episodes 28(2):93–104. Available at http://www.stratigraphy.org/GSSP/Turonian.pdf (accessed January 2015).

Kenworthy, J. P., and V. L. Santucci. 2006. A preliminary investigation of National Park Service paleontological resources in cultural resource contexts, Part 1: general overview. New Mexico Museum of Natural History and Science Bulletin 34:70–76. Available at http://nature.nps.gov/geology/paleontology/pub/fossil_conference_7/9%20Kenworthy.pdf (accessed December 2014).

Koch, A. L., and V. L. Santucci. 2003. Bent's Old Fort National Historic Site. Pages 5–6 *in* A. L. Koch and V. L. Santucci. Paleontological resource inventory and monitoring: Southern Plains Network. TIC# D-107. National Park Service, Denver, Colorado.

Linn, S. 1999. Geologic map of Bent's Old Fort National Historic Site and vicinity, Otero and Bent counties, Colorado. Unpublished map. National Park Service, Lakewood, Colorado. Scale 1:24,000.

Miller, S. 2013. Fossils and geology of the Greenhorn Cyclothem in the Comanche National Grassland, Colorado. Pages 269–278 *in* L. D. Abbott and G. S. Hancock, editors. Classic concepts and new directions: exploring 125 years of GSA discoveries in the Rocky Mountain Region. Geological Society of America, Boulder, Colorado. Field Guide 33.

Moore, J. W., Jr. 1964. Memoranda to research archeologist, Midwest Regional Office, September 18, 1964 and September 25, 1964. On file at BEOL.

Moore, J. W., Jr. 1973. Bent's Old Fort: an archeological study. State Historical Society of Colorado and the Pruett Publishing Company, Boulder, Colorado.

Moutoux, T. E., and L. S. Cummings. 1996. Pollen and phytolith analysis at sites 50t534 and 50t535, Bent's Old Fort National Historic Site, Colorado. Paleo Research Labs Technical Report 96-16, prepared for Alpine Archaeological Consultants, Inc., Montrose, Colorado. tDAR ID: 377798; doi:10.6067/XCV8TH8M1Z. Available at http://core.tdar.org/document/377798/pollen-and-

phytolith-analysis-at-sites-50t534-and-50t535-bents-old-fort-national-historic-site-colorado (accessed January 2015).

Santucci, V. L., and A. L. Koch. 2003. Paleontological resource monitoring strategies for the National Park Service. Park Science 22(1):22–25. Available at http://www.nature.nps.gov/ParkScience/archive/PDF/ParkScience22%281%29Fall2003.pdf (accessed January 2015).

Santucci, V. L., J. P. Kenworthy, and A. L. Mims. 2009. Monitoring in situ paleontological resources. Pages 189–204 *in* R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado.

Sayre, W. O., and M. H. Ort. 2011. A geologic study of the Capulin Volcano National Monument and surrounding areas, Union and Colfax counties, New Mexico. New Mexico Bureau of Geology and Mineral Resources, Socorro, New Mexico. Open File Report 541. Available at http://geoinfo.nmt.edu/publications/openfile/details.cfml?Volume=541 (accessed January 2015).

Schumacher, B. A. 2007. A new polycotylid plesiosaur (Reptilia, Sauropterygia) from the Greenhorn Limestone (Upper Cretaceous, lower upper Cenomanian), Black Hills, South Dakota. Pages 133–146 *in* J. E. Martin and D. C. Parris, editors. The geology and paleontology of the Late Cretaceous marine deposits of the Dakotas. Geological Society of America, Boulder, Colorado. Special Paper 427.

Scott, R. L., V. L. Santucci, and T. Connors. 2001. An inventory of paleontological resources from the national parks and monuments in Colorado. Pages 178-202 *in* Santucci, V. L. and L. McClelland, editors. Proceedings of the 6th fossil resource conference: 2001 a fossil odyssey. Technical Report - National Park Service, Geological Resource Division. National Park Service, Geologic Resources Division, Lakewood, Colorado. NPS/NRGRD/GRDTR-01/01. Available at http://www.nature.nps.gov/geology/paleontology/pub/fossil_conference_6/scott.htm (accessed January 2015).

Scott, R. W., P. C. Franks, M. J. Evetts, J. A. Bergen, and J. A. Stein. 1998. Timing of Mid-Cretaceous relative sea level changes in the Western Interior: Amoco No. 1 bounds core. Concepts in Sedimentology and Paleontology 6:11–34.

Sharps, J. A. 1969. Lateral migrations of the Arkansas River during the Quaternary: Fowler, Colorado, to the Colorado-Kansas state line. Pages C66–C70 *in* Geological Survey research 1969, Chapter C. U.S. Geological Survey, Washington, D.C. Professional Paper 650-C. Available at http://pubs.er.usgs.gov/publication/pp650C (accessed January 2015).

Sharps, J. A. 1976. Geologic map of the Lamar Quadrangle, Colorado and Kansas. U.S. Geological Survey, Washington, D.C. Miscellaneous Investigations Series 944. Scale 1:250,000. Available at http://pubs.er.usgs.gov/publication/i944 (accessed January 2015).

Shields, W. L. 1980. Preliminary investigations at the McEndree Ranch site, 5BA30. Southwestern Lore 46(3):1–11.

Swenson, F. A. 1970. Meandering of the Arkansas River since 1833 near Bent's Old Fort, Colorado. Pages B210–B213 *in* Geological Survey research 1970, Chapter B. U.S. Geological Survey, Washington, D.C. Professional Paper 700-B. Available at http://pubs.er.usgs.gov/publication/pp700B (accessed January 2015).

Tweet, J., V. L. Santucci, J. P. Kenworthy, and A. L. Mims. 2009. Paleontological resource inventory and monitoring: Southern Colorado Plateau Network. Natural Resource Technical Report NPS/NRPC/NRTR—2009/245. TIC# D-59. National Park Service, Fort Collins, Colorado.

Weishampel, D. B., P. M. Barrett, R. A. Coria, J. Le Loueff, Xu X., Zhao X., A. Sahni, E. M. P. Gomani, and C. N. Noto. 2004. Dinosaur distribution. Pages 517–606 *in* D. B. Weishampel, P. Dodson, and H. Osmólska, editors. The Dinosauria (2nd edition). University of California Press, Berkeley, California.

Weist, W. G., Jr., E. D. Jenkins, and C. A. Horr. 1965. Geology and occurrence of ground water in Otero County and southern part of Crowley County, Colorado. U.S. Geological Survey, Washington, D.C. Water-Supply Paper 1799. Scale 1:125,000. Available at http://pubs.er.usgs.gov/publication/wsp1799 (accessed January 2015).

Woodhull, A. A. 1872. On the elephant in Colorado. American Journal of Science 3:374. Available at http://biodiversitylibrary.org/page/36995566 (accessed January 2015).

Additional References

Baldridge, W. S. 2004. Geology of the American Southwest: a journey through two billion years of plate-tectonic history. Cambridge University Press, Cambridge, United Kingdom.

Cobban, W. A. 1985. Ammonite record from Bridge Creek Member of Greenhorn Limestone at Pueblo Reservoir State Recreation Area, Colorado. Pages 135–138 *in* L. M. Pratt, E. G. Kauffman, and F. B. Zelt, editors. Fine-grained deposits and biofacies of the Cretaceous Western Interior Seaway: evidence of cyclic sedimentary processes. Society of Economic Paleontologists and Geologists, Golden, Colorado. Field Trip Guidebook 4.

Cobban, W. A. 1987. A new ammonite from the Upper Cretaceous of Kansas. Pages B1–B3 in W. J. Sando, editor. Shorter contributions to paleontology and stratigraphy. U.S. Geological Survey, Reston, Virginia. Bulletin 1690. Available at http://pubs.er.usgs.gov/publication/b1690 (accessed January 2015).

Cobban, W. A. 1988. The Upper Cretaceous ammonite *Watinoceras* Warren in the Western Interior of the United States. U.S. Geological Survey, Reston, Virginia. Bulletin 1788. Available at http://pubs.er.usgs.gov/publication/b1788 (accessed January 2015).

Dane, C. H., W. G. Pierce, and J. B. Reeside, Jr. 1937. The stratigraphy of the Upper Cretaceous rocks north of the Arkansas River in eastern Colorado. U.S. Geological Survey, Washington,

D.C. Professional Paper 186-K. Available at http://pubs.er.usgs.gov/publication/pp186K (accessed January 2015).

Elias, S. A. 1997. The Ice Age history of southwestern National Parks. Smithsonian Institution Press, Washington, D.C.

Ellwood, B. B. 1996. Geology and America's National Park areas. Prentice Hall, Upper Saddle River, New Jersey.

Everhart, M. J. 2005. Oceans of Kansas: a natural history of the Western Interior Sea. Indiana University Press, Bloomington and Indianapolis, Indiana.

Graham, R. W. 1987. Late Quaternary mammalian faunas and paleoenvironments of the southwestern Plains of the United States. Pages 24–86 in R. W. Graham, H. A. Semken, Jr., and M. A. Graham, editors. Late Quaternary mammalian biogeography and environments of the Great Plains and prairies. Illinois State Museum, Springfield, Illinois. Scientific Papers 22.

Harris, A. H. 1985. Late Pleistocene vertebrate paleoecology of the west. University of Texas Press, Austin, Texas.

Hattin, D. E. 1977. Articulated lepadomorph cirripeds from the upper Cretaceous of Kansas: family Stramentidae. Journal of Paleontology 51(4):797–825.

Hattin, D. E. 1990. *Puebloites greenhornensis* Cobban & Scott from Turonian part of Greenhorn Limestone, north-central Kansas and northeastern Wyoming: contribution to Cretaceous paleobiogeography. Cretaceous Research 11(4):351–358.

Hattin, D. E., and W. A. Cobban. 1977. Upper Cretaceous stratigraphy, paleontology and paleoecology of western Kansas. Mountain Geologist 14(3–4):175–217.

Hay, O. P. 1927. The Pleistocene of the western region of North America and its vertebrated animals. Carnegie Institute of Washington Publication 322B.

Leckie, R. M. 1985. Foraminifera of the Cenomanian-Turonian boundary interval, Greenhorn Formation, Rock Canyon Anticline, Pueblo, Colorado. Pages 139–150 *in* L. M. Pratt, E. G. Kauffman, and F. B. Zelt, editors. Fine-grained deposits and biofacies of the Cretaceous Western Interior Seaway: evidence of cyclic sedimentary processes. Society of Economic Paleontologists and Geologists, Golden, Colorado. Field Trip Guidebook 4.

Liggett, G. A., K. Shimada, S. C. Bennett, and B. A. Schumacher. 2005. Cenomanian (Late Cretaceous) reptiles from northwestern Russell County, Kansas. Paleobios 25(2):9–17. http://boneblogger.com/pubs/liggett_etal.pdf (accessed January 2015).

Mayor, A. 2005. Fossil legends of the first Americans. Princeton University Press, Princeton, New Jersey.

NPS Geologic Resources Inventory Program. 2006. Unpublished Digital Geologic Map of Bents Old Fort National Historic Site and Vicinity, Colorado (NPS, GRD, GRE, BEOL, BEOL digital map) adapted from an unpublished National Park Service map by Linn and O'Meara (1999). NPS Geologic Resources Inventory Program. Lakewood, CO. Geospatial Dataset-1038951. Available at https://irma.nps.gov/App/Reference/Profile/1040284 (accessed January 2015).

Olsen, S. J. 1971. Zooarchaeology: animal bones in archaeology and their interpretation. Addison-Wesley Publishing Company, New York City, New York.

Wells, P. V., and J. D. Stewart. 1987. Spruce charcoal, conifer macrofossils, and landsnail and small-vertebrate faunas in Wisconsinan sediments on the High Plains of Kansas. Pages 129–140 in W. C. Johnson, editor. Quaternary environments of Kansas. Kansas Geological Survey, Lawrence, Kansas. Guidebook Series 5. Available at http://www.kgs.ku.edu/Publications/Bulletins/GB5/ (accessed January 2015).

Data Sets

Bent's Old Fort National Historic Site Paleontological Archives
5/1985–present. (hard copy data; reports; electronic data; photographs; maps; publications). Originated by Santucci, Vincent; status: Active.

Bent's Old Fort National Historic Site Collections
1964–present. (museum specimens; associated specimen notes; collection records; maps; etc.). Originated by BEOL staff; status: Active.

Bent's Old Fort National Historic Site Digital Geologic Map
1999–present. (geologic map data; electronic files; GIS metadata; associated report). Originated by NPS-Geologic Resources Inventory staff; status: Active. Online.
https://irma.nps.gov/App/Reference/Profile/1038951.

Capulin Volcano National Monument

Capulin Volcano National Monument (CAVO) protects Capulin Volcano, an exceptionally well-preserved cinder cone volcano that formed between 62,000 and 58,000 years ago (CAVO Figure 1). CAVO was proclaimed August 9, 1916, as Capulin Mountain National Monument. It was renamed Capulin Volcano National Monument December 31, 1987, and had a boundary change September 3, 1962. It encompasses 320.86 ha (792.84 acres), all of which are federal.



CAVO Figure 1. Capulin Volcano, a Late Pleistocene cinder cone, rising over the landscape (USGS, http://3dparks.wr.usgs.gov/cavo/html/capu71.htm).

Geologic Background

CAVO is located in northwestern Union County, New Mexico, in the northeastern corner of the state. This region is sparsely populated. The largest cities in the area are Raton, New Mexico, about 53 km (33 mi) to the west-northwest, and Trinidad, Colorado, about 64 km (40 mi) to the northwest. Geologically, Capulin Volcano is part of the Raton–Clayton Volcanic Field, and several other volcanic features pertaining to the same volcanic field are found in the immediate vicinity, including Baby Capulin and Twin Mountain to the northeast and Sierra Grande to the southeast. Capulin Volcano has been discussed in a number of documents, although relatively little detailed analysis occurred until the last two decades of the 20th century. Documents discussing the geology of CAVO include Muehlberger (1955), Baldwin and Muehlberger (1959), Stormer (1972, 1987), Kudo (1976), Hart and Smith (1979), Chronic (1987), Hunt et al. (1987), Sayre et al. (1995), Stroud (1996), Kiver and Harris (1999), Sayre and Ort (1999, 2011), Aubele and Crumpler (2001), Koch and Santucci (2003), Richman (2010a, 2010b), Muehlberger et al. (2010), KellerLynn (2011), and NPS (2011a,

2011b). The NPS Geologic Resources Division coordinated a Geologic Resource Inventory workshop for CAVO in May 2011 (KellerLynn 2011), and produced digital maps of the volcanic features in 2011 (NPS 2011a, 2011b). Koch and Santucci (2003) prepared the original paleontologic resource inventory and summary for CAVO.

The exposed geologic history of CAVO is limited to the past few tens of thousands of years, pertaining to the latest Pleistocene and Holocene (see Appendix A for a geologic time scale). However, Capulin Volcano is one part of a longer geologic story. The bedrock of the northeastern corner of New Mexico includes Precambrian, Paleozoic, Mesozoic, and Cenozoic rocks and deposits, although most of what is exposed at the surface dates to the Mesozoic and Cenozoic. Relatively little remains of the Paleozoic, due to the uplift of the Sierra Grande Arch during the Pennsylvanian as part of the growth of a mountain range known as the Ancestral Rockies. The growth of this range led to the erosion of most older Paleozoic rocks. After the erosion of these highlands, the region was near sea level for tens of millions of years. A mountain-building event beginning toward the end of the Cretaceous, beginning roughly 75 Ma (million years ago), uplifted the region far above sea level. This event, called the Laramide Orogeny, was the first step in the creation of the modern Rocky Mountains. Erosion wore down these peaks until tectonic activity resulted in renewed uplift during the past few million years (Sayre and Ort 2011).

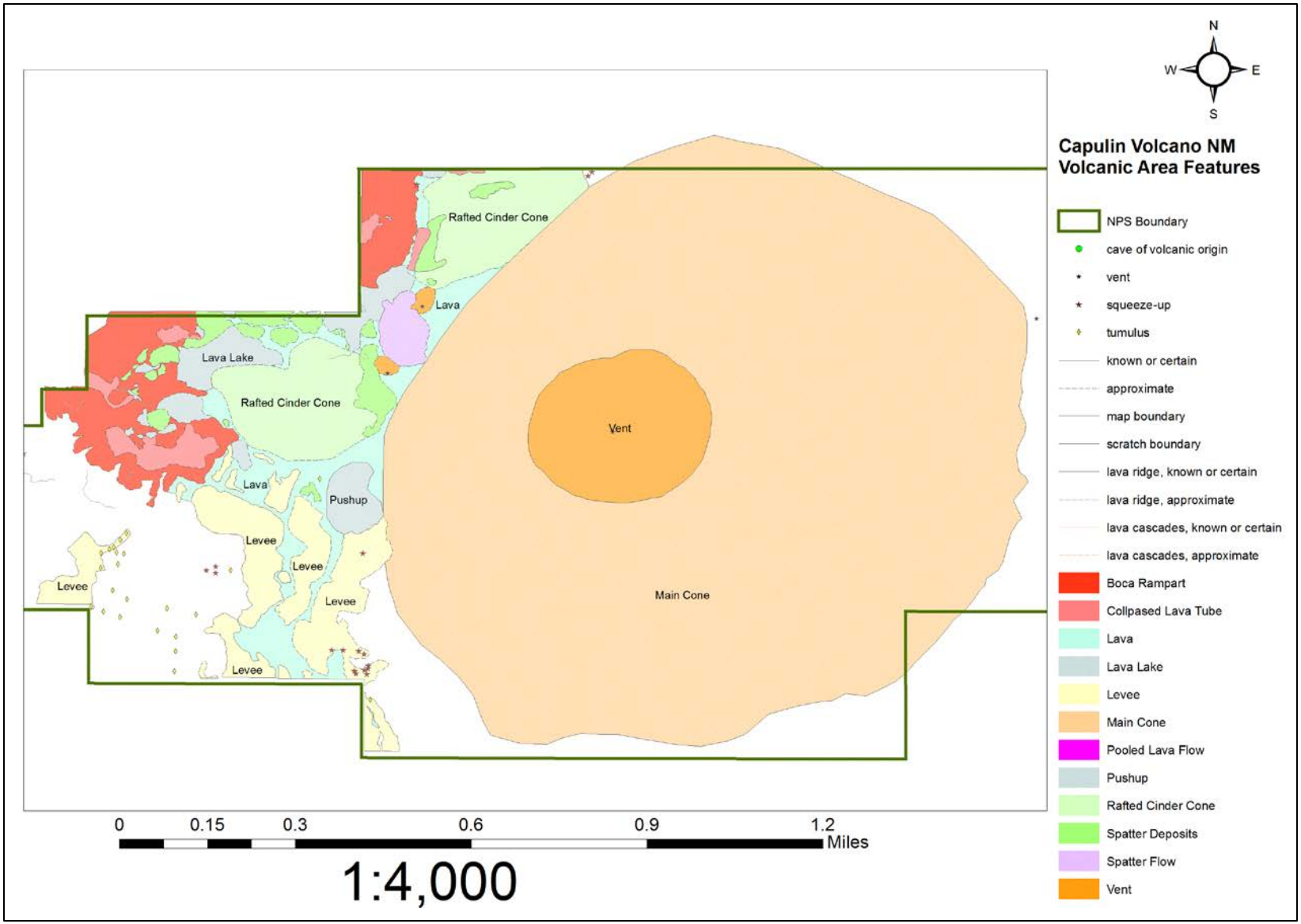
As noted above, Capulin Volcano is part of the Raton–Clayton Volcanic Field, which features approximately 125 vents over an area of 20,000 km^2 (8000 mi^2) (Aubele and Crumpler 2001). CAVO is located near the center of the volcanic field (Stormer 1987). The Raton–Clayton Volcanic Field is the easternmost volcanic field of the Jemez lineament, a feature that crosses eastern Arizona and northern New Mexico (Kiver and Harris 1999). The Jemez Lineament is an ancient feature representing a crustal suture or weakness that formed roughly 1.68 to 1.65 billion years ago between two crustal blocks, the Yavapai province on the north and the Mazatzal province on the south (Magnani et al. 2004). Igneous activity on the eastern section of the lineament is related to the formation of the Rio Grande Rift during the late Cenozoic (Stormer 1987). This rift became active about 26 Ma and remains active in the present (Sayre and Ort 2011). The generally northeast–southwest lineament crosses the north–south rift in north-central New Mexico (Kiver and Harris 1999). Other nearby volcanic fields associated with the lineament include the Jemez Volcanic Field, the Taos Plateau Volcanic Field, and the Ocate Volcanic Field. These fields were all active over the same general time frame, roughly the past 9 million years (Sayre and Ort 2011). The Raton–Clayton and Ocate volcanic fields represent the most significant late Cenozoic volcanic activity east of the Rockies (Aubele and Crumpler 2001).

The Raton–Clayton Volcanic Field has been active in three main phases. The oldest, the Raton phase, occurred from about 9 to 3.6 Ma, in the western part of the field. The middle phase, the Clayton phase, occurred from about 3.0 to 2.2 Ma, in the eastern part of the field (Sayre and Ort 2011). This phase produced Sierra Grande (Aubele and Crumpler 2001), the peak of which is about 11 km (8 mi) southeast of CAVO. Sierra Grande is the largest feature of the volcanic field (Stormer 1987). The most recent phase, the Capulin phase, occurred from about 1.7 Ma to 50,000 years ago, and may not be finished. Capulin Volcano itself erupted between 62,000 and 58,000 years ago, probably over a

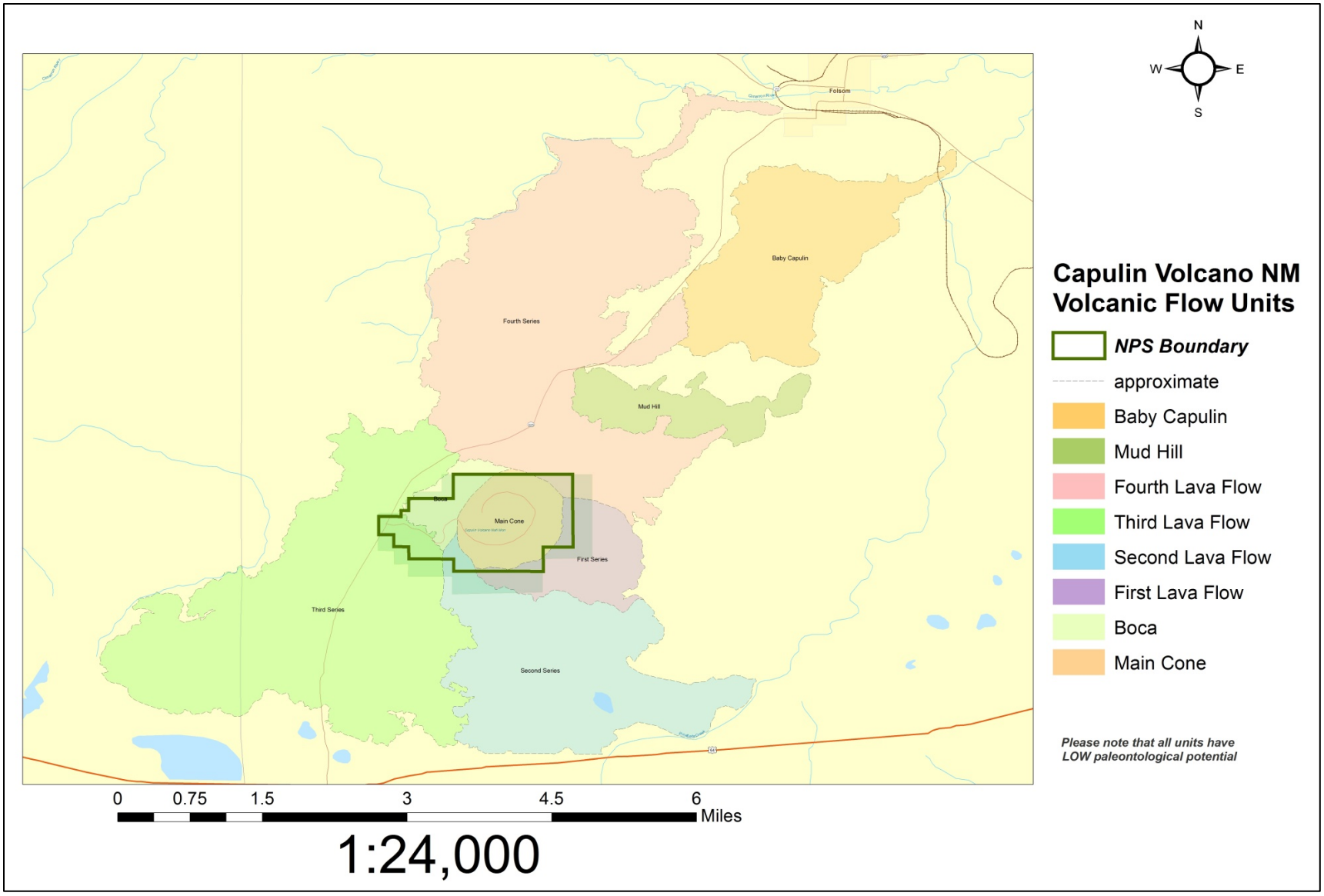
month to a few years. It was one of the last eruptions of the volcanic field, followed shortly by Baby Capulin, and then Purvine Mesa and Twin Mountain (Sayre and Ort 2011). It was thought for several decades that Capulin Volcano and these nearby volcanic features were formed by eruptions that took place less than 10,000 years ago. This was based on correlations with sediment layers at the nearby Folsom archeological site (Muehlberger 1955), which later proved to be incorrect (Sayre et al. 1995; Aubele and Crumpler 2001). Over the history of the Raton–Clayton Volcanic Field, various vents produced several major types of igneous rocks, including basalts, andesites, dacites, basinites, and nephelinites (Stormer 1987). Volcanic fields have relatively small batches of magma, and each batch tends to be distinct because residence time exceeds cooling time (Aubele and Crumpler 2001). Capulin Volcano itself is primarily composed of basalt and basaltic andesite (Stormer 1987).

Humans have been in northeastern New Mexico since the latest Pleistocene, and some of the most important Paleoindian sites are from the area. Clovis, in Curry County in east-central New Mexico, gave its name to the Clovis tradition, and the slightly younger Folsom tradition is named for the archeological site near Folsom, discussed in greater detail under "Quaternary sedimentary deposits" below. The Clovis tradition existed between approximately 11,200 and 10,900 radiocarbon years before present, and the Folsom tradition existed between approximately 10,900 and 10,200 radiocarbon years before present (Holliday 2000). (Note that radiocarbon dates are not the same as calendar dates, and must be calibrated to approximate calendar years. Dates can be calibrated using a calibration program such as Calib 7.1 [http://calib.qub.ac.uk/calib/] if error ranges are provided. "Present" in "before present" is 1950.) Regional climate during Clovis time appear to have been wetter than present, with drier conditions in Folsom time, followed by a general continuation of drying until the warm and dry Altithermal began around 8,000 years ago (Holliday 2000). Valley fills in the area northeast of CAVO show nine millennial-scale cycles of aggradation and incision over the past 12,000 years or so. The cycles are thought to be tied to the strength of the North American monsoon system, with a stronger monsoon bringing more rain and more incision, and a weaker monsoon resulting in less rain, less vegetation, and increased filling of channels (Mann and Meltzer 2007).

The exposed bedrock and surficial geology of CAVO is limited to four volcanic flows and a cinder cone dating to the late Pleistocene (NPS 2011a, 2011b) (CAVO Figure 2, 3), and sediments formed by the erosion of the volcanic units since then. Fossils have not been reported from any of these units (CAVO Table 1).



CAVO Figure 2. Schematic geologic map of CAVO. Map graphic adapted from digital geologic map data available at the following URL: https://irma.nps.gov/App/Reference/Profile/2164823.



CAVO Figure 3. Map of volcanic flows at CAVO and the vicinity. Map graphic adapted from digital geologic map data available at the following URL: https://irma.nps.gov/App/Reference/Profile/2164825.

CAVO Table 1. Summary of CAVO stratigraphy, fossils, and depositional settings in descending order of age, from youngest to oldest. Details and references can be found in the text.

Formation	Age	Fossils	Depositional Environment
Quaternary sediments	late Pleistocene–Holocene	None to date; potential fossils based on regional finds include isolated bones of extinct Pleistocene fauna (mammoths, horses, camels, extinct bison, etc.)	Local erosion of volcanic rocks
Quaternary volcanic rocks	late Pleistocene	None to date; fossils are unlikely, but not impossible, and packrat middens may be present if there are any significant open spaces	Volcanic eruptions

Potential Sources of Paleontological Resources

Fossils have not yet been documented from the following geologic units within CAVO. However, they (or similar rocks) are known to preserve fossils elsewhere, and future field investigations within the monument may result in the discovery of fossils from one or more of these units.

Quaternary volcanic rocks (upper Pleistocene)

As noted, the exposed bedrock of CAVO is composed of late Pleistocene volcanic rocks. Fossils are not common in volcanic rocks, although tree molds are occasionally found (Koch and Santucci 2003). Tree molds are hollows and impressions sometimes left behind after a trunk has been engulfed by lava.

The topography formed by Capulin Volcano may permit the long-term preservation of packrat middens. Packrat middens are collections of plant material and food waste constructed by packrats (*Neotoma* spp.) and cemented by their viscous urine. They can be well-preserved in dry caves and rockshelters, and illustrate the environment of the builder's foraging range. Middens are important tools for reconstructing the ecology and climate of the late Pleistocene and Holocene of the southwestern United States (Strickland et al. 2001). Middens have been found as close to CAVO as West Carrizo Canyon, Colorado, over 75 km (47 mi) northeast of the monument, near the area where Colorado, New Mexico, and Oklahoma meet (Anderson and Feiler 2009; Lesser and Johnson 2011). The West Carrizo Canyon middens only date back about 7,000 years (Anderson and Feiler 2009), but middens can be found elsewhere that exceed the range of radiocarbon dating (about 50,000 years). Middens, such as those in West Carrizo Canyon, typically include fragments of conifers and angiosperms, pollen, and packrat coprolites (fossil feces), but can hold anything a packrat finds interesting and portable, as well as the remains of other animals that scavenged or took over middens (other rodents, small reptiles, arthropods, and so on). Tweet et al. (2012) presented an overview of packrat middens in NPS units.

Quaternary sedimentary deposits (upper Pleistocene–Holocene)

Capulin Mountain has not been heavily eroded, and there are no notable drainages within CAVO, which limits the possibility of finding fossils in post-volcanic sediments. It is not impossible, though, that isolated teeth and/or other durable remains of late Pleistocene mammals may one day be found in the monument. About a dozen late Pleistocene or Holocene sites have been reported within 100

km (60 mi) of CAVO (Dalquest et al. 1990; Smith and Cifelli 2000; Morgan et al. 2001; Morgan and Lucas 2005), and fossils of terrestrial and freshwater mollusks are also common in northeastern New Mexico (Frye et al. 1978). Some of these records are of only general relevance to CAVO; for example, the lack of significant standing or flowing water means that the filled beaver dams described by Dalquest et al. (1990) and the mollusks described in Frye et al. (1978) are unlikely. The most commonly reported large mammals from the vicinity of CAVO are extinct bison and mammoths. A fauna including mollusks, catfish and other fish, frogs, salamanders, lizards, snakes, waterfowl, shrews, rodents, rabbits, mammoths, horses, peccaries, camels, deer, bison, and pronghorns is known from the 100 km radius (Dalquest et al. 1990; Morgan and Lucas 2005). Useful online paleontological resources for this area include the Neotoma paleoecology database (http://www.neotomadb.org/), Faunmap, which is the vertebrate element of Neotoma (http://www.ucmp.berkeley.edu/faunmap/), and Arthur Harris's "Pleistocene Vertebrates of Southwestern USA and Northwestern Mexico" (http://www.utep.edu/leb/pleistNM/).

One of the nearest sites, and certainly the most significant, is the Folsom site, about 13 km (8 mi) northwest of CAVO. Capulin Volcano can be seen from the site (Cook 1927). The Folsom site is notable as the first location to show that now-extinct Pleistocene mammals coexisted with humans in North America (Hay and Cook 1930; Cordell 1976), and as the type location for the Folsom tradition. More than 30 skeletons of an extinct bison species were found here associated with 17 stone points of a type now known as Folsom points (Hay and Cook 1930; Morgan and Lucas 2005). Hay and Cook (1928) originally assigned the bison to new species *B. taylori*, but this is now considered to be *B. antiquus*, which went extinct around 5,000 years ago (Morgan and Lucas 2005). Other paleontological resources from this site include charcoal (Haynes et al. 1992), gastropod shells (Balakrishnan et al. 2005), and remains of rodents, rabbits, and deer (Hay and Cook 1930). Radiocarbon dates on bison bone amino acids from the site give an average date of approximately 10,500 radiocarbon years before present (Meltzer et al. 2002).

Park Collections

No fossils are currently reported to be in CAVO collections, and no CAVO fossils are currently reported to be in the collections of other institutions.

Cultural Resources Connections

No fossils have been reported from cultural resource contexts at CAVO, although such associations would not be unprecedented. The most likely type of cultural association for this area would be fossiliferous stone used for artifacts. For example, in the Southwest, petrified wood from the Upper Triassic Chinle Formation was often used for artifacts. The majority of parks in the neighboring Southern Colorado Plateau Network have examples (Tweet et al. 2009). Kenworthy and Santucci (2006) presented an overview and cited selected examples of National Park Service fossils found in cultural resource contexts.

Paleontological Resource Management, Preliminary Recommendations

- Staff from the monument should be encouraged to observe exposed rocks and sedimentary deposits for fossil material while conducting their usual duties. To promote this, staff should also receive guidance regarding how to recognize common local fossils. When opportunities

arise to observe paleontological resources in the field and take part in paleontological field studies with trained paleontologists, staff should take advantage of them, if funding and time permit.

- Staff should photodocument and monitor any occurrences of paleontological resources that may be observed in situ. Fossils and their associated geologic context (surrounding rock) should be documented but left in place unless they are subject to imminent degradation by artificially accelerated natural processes or direct human impacts. A Geologic Resource Monitoring Manual by the Geological Society of America and NPS Geologic Resources Division includes a section on paleontological resource monitoring (Santucci et al. 2009). Santucci and Koch (2003) present information on paleontologic resource monitoring.

- Fossils found in a cultural context should be documented like other fossils, but will also require the input of an archeologist or a cultural resource specialist. Any fossil which has a cultural context may be culturally sensitive as well (e.g., subject to NAGPRA) and should be regarded as such until otherwise established. The Geologic Resources Division can coordinate additional documentation/research of such material.

- If a fossil packrat midden is located, there are several midden researchers in the Southwest who may be contacted. The GRD maintains a list of active researchers and can facilitate communication between the park and these researchers. Fossil packrat middens are typically found in dry caves and rock shelters, and resemble piles or mounds of plant material with a dark glossy coating of crystallized packrat urine. Fossil middens can provide important paleoecological information.

- Contact the NPS Geologic Resources Division for technical assistance with paleontological resource management issues.

References Cited

Anderson, R. S., and E. Feiler. 2009. Holocene vegetation and climate change on the Colorado Great Plains, USA, and the invasion of Colorado piñon (*Pinus edulis*). Journal of Biogeography 36:2279–2289. Available at http://www2.nau.edu/envsci/faculty/ScottAnderson/docs/119.pdf (accessed January 2015).

Aubele, J. C., and L. S. Crumpler. 2001. Raton-Clayton and Ocate volcanic fields. Pages 69–76 *in* S. G. Lucas and D. S. Ulmer-Scholle, editors. Geology of the Llano Estacado. New Mexico Geological Society, Socorro, New Mexico. Guidebook 52. Available at http://nmgs.nmt.edu/publications/guidebooks/downloads/52/52_p0069_p0076.pdf (accessed January 2015).

Balakrishnan, M., C. J. Yapp, D. J. Meltzer, and J. L. Theler. 2005. Paleoenvironment of the Folsom archaeological site, New Mexico, USA, approximately 10,500 14C yr B.P. as inferred from the stable isotope composition of fossil land snail shells. Quaternary Research 63(1):31–44.

Baldwin, B., and W. R. Muehlberger. 1959 (reprinted 1981). Geologic studies of Union County, New Mexico. New Mexico Bureau of Geology and Mineral Resources, Socorro, New Mexico. Bulletin 63.

Chronic, H. 1987. Roadside geology of New Mexico. Mountain Press Publishing Company, Missoula, Montana.

Cook, H. J. 1927. New geological and paleontological evidence bearing on the antiquity of man in America. Natural History 27(3):240–247.

Cordell, L. S. 1976. The Folsom Site in retrospect. Pages 83–86 *in* R. C. Ewing and B. S. Kues, editors. Vermejo Park. New Mexico Geological Society, Socorro, New Mexico. Guidebook 27. Available at http://nmgs.nmt.edu/publications/guidebooks/downloads/27/27_p0083_p0086.pdf (accessed January 2015).

Dalquest, W. W., F. B. Stangl, Jr., and M. J. Kocurko. 1990. Zoogeographic implications of Holocene mammal remains from ancient beaver ponds in Oklahoma and New Mexico. Southwestern Naturalist 35(2):105–110.

Frye, J. C., A. B. Leonard, and H. D. Glass. 1978. Late Cenozoic sediments, molluscan faunas, and clay minerals in northeastern New Mexico. New Mexico Bureau of Geology & Mineral Resources, Socorro, New Mexico. Circular 160.

Hart, D. L., and C. Smith. 1979. Ground water in the vicinity of Capulin, New Mexico. U.S. Geological Survey, Washington, D.C. Water-Resources Investigative Report 79-79. Scale 1:181,000.

Hay, O. P., and H. J. Cook. 1928. Preliminary descriptions of fossil mammals recently discovered in Oklahoma, Texas, and New Mexico. Colorado Museum of Natural History, Proceedings 8(2, Part 1):33.

Hay, O. P., and H. J. Cook. 1930. Fossil vertebrates collected near, or in association with, human artifacts at localities near Colorado, Texas; Frederick, Oklahoma; and Folsom, New Mexico. Proceedings of the Colorado Museum of Natural History 9(2):1–40

Haynes, C. V., Jr., R. P. Buekens, A. J. T. Jull, and O. K. Davis. 1992. New radiocarbon dates for some old Folsom sites: accelerator technology. Pages 83–100 *in* D. J. Stanford and J. S. Day, editors. Ice Age hunters of the Rockies. Denver Museum of Natural History and University Press of Colorado, Niwot, Colorado.

Holliday, V. T. 2000. Folsom drought and episodic drying on the Southern High Plains from 10,900-10,200 ^{14}C yr B.P. Quaternary Research 53(1):1–12. Available at http://www.argonaut.arizona.edu/articles/holliday2000_2.pdf (accessed January 2015).

Hunt, A. P., S. G. Lucas, and B. S. Kues. 1987. Third-day road log, from Clayton to Des Moines, Capulin, Capulin Mountain National Monument, Folsom, Raton and the Cretaceous/Tertiary

boundary on Goat Hill. Pages 41–54 *in* S. G. Lucas and A. P. Hunt, editors. Northeastern New Mexico. New Mexico Geological Society, Socorro, New Mexico. Guidebook 38.

KellerLynn, K. 2011. Geologic resources inventory scoping summary: Capulin Volcano National Monument, New Mexico. National Park Service, Geologic Resources Division, Denver, Colorado. Available at http://www.nature.nps.gov/geology/inventory/publications/reports/CAVO_GRI_Scoping_Summary_2011-0919.pdf (accessed January 2015).

Kenworthy, J. P., and V. L. Santucci. 2006. A preliminary investigation of National Park Service paleontological resources in cultural resource contexts, Part 1: general overview. New Mexico Museum of Natural History and Science Bulletin 34:70–76. Available at http://nature.nps.gov/geology/paleontology/pub/fossil_conference_7/9%20Kenworthy.pdf (accessed December 2014).

Kiver, E. P., and D. V. Harris. 1999. Geology of U.S. parklands. 5th edition. John Wiley & Sons, Inc., New York, New York.

Koch, A. L., and V. L. Santucci. 2003. Capulin Volcano National Monument. Pages 7–8 *in* A. L. Koch and V. L. Santucci. Paleontological resource inventory and monitoring: Southern Plains Network. TIC# D-107. National Park Service, Denver, Colorado.

Kudo, A. M. 1976. A review of the volcanic history and stratigraphy of northeastern New Mexico. Pages 109–110 *in* R. C. Ewing and B. S. Kues, editors. Vermejo Park. New Mexico Geological Society, Socorro, New Mexico. Guidebook 27. Available at http://nmgs.nmt.edu/publications/guidebooks/downloads/27/27_p0109_p0110.pdf (accessed January 2015).

Lesser, M. R., and S. T. Jackson. 2011. Reliability of macrofossils in woodrat (*Neotoma*) middens for detecting low-density tree populations. Paleobiology 37(4):603–615.

Magnani, M. B., K. C. Killer, A. Levander, and K. Karlstrom. 2004. The Yavapai-Mazatzal boundary: a long-lived tectonic element in the lithosphere of southwestern North America. Geological Society of America Bulletin 116(9–10):1137–1142.

Mann, D. H., and D. J. Meltzer. 2007. Millennial-scale dynamics of valley fills over the past 12,000 ^{14}C yr in northeastern New Mexico, USA. Geological Society of America Bulletin 119(11–12):1433–1448.

Meltzer, D. J., L. C. Todd, and V. T. Holliday. 2002. The Folsom (Paleoindian) type site: past investigations, current studies. American Antiquity 67:5 –36.

Morgan, G. S., and S. G. Lucas. 2005. Pleistocene vertebrate faunas in New Mexico from alluvial, fluvial, and lacustrine deposits. New Mexico Museum of Natural History and Science Bulletin 28:185–248.

Morgan, G. S., S. G. Lucas, P. L. Sealey, and A. P. Hunt. 2001. A review of Pleistocene vertebrate faunas from northeastern New Mexico. Pages 265–284 *in* S. G. Lucas and D. S. Ulmer-Scholle, editors. Geology of the Llano Estacado. New Mexico Geological Society, Socorro, New Mexico. Guidebook 52. Available at http://nmgs.nmt.edu/publications/guidebooks/downloads/52/52_p0265_p0284.pdf (accessed January 2015).

Muehlberger, W. R. 1955. Relative age of Folsom Man and the Capulin Mountain eruption, Colfax and Union counties, New Mexico. Geological Society of America Bulletin 66(12, Part 2):1600–1601.

Muehlberger, W. R., S. J. Muehlberger, and L. G. Price. 2010. Capulin Volcano National Monument. Pages 313–318 *in* L. G. Price, editor. The geology of northern New Mexico's parks, monuments, and public lands. New Mexico Bureau of Geology and Mineral Resources, Socorro, New Mexico.

National Park Service (NPS), Geologic Resources Inventory Program. 2011a. Unpublished Digital Volcanic Lava Flow Map of the Capulin Volcano Area, New Mexico (NPS, GRD, GRI, CAVO, CVLF digital map) adapted from unpublished National Park Service digital data by Richman (2010). NPS Geologic Resources Inventory Program. Lakewood, Colorado. Geospatial Dataset-2164825. Available at https://irma.nps.gov/App/Reference/Profile/2164825 (accessed January 2015).

National Park Service (NPS), Geologic Resources Inventory Program. 2011b. Unpublished Digital Volcanic Map of Capulin Volcano National Monument and Vicinity, New Mexico (NPS, GRD, GRI, CAVO, CAVO digital map) adapted from unpublished National Park Service digital data by Richman (2010). NPS Geologic Resources Inventory Program. Lakewood, Colorado. Geospatial Dataset-2164823. Available at https://irma.nps.gov/App/Reference/Profile/2164823 (accessed January 2015).

Richman, R. 2010a. Capulin Volcano National Monument geology inventory. Unpublished report.

Richman, R. 2010b. Digital volcanic geology of Capulin Volcano National Monument and vicinity, New Mexico. National Park Service, U.S. Department of Interior. Unpublished digital data. Scale 1:24,000.

Santucci, V. L., and A. L. Koch. 2003. Paleontological resource monitoring strategies for the National Park Service. Park Science 22(1):22–25. Available at http://www.nature.nps.gov/ParkScience/archive/PDF/ParkScience22%281%29Fall2003.pdf (accessed January 2015).

Santucci, V. L., J. P. Kenworthy, and A. L. Mims. 2009. Monitoring in situ paleontological resources. Pages 189–204 *in* R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado.

Sayre, W. O., and M. H. Ort. 1999. A geologic study of Capulin Volcano National Monument and surrounding areas. Final report, Cooperative Agreement CA7029-2-0017. Prepared for Capulin Volcano National Monument, Capulin, New Mexico, USA. College of Santa Fe and Northern Arizona University, Santa Fe, New Mexico, and Flagstaff, Arizona, USA.

Sayre, W. O., and M. H. Ort. 2011. A geologic study of the Capulin Volcano National Monument and surrounding areas, Union and Colfax counties, New Mexico. New Mexico Bureau of Geology and Mineral Resources, Socorro, New Mexico. Open File Report 541. Available at http://geoinfo.nmt.edu/publications/openfile/details.cfml?Volume=541 (accessed January 2015).

Sayre, W. O., M. H. Ort, and D. Graham. 1995. Capulin Volcano is approximately 59,100 years old. Park Science 15(2):10–11. Available at http://www.nature.nps.gov/ParkScience/archive/PDF/ParkScience15%282%29Spring1995.pdf (accessed January 2015).

Smith, K. S., and R. L. Cifelli. 2000. A synopsis of the Pleistocene vertebrates of Oklahoma. Oklahoma Geological Survey Bulletin 147. Available at http://www.ogs.ou.edu/pubsscanned/BULLETINS/Bulletin147.pdf (accessed January 2015).

Stormer, J. C., Jr. 1972. Ages and nature of volcanic activity on the southern High Plains, New Mexico and Colorado. Geological Society of America Bulletin 83(8):2443–2448.

Stormer, J. C., Jr. 1987. Capulin Mountain Volcano and the Raton-Clayton volcanic field, northeastern New Mexico Pages 421–424 *in* Beus, S., editor. Rocky Mountain section of the Geological Society of America. Geological Society of America, Boulder, Colorado. Centennial field guide.

Strickland, L. E., R. S. Thompson, and K. H. Anderson. 2001. USGS/NOAA North American packrat midden database data dictionary. U.S. Geological Survey, Reston, VA. Open File Report 01-022. Available at http://pubs.er.usgs.gov/publication/ofr0122 (accessed January 2015).

Stroud, J. R. 1996. The volcanic history and landscape evolution of the Raton–Clayton Volcanic Field. Thesis. New Mexico Institute of Mining and Technology, Socorro, New Mexico.

Tweet, J. S., V. L. Santucci, and A. P. Hunt. 2012. An inventory of packrat (*Neotoma* spp.) middens in National Park Service areas. New Mexico Museum of Natural History and Science Bulletin 57:355–368.

Tweet, J., V. L. Santucci, J. P. Kenworthy, and A. L. Mims. 2009. Paleontological resource inventory and monitoring: Southern Colorado Plateau Network. Natural Resource Technical Report NPS/NRPC/NRTR—2009/245. TIC# D-59. National Park Service, Fort Collins, Colorado.

Additional References

Anthony, E. D., Jr. 1955. Geography and geology of the Dry Cimarron River Valley. Panhandle Geonews 3(1):13–16.

Baldridge, W. S. 2004. Geology of the American Southwest: a journey through two billion years of plate-tectonic history. Cambridge University Press, Cambridge, United Kingdom.

Betancourt, J. L., T. R. Van Devender, and P. S. Martin, editors. 1990. Packrat middens: the last 40,000 years of biotic change. University of Arizona Press, Tucson, Arizona.

Elias, S. A. 1997. The Ice Age history of southwestern National Parks. Smithsonian Institution Press, Washington, D.C.

Ellwood, B. B. 1996. Geology and America's National Park areas. Prentice Hall, Upper Saddle River, New Jersey.

Graham, R. W. 1987. Late Quaternary mammalian faunas and paleoenvironments of the southwestern Plains of the United States. Pages 24–86 *in* R. W. Graham, H. A. Semken, Jr., and M. A. Graham, editors. Late Quaternary mammalian biogeography and environments of the Great Plains and prairies. Illinois State Museum, Springfield, Illinois. Scientific Papers 22.

Harris, A. H. 1985. Late Pleistocene vertebrate paleoecology of the west. University of Texas Press, Austin, Texas.

Hay, O. P. 1924. The Pleistocene of the middle region of North America and its vertebrated animals. Carnegie Institute of Washington Publication 322A. Available at https://archive.org/details/pleistoceneofmid00hayo (accessed January 2015).

Hay, O. P. 1927. The Pleistocene of the western region of North America and its vertebrated animals. Carnegie Institute of Washington Publication 322B.

Haynes, C. V. 1980. The Clovis culture. Canadian Journal of Anthropology 1(1):115–121.

Holliday, V. T. 1997. Paleoindian geoarchaeology of the southern High Plains. University of Texas Press, Austin, Texas.

Holliday, V. T. 2009. Geoarchaeology and the search for the first Americans. Catena 78(3):310–322.

Hoppe, K. A. 2004. Late Pleistocene mammoth herd structure, migration patterns, and Clovis hunting strategies inferred from isotopic analyses of multiple death assemblages. Paleobiology 30(1):129–145.

Howard, E. B. 1936. The association of a human culture with an extinct fauna in New Mexico. American Naturalist 70(729):314–323.

Lucas, S. G., and J. A. Effinger. 1991. *Mammuthus* from Lincoln County and a review of the mammoths from the Pleistocene of New Mexico. Pages 277–282 *in* J. M. Barker, B. S. Kues, G. S. Austin, and S. G. Lucas, editors. Geology of the Sierra Blanca, Sacramento and Capitan Ranges, New Mexico. New Mexico Geological Society, Socorro, New Mexico. Guidebook 42. Available at http://nmgs.nmt.edu/publications/guidebooks/downloads/42/42_p0277_p0282.pdf (accessed January 2015).

Luedke, R. G., and R. L. Smith. 1991. Quaternary volcanism in the western conterminous United States. Pages 75–92 *in* R. B. Morrison, editor. Quaternary nonglacial geology, conterminous U.S. Geological Society of America, Boulder, Colorado. The geology of North America K-2

Mayor, A. 2005. Fossil legends of the first Americans. Princeton University Press, Princeton, New Jersey.

Muehlberger, W. R., B. Baldwin, and R. W. Foster. 1961. High Plains, northeastern New Mexico, Raton-Capulin Mountain-Clayton. New Mexico Bureau of Geology and Mineral Resources, Socorro, New Mexico. Scenic Trips to the Geologic Past 7. Available at http://geoinfo.nmt.edu/publications/guides/scenictrips/downloads/7/Scenic%20Trip%2007.pdf (accessed January 2015).

Olsen, S. J. 1971. Zooarchaeology: animal bones in archaeology and their interpretation. Addison-Wesley Publishing Company, New York City, New York.

Panhandle Geological Society. 1955. Field trip of Dry Cimarron River Valley, the Panhandle of Oklahoma, northeastern New Mexico, lower Front Range of the Rocky Mountains, and southeastern Colorado, May 19-21, 1955. Panhandle Geological Society, Amarillo, Texas.

Schumacher, B. A. 2001. A new late Neogene paleo-fauna from the Kiowa/Rita Blanca National Grassland, northeastern New Mexico. Pages 293–296 *in* S. G. Lucas and D. S. Ulmer-Scholle, editors. Geology of the Llano Estacado. New Mexico Geological Society, Socorro, New Mexico. Guidebook 52. Available at http://nmgs.nmt.edu/publications/guidebooks/downloads/52/52_p0293_p0295.pdf (accessed January 2015).

U.S. Geological Survey and National Oceanographic and Atmospheric Administration. 2007 (most recent update). USGS/NOAA North American Packrat Midden Database. Version 3. Available at http://geochange.er.usgs.gov/midden/ (accessed January 2015).

White, R. S., Jr., and G. S. Morgan. 2011. *Capromeryx* (Artidactyla, Antilocapridae) from the Rancholabrean Tramperos Creek fauna, Union County, New Mexico, with a review of the occurrence and paleobiology of *Capromeryx* in the Rancholabrean of New Mexico. New Mexico Museum of Natural History and Science Bulletin 53:641–651.

Wisniewski, P. A., and F. J. Pazzaglia. 2002. Epeirogenic controls on Canadian River incision and landscape evolution, Great Plains of northeastern New Mexico. Journal of Geology 110(4):437–456.

Data Sets

Capulin Volcano National Monument Paleontological Archives
5/1985–present. (hard copy data; reports; electronic data; photographs; maps; publications).
Originated by Santucci, Vincent; status: Active.

Capulin Volcano National Monument Digital Volcanic Lava Flow Map

2011–present. (geologic map data; electronic files; GIS metadata; associated report). Originated by NPS-Geologic Resources Inventory staff; status: Active. Online. https://irma.nps.gov/App/Reference/Profile/2164825.

Capulin Volcano National Monument Digital Volcanic Map
2011–present. (geologic map data; electronic files; GIS metadata; associated report). Originated by NPS-Geologic Resources Inventory staff; status: Active. Online. https://irma.nps.gov/App/Reference/Profile/2164823.

Chickasaw National Recreation Area

Chickasaw National Recreation Area (CHIC) protects an area of south-central Oklahoma surrounding the Lake of the Arbuckles. This recreation area has one of the longest and most complex histories of any National Park Service (NPS) unit. The area was first officially recognized July 1, 1902, as Sulphur Springs Reservation, set aside to preserve an area of springs in what is now the northeastern arm of CHIC. The name was changed June 29, 1906 to Platt National Park. The construction of Arbuckle Dam and subsequent filling of Lake of the Arbuckles during the 1950s and 1960s led to the creation of Arbuckle Recreation Area south and west of Platt National Park, which was authorized August 24, 1962. The two park units were merged and redesignated Chickasaw National Recreation Area on March 17, 1976. The boundaries of the units that became CHIC have changed on several occasions: April 21, 1904; June 18, 1940; March 17, 1976; December 9, 1991; and October 30, 2004. The recreation area currently encompasses 4,001.87 ha (9,888.83 acres), all but 1.82 ha (4.50 acres) of which are federal.



CHIC Figure 1. The Lake of the Arbuckles occupies part of the Rock Creek drainage system. The locations of the creek and lake are related to faults and folds created during the formation of the Arbuckle Mountains (NPS).

Geologic Background

CHIC is located in central Murray County, south-central Oklahoma. The major geographic feature within the recreation area is the Lake of the Arbuckles, a reservoir formed behind Arbuckle Dam at

the confluence of three waterways. Clockwise from north to east, they are Guy Sandy Creek, Rock Creek, and Buckhorn Creek. Rock Creek is the major stream, and flows south to the Washita River. The boundaries of CHIC are such that the three streams and associated sections of the lake are contained in three arms (CHIC Figure 2). The lake and drainage system are within the northwestern Arbuckle Mountains, a heavily eroded mountain range now expressed as hills. The formation of these mountains involved extensive folding and faulting, and several large folds and faults are important controls on the geography of CHIC. Two of the most significant features are the Reagan Fault, which roughly parallels the now-submerged course of Buckhorn Creek on the north side of the fault in CHIC, and the Tishomingo Anticline, a great concave-down fold parallel to Buckhorn Creek on its south. The axis of the anticline is more or less on the southern boundary of CHIC, east of the dam (Blome et al. 2013). The city of Sulphur, Oklahoma, borders the northeast arm of CHIC, and downtown Oklahoma City is about 120 km (75 mi) north-northwest of CHIC.

The geology of the Arbuckle Mountains has been described in many publications, not least of which because of the complex structural geology of the mountains, and because several of the rock formations have long been utilized for energy resources. The land within the modern boundaries of CHIC is included in many of those publications. Publications documenting the paleontology of CHIC include Girty (1909), Amsden (1958a, 1958b, 1960), Wilson and Urban (1963), Glaser (1965), Sutherland (1965), Alberstadt (1967, 1973), Campbell (1967, 1977), Lundin (1968), Zidek (1972, 1975), Barrick and Klapper (1992), Cuffey et al. (1995a), Stanley (2001), and Koch and Santucci (2003). Other documents concerning the geology of CHIC include Taff (1903), Decker and Merritt (1931), Gould and Schoff (1939), Gorman and Flint (1944), Gorman et al. (1945), Lehman (1945), Ham et al. (1954, updated as Johnson 1990), Elias and Branson (1959), Jackson (1969), Ham (1973), Johnson et al. (1984), Donovan and Heinlen (1988), Cates (1989, 1991), Chaplin (1989), Cardott and Chaplin (1993), Hanson and Cates (1994), Nicholl et al. (1999), Hacker (2001), Scheirer and Scheirer (2006), Graham (2008), Faith et al. (2010), Christenson et al. (2011), Blome et al. (2013), and National Park Service (2014). The NPS Geologic Resources Division coordinated a Geologic Resource Evaluation scoping summary for CHIC in October 2007 (Graham 2008), and produced a digital map of the recreation area in 2010, which was updated in 2014 (National Park Service 2014). Koch and Santucci (2003) prepared the original paleontologic resource inventory and summary for CHIC.

CHIC and the immediate vicinity have an excellent geologic record of the Paleozoic Era (see the Appendix for a geologic time scale), from approximately 500 to 300 Ma (million years ago). The geology of the CHIC area was shaped by two major tectonic events: the formation of a failed continental rift, the Southern Oklahoma Aulacogen, during the late Precambrian and Cambrian, which provided a long-lived depositional basin; and the formation of mountain ranges, including the Arbuckle Mountains, during the Mississippian and Pennsylvanian. Between these two events, a general pattern persisted for many tens of millions of years involving multiple cycles of basin filling and subsidence. Sediments would fill the aulacogen, then the floor of the basin would subside, and the process would begin again. This resulted in an exceptional geologic record with relatively few gaps. The collision of North America with the southern landmass Gondwana caused the cycles to end, leading to intense folding and faulting.

The Southern Oklahoma Aulacogen formed during a continental rifting event. In such events, three rifts often form, meeting at a point; two of the rifts continue to completion, but the third fails, leaving a faulted basin behind. The Arbuckles Mountains and CHIC are on the northeast side of the aulacogen (Brown and Grayson 1985). Rifting was accompanied by the production of igneous rocks, ending about 530 Ma (Hanson et al. 2013). The oldest rocks exposed within CHIC belong to the Simpson Group, deposited in the aulacogen during the Ordovician over earlier sedimentary rocks (Ham et al. 1954). At that time, the aulacogen was a long linear basin, with prolonged slow subsidence (Bauer 2010). Rocks deposited within the aulacogen are often significantly different from those deposited on the shallower periphery (Denison 1997). Each of the formations in the Simpson Group above the Joins Formation represents a marine transgression (advance)-regression (retreat) cycle (Bauer 2010). Deposition of each geologic unit began with a "sheet" of sandstone (McPherson et al. 1988). At the end of the preceding cycle, lowering sea level would expose some of the land, and a blanket of sand would form. When sea level began to rise again, the sand blanket would be submerged, and eventually shale and limestone would be deposited above the sand, before sea level dropped and a new cycle began (Johnson 1991). Marine sedimentation was not the only active process; bentonite beds near the top of the Simpson Group, the altered remnants of volcanic ash layers, may represent widespread ash beds found elsewhere in the eastern United States, produced during massive volcanic eruptions. Interestingly, although the climate appears to have shifted from "greenhouse" to "icehouse" conditions at about this time, stable isotope data is inconsistent with cooling at the close of Simpson Group deposition (Rosenau et al. 2012).

The limestones of the Viola Group are the next rocks in ascending order, and initially were deposited in deeper water than the rocks of the Simpson Group. The deeper deposition was also marked by low oxygen in the bottom water. The low oxygen is reflected by the presence of fewer fossils compared to the Simpson Group (Finney 1988). The succeeding Sylvan Shale was deposited during another marine transgression (Eriksson and Leslie 2003), and appears to have been a relatively deep-water formation compared to the other Paleozoic units (Jenkins 1970). The Sylvan Shale is succeeded by the Hunton Group. The Hunton Group is composed of a series of predominantly limestone formations deposited in quiet shallow seas on a gently inclined ramp. Fluctuations of sea level led to a number of minor internal hiatuses (Hollrah 1978; Al-Shaieb et al. 2001). These formations tend to be relatively thin (less than 30 m or 100 ft thick) and are often very fossiliferous. Deposition occurred from the Late Ordovician into the Early Devonian in the CHIC area (Blome et al. 2013).

Following the Hunton Group, the former marine shelf was exposed to subaerial exposure during the Middle Devonian (Hollrah 1978). Karst features, which today form in areas underlain by limestones and include structures like caves and sinkholes, appear to have formed during this period of exposure and non-deposition (Matthews and Al-Shaieb 1993). This gap was ended by another marine transgression and the deposition of the Woodford Shale. The dark Woodford Shale is an example of a more broadly distributed group of Late Devonian–Mississippian black shales (Over 1992). It was deposited under a strongly stratified body of water with low oxygen levels at the bottom, restricting many forms of life (Siy 1994). There is, however, evidence for marine upwelling (Over and Barrick 1990), which promotes productivity, and algal productivity was high (Siy 1994). More marine shale and limestone formations were deposited through the Mississippian (Sycamore Limestone, Caney

Shale), but by the Late Mississippian mountain-building activity had begun, ending the era of marine deposition in and around the aulacogen.

The orogenies (mountain-building events) that created the Arbuckle Mountains and other related ranges in Oklahoma occurred from the Late Mississippian to the Late Pennsylvanian (Brown and Grayson 1985). Deformation occurred intermittently over this time (Billingsley et al. 1996). Each of the three rock units deposited in CHIC during this time shows evidence of the tectonic events, and each is progressively more terrestrial in influence and setting, from the coastal and nearshore Springer Formation (Keighin and Flores 1989), to the mixed terrestrial and marine Deese Group (Billingsley et al. 1996), to the terrestrial Vanoss Formation, formed from alluvial deposits (Donovan and Heinlen 1988). Multiple pulses of folding and faulting affected the rocks (Lehman 1945; Dunham 1955). The culmination of the activity appears to have occurred during the Late Pennsylvanian (Virgilian) (Dunham 1955; Lang 1966), before the deposition of the Vanoss Formation (Dunham 1955), around 300 Ma.

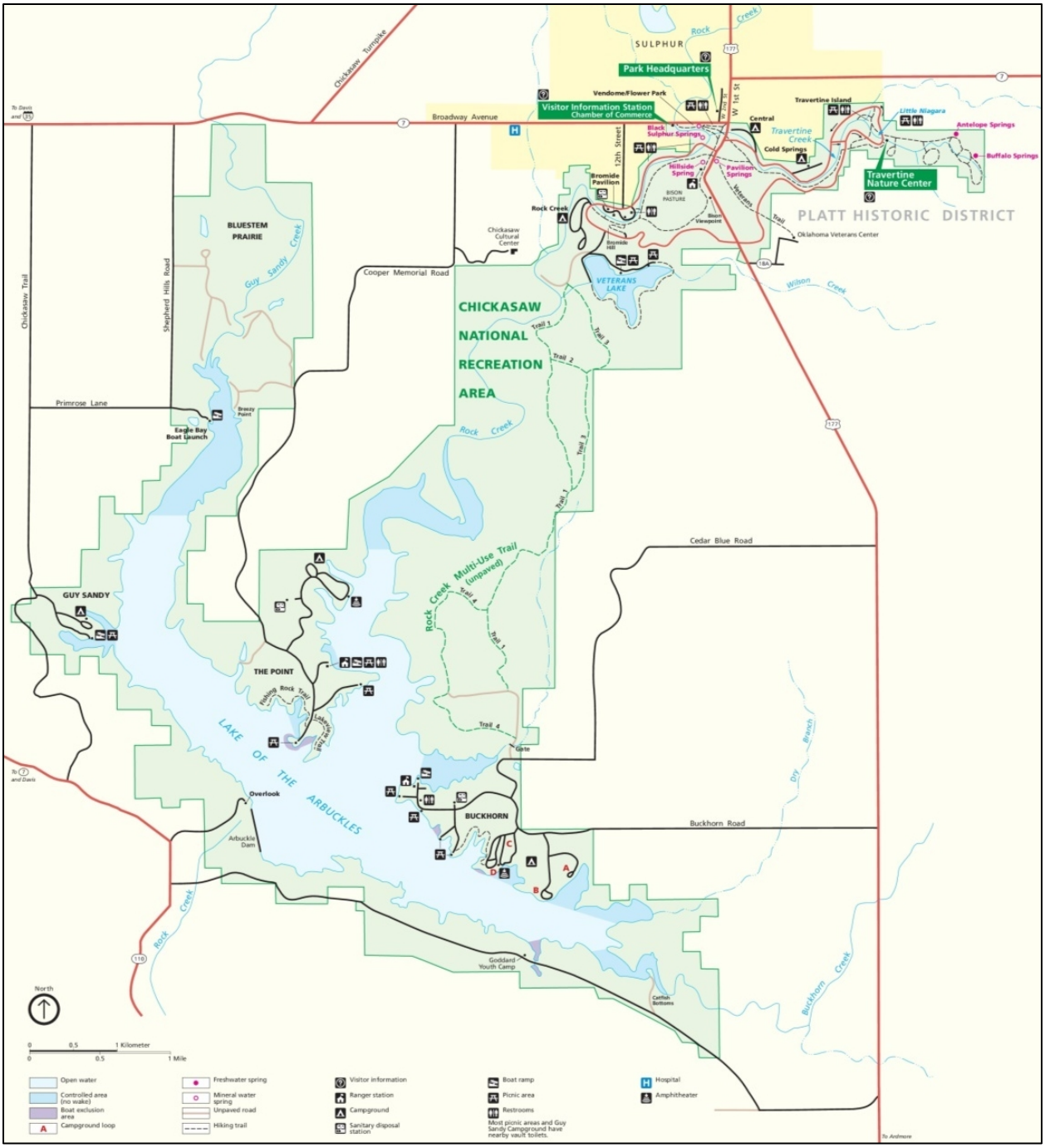
There are no formations younger than the Vanoss Formation present at CHIC, although Permian rocks are present within a few km or mi of the recreation area (Blome et al. 2013). As a result, there is little direct evidence for the events of the following 300 million years. One event that can be discerned through "negative" evidence is the erosion of the Arbuckle Mountains to their present form and the subsequent transport of the rock debris. The mountains were largely eroded by the Cretaceous, when shallow seas once again returned to central Oklahoma (Christenson et al. 2011). Humans arrived in the area by at least 11,000 to 10,000 years ago, as shown by the presence of local Folsom culture material (Ray 1960).

A number of different formations are present within CHIC, although many are only mapped in a small area (Blome et al. 2013), and vegetation and other cover are common (Jackson 1969). The basic configuration features the relatively flat-lying Vanoss Formation overlying highly folded and faulted older Paleozoic rocks (Jackson 1969). In ascending order, the geologic units mapped within CHIC include the Simpson Group (some or all of the Joins, Oil Creek, McLish, Tulip Creek, and Bromide formations) (Middle–Upper Ordovician), the Viola Group (Upper Ordovician), the Sylvan Shale (Upper Ordovician), the Hunton Group (Cochrane, Clarita, Henryhouse, Haragan, and Bois d'Arc formations; Keel Formation omitted; see below) (lower Silurian–Upper Devonian), an undivided unit possibly including the Woodford Shale, Welden Limestone (omitted; see below), and Sycamore Limestone (Upper Devonian–Middle Mississippian), the Caney Shale (Middle–Upper Mississippian), the Springer Formation (Upper Mississippian–Lower Pennsylvanian), the Deese Group (Middle Pennsylvanian), the Vanoss Formation (Upper Pennsylvanian), and Quaternary sediments (Pleistocene–Holocene) (Ham et al. 1954; Blome et al. 2013) (CHIC Figure 3; CHIC Table 1).

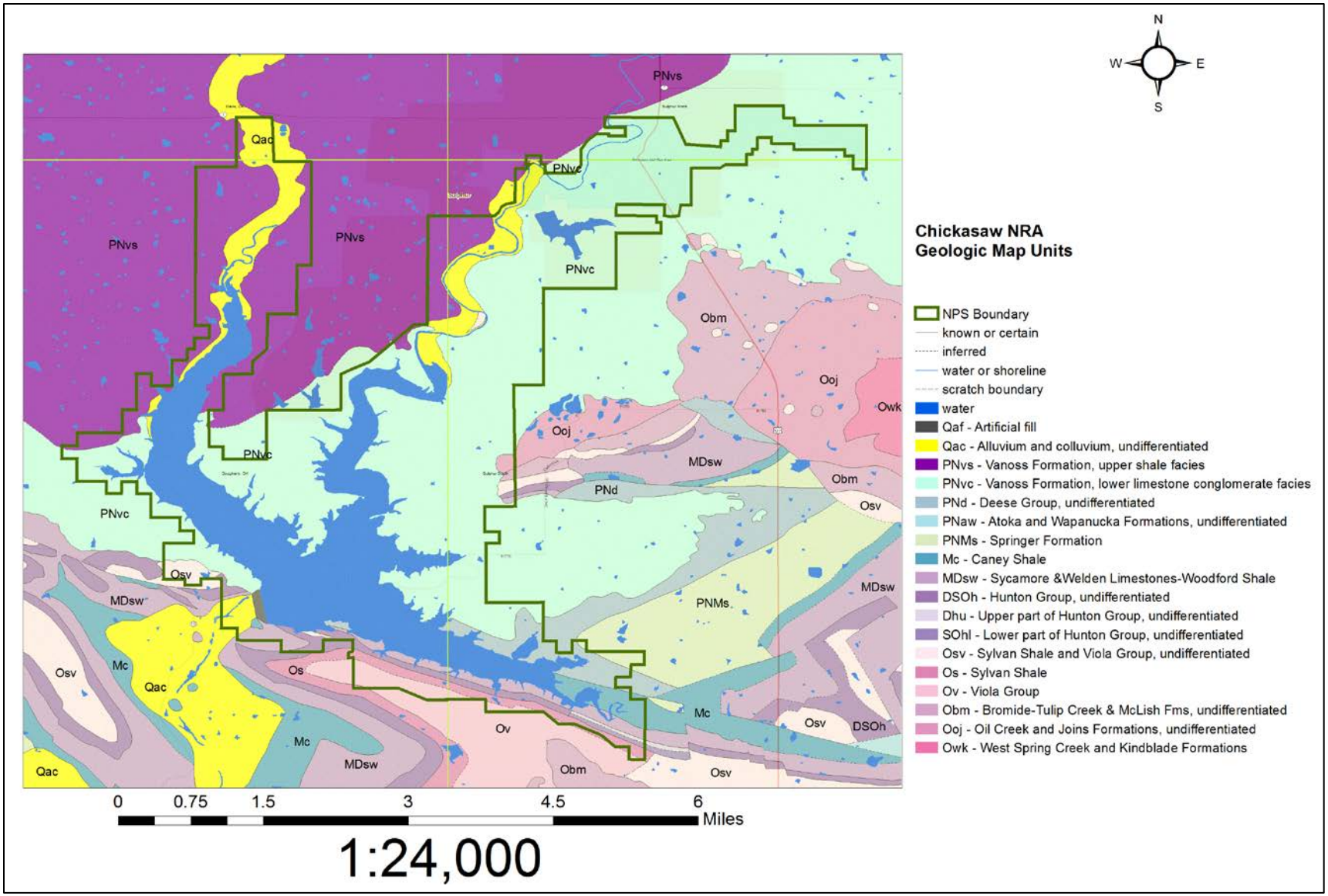
Although there is some possibility that only some of the Simpson Group formations are present in CHIC, for example just the McLish and Bromide formations as mapped in Decker and Merritt (1931), all five are provisionally included here because of the use of undivided units in the primary geologic maps (Ham et al. 1954; Blome et al. 2013), and because the other three units were mapped within a few miles of CHIC by Decker and Merritt (1931). The Keel Formation is omitted from

discussion because it does not appear to be present in the area including CHIC (Amsden 1960). The Welden Limestone is omitted because it was not mapped in CHIC in Decker and Merritt (1931), and it is stated to be absent from the western Arbuckles (Ham et al. 1954, updated as Johnson 1990).

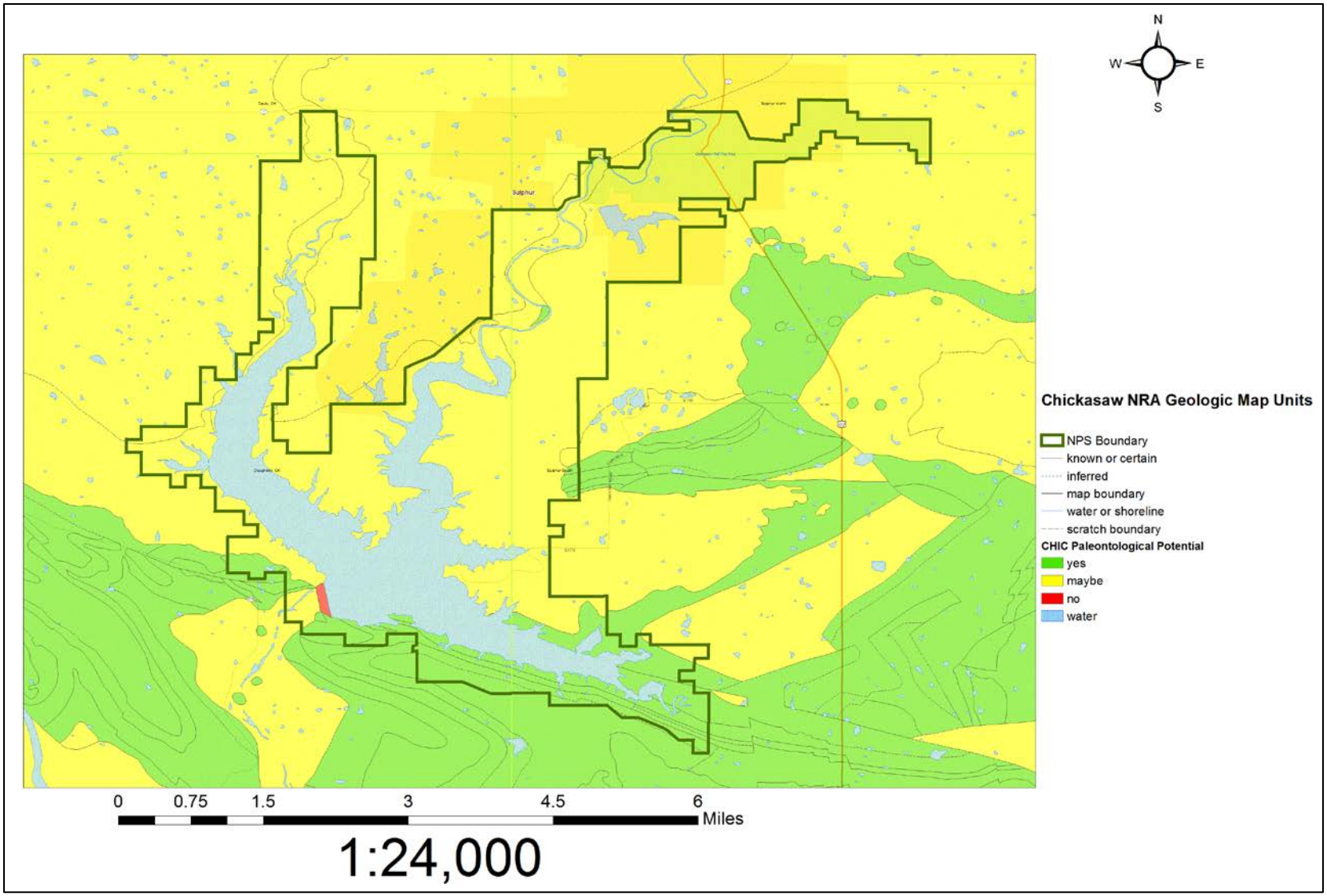
About half of the formations listed above are confirmed to have yielded fossils within CHIC, including the Viola Group, Cochrane Formation, Clarita Formation, Henryhouse Formation, Haragan Formation, Bois d'Arc Formation, Woodford Shale, and Caney Shale. There are equivocal reports of fossils from three other formations: the Bromide Formation, Sylvan Shale, and Deese Group. The formations not known to have yielded fossils in CHIC are the Joins Formation, Oil Creek Formation, Tulip Creek Formation, McLish Formation, Sycamore Limestone, Vanoss Formation, and Quaternary sediments. Although these units have not yet yielded fossils within the recreation area, there is at least some possibility for each (CHIC Figure 4, Table 1), and a ground survey would probably confirm some as fossiliferous. A map of localities is included for reference (CHIC Figure 5). In addition to in situ fossils, CHIC has a small number of fossils in its collection, a few outside institutions have fossils from CHIC, and there is at least one building within the recreation area that includes fossils as building stone.



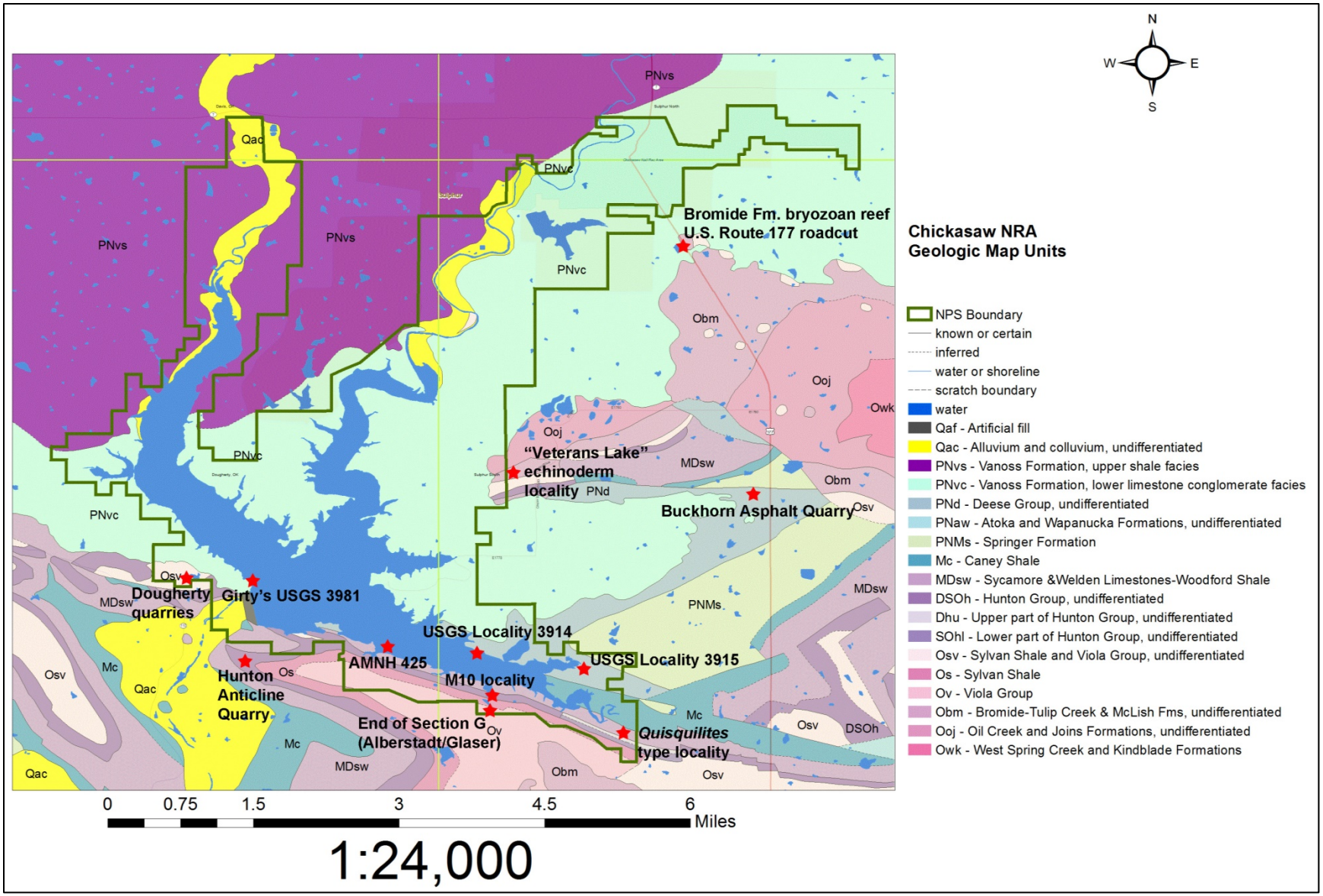
CHIC Figure 2. Geography of CHIC (NPS).



CHIC Figure 3. Schematic geologic map of CHIC. Map graphic adapted from digital geologic map data available at the following URL: https://irma.nps.gov/App/Reference/Profile/2165116.



CHIC Figure 4. Paleontological potential map of CHIC, showing the distribution of geologic units where fossils have been found and may be found. Map graphic adapted from digital geologic map data available at the following URL: https://irma.nps.gov/App/Reference/Profile/2165116.



CHIC Figure 5. Approximate locations of important sites mentioned in the text, using CHIC Figure 3 as a base.

CHIC Table 1. Summary of CHIC stratigraphy, fossils, and depositional settings in descending order of age, from youngest to oldest. Details and references can be found in the text.

Formation	Age	Fossils Within CHIC	Depositional Environment
Quaternary sediments	Pleistocene–Holocene	None to date; isolated fossils of large mammals (mastodons, mammoths, bison) most likely	Fluvial
Vanoss Formation	Late Pennsylvanian	None to date; fossils are uncommon elsewhere	Alluvial
Deese Group	Middle Pennsylvanian	Foraminifera and brachiopods (if USGS locality 3915 pertains to the Deese Group and not the Caney Shale)	Shallow marine to coastal terrestrial
Springer Formation	Late Mississippian–Early Pennsylvanian	None to date; burrows and fossil debris are most likely	Coastal and nearshore
Caney Shale	Middle–Late Mississippian	Brachiopods, ostracodes, acanthodians and unspecified fossils; possibly also foraminifera	Marine
Sycamore Limestone	Early–Middle Mississippian	None to date; fossils are uncommon elsewhere	Marine
Woodford Shale	Late Devonian–Early Mississippian	Acritarchs, chlorophyte algae (*Tasmanites*), other palynomorphs (*Quisquilites*)	Shallow marine, but deeper than the five underlying formations
Hunton Group: Bois d'Arc Formation	Early Devonian	Brachiopods, trilobites, crinoids, and unspecified fossils	Shallow marine
Hunton Group: Haragan Formation	Early Devonian	Rugose corals, bryozoans, brachiopods, bivalves, gastropods, trilobites, ostracodes, crinoids, conodonts, and burrows; possibly ammonites and straight cephalopods (unclear provenance)	Shallow marine
Hunton Group: Henryhouse Formation	late Silurian	Corals, bryozoans, brachiopods, trilobites, and crinoids in situ; ostracodes reworked into the overlying lower Haragan Formation	Shallow marine
Hunton Group: Clarita Formation	early–middle Silurian	Foraminifera, brachiopods, pelmatozoan plates, and conodonts	Shallow marine
Hunton Group: Cochrane Formation	early Silurian	Conodonts	Shallow marine
Sylvan Shale	Late Ordovician	Graptolites? (unclear provenance)	Basinal marine
Viola Group	Late Ordovician	Bryozoans, brachiopods, trilobites, ostracodes, and echinoderms	Basinal marine shallowing over time
Simpson Group: Bromide Formation	Middle–Late Ordovician	Bryozoans, brachiopods, bivalves, ostracodes, trilobites, echinoderms, and graptolites? (unclear provenance)	Reworked coastal sand followed by shallow marine
Simpson Group: Tulip Creek Formation	Middle Ordovician	None to date; bryozoans, ostracodes, and conodonts are most likely	Reworked coastal sand followed by shallow marine
Simpson Group: McLish Formation	Middle Ordovician	None to date; mollusk and echinoderm fragments are most likely	Reworked coastal sand followed by shallow marine
Simpson Group: Oil Creek Formation	Middle Ordovician	None to date; bryozoans, brachiopods, gastropods, trilobites, and ostracodes are most likely	Reworked coastal sand followed by shallow marine
Simpson Group: Joins Formation	Middle Ordovician	None to date; brachiopods, ostracodes, graptolites, and conodonts are most likely	Shallow marine

Sources of Paleontological Resources

The fossils of CHIC present opportunities for education, interpretation, and continued or future scientific research in the recreation area.

Simpson Group: Bromide Formation (Middle–Late Ordovician)

The Bromide Formation is the uppermost unit of the Simpson Group. This geologic unit varies widely both laterally and vertically, although it has a basic configuration of a basal sandstone interval passing into alternating shale and limestone, and finally to limestone (Williams and Siveter 1996). In the CHIC area, the Bromide Formation is composed of a basal brown to white sandstone and an overlying section of interbedded buff-colored limestone and grayish-green shale. It ranges from 96 m (315 ft) to as much as 197 m (647 ft), with the lower sandstone contributing up to 90 m (300 ft). In CHIC, it has been mapped undivided with the other two units of the upper Simpson Group, the McLish and Tulip Creek formations, in one area: the central part of Section 21, T. (Township) 1 S, R. (Range) 3 E (Blome et al. 2013) (the McLish and Tulip Creek formations are discussed under "Potential Sources of Paleontological Resources" below, with the other formations that are exposed in CHIC but are not known to have yielded fossils in the recreation area). Generally, the Bromide Formation is divided into two or three members. The basal sandstone and overlying interbedded shale and limestone belong to the Mountain Lake Member. The overlying limestone interval above belongs to the Pooleville Member (Fay and Graffham 1982). A third member, the Corbin Ranch Member, is sometimes differentiated at the top of the formation (Grahn and Miller 1986), but it is more commonly designated a facies (rocks from a distinct depositional setting) of the upper Pooleville Member (Longman 1981; Fay and Graffham 1982; Bauer 1994). It may be called the Corbin Ranch Submember in the CHIC area (Amsden and Sweet 1983). Historically, the Bromide Formation has been dated to the Middle Ordovician, but it is attributed to time subdivisions that are now considered to cross into the early Late Ordovician (Werts et al. 2001; Carlucci et al. 2012), between about 460 and 455 Ma. The upper contact with the Viola Group is disconformable, but the hiatus is thought to have been short (Lehman 1945; Brown and Grayson 1985).

The Bromide Formation is a marine unit deposited during a transgression-regression cycle, with the Mountain Lake Member representing the transgression and the Pooleville Member representing the regression. The maximum water depth is interpreted as about 80 m (250 ft) (Longman 1981, 1982). At the onset, rising sea level reworked sandy desert deposits, forming the sandstone interval at the base. The sand supply was cut off as sea level continued to rise, and the area became a marine carbonate shelf where shale and limestone were deposited (carbonates are minerals with the carbonate ion CO_3^{-2}, and rocks composed of these minerals, such as limestone). Eventually, the transgression was extensive enough to eliminate other sources of terrestrial sediments, and only limestone was deposited, forming the Pooleville Member. Regression followed, and the area around the aulacogen became a broad tidal flat, represented by the Corbin Ranch facies (Longman 1981, 1982). The deeper aulacogen remained an open marine setting (Denison 1997). Evidence of volcanic eruptions is present in the form of thin layers of bentonite near the top of the formation. These may include the Deicke and Millbrig bentonites, which are found through much of the eastern United States and parts of Europe (Rosenau et al. 2012). If one of the bentonite layers is indeed the Deicke, the upper Bromide Formation can be dated by the age of the bentonite, found to be 454.59 ± 0.56 Ma

by Renne et al. (2010). The bentonite layers are not widely distributed in the Bromide Formation, indicating that central Oklahoma was near the edge of the ash deposition (Leslie et al. 2008).

The Bromide Formation is very fossiliferous, with a diverse faunal assemblage (Rohr and Johns 1990). Bryozoans (moss animals), brachiopods (lamp shells), bivalves, trilobites, ostracodes (seed shrimp), echinoderms (the group including sea stars, sea urchins, and other animals with five-fold symmetry), and graptolites (generally planktonic colonial filter-feeders, perhaps represented today by pterobranch worms) were reported as having been found in CHIC by Koch and Santucci (2003). However, the original list, primarily derived from a written communication (R. Burkhalter, University of Oklahoma, to G. McDonald, NPS, April 2003), appears to be a list of fossils reported from the formation as a whole, not necessarily from within CHIC. A survey of the literature has not revealed any published reports of fossils from the Bromide Formation that can be ascribed to CHIC, but that does not mean fossils are not present. Blome et al. (2013) noted that the limestone is commonly fossiliferous in their mapping area, which includes CHIC, with brachiopods and ostracodes as typical fossils, but specific localities are not mentioned. The Bromide Formation is provisionally accepted as fossiliferous within CHIC, due to the abundance of fossils at localities immediately outside of the recreation area; there is every reason to expect that the formation will prove to be similarly fossiliferous within CHIC.

There are several published fossil localities within about 1.6 km (1 mi) of CHIC. The two areas that have been most thoroughly described are the US 177 (formerly Oklahoma Highway 18) roadcut in the northwest quarter (NW¼) of Section 11, T. 1 S, R. 3 E, and the southern half of Section 3, T. 2 S, R. 3 E. Fossils from the US 177/Highway 18 roadcut have been described in several publications. Loeblich (1942) reported bryozoans there, Bassler (1943) collected examples of the paracrinoid (one of many groups of extinct stalked echinoderms) *Amygdalocystites tribrachiatus* from the locality, Cooper (1956) described brachiopods from the site, Frest et al. (1980) described the paracrinoid *Oklahomacystis spissus* from the Mountain Lake Member at the roadcut, and Carlucci et al. (2012) included trilobites from this locality. Fay et al. (1982) included the roadcut as measured section 10 (Sulphur) for the Bromide Formation echinoderm monograph. They reported finding bryozoans, brachiopods, rhombiferan cystoids (extinct stalked echinoderms), paracrinoids, crinoids (sea lilies), and echinoderm holdfasts (“roots”) in the Mountain Lake Member, and bryozoans and echinoderms in the Pooleville Member. The most notable occurrence at the roadcut is a bryozoan reef that apparently fossilized in place, and includes at least 120 colonies of 21 species (Werts et al. 2001). The reef is high on the west side of the roadcut, in the lower Mountain Lake Member just above the base of the formation, about 0.5 km (0.3 mi) south of the junction with modern Oklahoma Highway 18. It formed under perhaps 3 to 5 m (10 to 16 ft) of tropical marine water. The reef can be described as a crust mound, with the bryozoans growing over their predecessors. Crinoid debris is found around and over the mound (Cuffey and Cuffey 1995).

In Section 3, Bassler (1943) reported collecting examples of the paracrinoid *Amygdalocystites tribrachiatus*, Cooper (1956) described brachiopods from near a ranch road in the southeast quarter of the section, and Rohr and Johns (1990) named the gastropod *Oriostoma bromidensis* from a strip quarry within a mile of CHIC in the NE¼ SW¼ SW¼ (northeast quarter of the southwest quarter of

the southwest quarter) of the section. This locality is interpreted as lagoonal, with a water depth perhaps 20 to 30 m (65 to 100 ft). The fauna also includes bryozoans, brachiopods, nautiloids (cephalopods related to the modern *Nautilus*, although many had straight shells instead of coiled shells), echinoderms, and other organisms (Rohr and Johns 1990). Outcrops in the NE¼ SW¼ SW¼ of Section 3, about 0.8 km (0.5 mi) east of the ranch house, were also used for a measured section (Section 9, Buckhorn) in the echinoderm volume. Fay et al. (1982) found bryozoans, brachiopods, cephalopods, rhombiferan cystoids, paracrinoids, crinoids, edrioasteroids (extinct echinoderms resembling a bulb or disc with a sea star laying on it), and edrioblastoids (another group of extinct echinoderm) in the Mountain Lake Member, and bryozoans and brachiopods in the Pooleville Member.

Other localities very near CHIC have also been described in the literature, but not as extensively. Cooper (1956) also described brachiopods from the NW¼ of Section 23, T. 1 S, R. 3 E, and several points in the vicinity of CHIC were used as additional collecting localities for the echinoderm volume. The locality nearest to CHIC is the Veterans Lake site at NW¼ SW¼ NE¼ SE¼ Section 21, T. 1 S, R. 3 E, where paracrinoids and edrioasteroids were collected from the Mountain Lake Member on the steep rubbly southeast bank of a small stream (Fay et al. 1982). Harris (1957) included a graphic of ostracode ranges from a site reportedly along Highway 99 in Section 11, T. 1 S, R. 3 E, which would be just outside of CHIC, but there appears to be an error in the location; the site is also stated to be “3 miles S. Fittstown,” which would actually be over 32 km (20 mi) northeast of the stated section, and Highway 99 is not near CHIC, but is near Fittstown. Because the road and town descriptions are in agreement, it seems most likely that the section-township-range location is in error.

Numerous fossils have been described from the Bromide Formation over its entire depositional area. Broadly speaking, the Mountain Lake and Pooleville members have similar types of fossils, with different depositional settings yielding different assemblages. Notable among them are the Corbin Ranch beds at the top of the formation, featuring microbial structures that formed near sea level (Longman 1982). Invertebrate groups represented by body fossils include glass sponges (sponges with a skeletal framework of silica) (Rigby and Gutschick 1976), stromatoporoid sponges, the possible sponge *Solenopora compacta* (Decker and Merritt 1931), possibly corals (Amsden 1957a), conulatans (extinct animals related to corals and hydras, which formed triangular body structures of rods in a herringbone pattern) (Decker and Merritt 1931), bryozoans (Loeblich 1942; Key 1990, 1991), brachiopods (Cooper 1956), cornulitids (a type of extinct “tube worm”), monoplacophorans (limpet-like mollusks) (Decker and Merritt 1931), rostroconchs (bivalve-like mollusks) (Branson 1966), bivalves, nautiloids (Decker and Merritt 1931), gastropods (Rohr and Johns 1990), trilobites (Shaw 1974), ostracodes (Harris 1957), diverse echinoderms (Sprinkle 1982a), graptolites (Amsden 1957a), and conodonts (eel-like vertebrate relatives known from “jaw” elements) (Harris 1964; Bauer 1990a, 1994). Other types of fossils reported from the Bromide Formation include microbial structures (e.g., the flat-layered structures known as stromatolites; Longman 1982), cyanobacteria (Amsden and Sweet 1983), acritarchs (organic microfossils that cannot be assigned to any other group) (Loeblich and Tappan 1971a, 1971b; Tappan and Loeblich 1972), chitinozoans (flask-shaped organic microfossils) (Grahn and Miller 1986), receptaculitids (enigmatic, formerly identified as

sponges or algae), calcareous red algae (formerly known as the coral *Tetradium*) (Amsden 1957a), borings on other fossils, (Brett 1985), bioturbation (general sediment disruption by living things) and burrows (Karim and Westrop 2002), and coprolites (fossil feces) (Harris and Harris 1965). The Pooleville Member is more fossiliferous than the Mountain Lake Member (Longman 1981). Trilobites are sometimes found in clusters that are interpreted as molting aggregations (Karim and Westrop 2002).

The Bromide Formation has perhaps the largest and most diverse assemblage of echinoderms known from an Ordovician formation, and over 11,000 specimens were described in the Sprinkle (1982a) monograph. Most came from one of three zones, the narrow Lower and Upper Echinoderm Zones in the Mountain Lake Member, and the broader Pooleville Echinoderm Zone in the upper Pooleville Member (Sprinkle 1982b). Groups represented, most of which are now extinct, include homoiosteleans (enigmatic), stylophorans (enigmatic), eocrinoids (stalked), diploporan and rhombiferan cystoids (stalked), crinoids, paracrinoids, echinoids (sea urchins), edrioasteroids, edrioblastoids, cyclocystoids (disc-like), asteroids (sea stars) (Sprinkle 1982b), and extinct asteroid relatives (Blake 2008). Possible holothurian (sea cucumber) sclerites described by Reso and Wegner (1964) have been provisionally accepted by several authorities, although they may instead be from embryonic crinoids or ophiocistioids (extinct echinoderms that somewhat resembled echinoids) (Sprinkle 1982c), or could even be broken fragments of trilobites (Branson 1964a).

Viola Group (Upper Ordovician)

The Viola Group represents a new transgression in the aulacogen basin following the filling that produced the Simpson Group. In the CHIC area, the Viola Group is composed of the Viola Springs and overlying Welling formations, undivided on the Blome et al. (2013) map. The Viola Springs Formation is composed of white to bluish-gray chert-rich limestone with thin interbedded layers of green to gray shale. The Welling Formation is composed of gray limestone, coarser than that of the Viola Springs Formation. Together, they are about 210 m (700 ft) thick (Blome et al. 2013). Older references may call the Viola Springs Formation interval the Viola Limestone, and the Welling Formation interval the Fernvale Limestone (Finney 1988). In the CHIC area, the Viola Group is sometimes mapped with the overlying Sylvan Shale and sometimes mapped separately. The two formations are mapped undivided in CHIC northwest of the Arbuckle Dam, a small area in the floodplain of Rock Creek near the middle of the north boundary line of Section 16, T. 1 S, R. 3 E, and south of the Simpson Group in the south-central part of Section 21, T. 1 S, R. 3 E. The Viola Group is mapped by itself in the core of the Tishomingo Anticline along the southeast boundary of the park (Blome et al. 2013). Viola Group asphalt was formerly mined from quarries within what is now CHIC (U.S. Asphalt No. 1 and No. 2, the latter also known as the Dougherty Asphalt Quarry), in the SE¼ of Section 25, T. 1 S, R. E, and the SW¼ of Section 30, T. 1 E, R. 3 E (Gorman and Flint 1944). Extraction went on from 1890 to 1960 (Cardott and Chaplin 1993).

The Viola Springs Formation is dated by fossils to the early Late Ordovician (late Mohawkian to early Cincinnatian, today dated around 453 Ma), and the Welling Formation dates to a slightly later part of the early Late Ordovician (Derby et al. 1991). The Viola Springs Formation grades into the Welling Formation, although there does appear to be a hiatus within the Viola Springs Formation

(Amsden and Sweet 1983). The contact with the overlying Sylvan Shale is interpreted as conformable (Amsden and Sweet 1983), although paleokarst features provide evidence for a period of nondeposition and exposure after deposition of the Welling Formation (Sykes et al. 1997).

Deposition of the Viola Group took place in and around the aulacogen. Subsidence of the aulacogen following deposition of the shallow-water Corbin Ranch rocks of the Bromide Formation led to deep basinal deposition for the lower Viola Group. The bottom waters were poorly oxygenated during the early part of deposition, but over time as the basin shallowed, the waters became more oxygenated. This is reflected by the presence of relatively few fossils in the lower rocks, and more up-section (Finney 1988). The Welling Formation was deposited in shallower water than the Viola Springs Formation, mostly at shallow subtidal to intertidal depths (Sykes et al. 1997).

The Viola Group is fossiliferous within CHIC. Section G, one of the stratigraphic sections described by Glaser (1965) and Alberstadt (1967, 1973), begins outside of CHIC and finishes within CHIC, in the NW¼ NE¼ of Section 4, T. 2 S, R. 3E. The lowest measured part of the stratigraphic section begins 360 m (1,200 ft) south of the north line of the geographic section, and 710 m (2,340 ft) west of the east line, in a valley formerly leading to Buckhorn Creek (now entering the Lake of the Arbuckles). The stratigraphic section measures 130 m (420 ft) of the middle and upper Viola Group. Because the beds dip (northeast from 9° to 40°), a foot up-section is not equivalent to a horizontal foot of distance. The contact with the Sylvan Shale was not located, but the Sylvan Shale is exposed 90 m (300 ft) down the valley from the upper terminus of the stratigraphic section (Glaser 1965). Although the exact trace of the stratigraphic section is not depicted, from the geographic and geologic information the upper part of the section is within CHIC. Both Glaser (1965) and Alberstadt (1967, 1973) observed “abundant” trilobites and echinoderms in the uppermost 6 m (20 ft) of the stratigraphic section (unit 3C), which is now considered to be the Welling Formation. Alberstadt (1967, 1973) found several species of brachiopods in this interval as well. Furthermore, Glaser (1965) made petrographic thin sections of rocks from this interval and identified pieces of bryozoans, brachiopods, trilobites, ostracodes, and echinoderms, as well as possible indications of burrowing. Koch and Santucci (2003) reported trilobites and graptolites, although it is unclear if this is a reference to CHIC or to the formation as a whole.

There are also several references to fossils found within about a km or mi of CHIC. Aside from the G section of Glaser and Alberstadt, which is split by the recreation area boundary, Section P is just outside of the park in the SE¼ SE¼ of Section 2, T. 2 S, R. 3 E. Alberstadt (1973) described brachiopods from this site. Shaw (1991) reported trilobites from along Wilson Creek in the NW¼ of Section 11, T. 1 S, R. 3 E, and the southeast corner of Section 3, T. 2 S, R. 3 E, just outside of CHIC. Bates and Kirk (1991) discussed graptolites from several locations, including one made up of material excavated from a swimming pool on the Jones (Buckhorn) Ranch. The exact location is not clear from the description, but it should be within a few km or mi of CHIC.

In the past, the Welling (or Fernvale) interval was not always distinguished or consistently separated from the Viola Springs interval, and because of this, and the fact that the two are not distinguished on geologic maps of CHIC to date, the assemblages of the two will be considered together. If it becomes necessary to distinguish between the fossils of the two, Taff (1903) and Decker (1933) present lists

by members or zones, although note that they may not be found to correspond precisely to modern stratigraphic definitions or taxonomy. Fossils reported from the Viola Group including areas outside of CHIC include chitinozoans (Jenkins 1969; Grahn and Miller 1986), foraminifera ("amoebas with shells") (Amsden 1957a), receptaculitids (Decker 1933), red algae ("*Tetradium*") (Taff 1903), sponge spicules (Amsden and Sweet 1983), rugose corals (extinct corals; solitary examples are known as horn corals), conulatans, bryozoans (Decker 1933), brachiopods (Alberstadt 1973; Amsden and Sweet 1983), bivalves, nautiloids, gastropods (Decker 1933), polychaete (bristle worm) jaws (Colbath and Larson 1980), trilobites (Amsden and Ham 1959; Amati and Westrop 2006; Carlucci et al. 2010), ostracodes (Amsden 1957a), crinoids and other echinoderms (Ossian and Halseth 1976), graptolites (Ruedemann and Decker 1934), conodonts (Amsden and Sweet 1983), heterostracan fish (early jawless fish) (Ossian and Halseth 1976), and bioturbation and burrows (Amati and Westrop 2006). Trilobites and graptolites are among the most common fossils (Decker 1933).

Sylvan Shale (Upper Ordovician)

The Sylvan Shale is a shale interval between the carbonate rocks of the Viola Group and Hunton Group. In the CHIC area, the Sylvan Shale is mostly composed of green, gray, or tan lime-rich and dolomite-rich shale, but it is rarely exposed because it weathers easily. It ranges from 15 to 90 m (50 to 300 ft) thick. The Sylvan Shale is mapped undivided with the underlying Viola Group in CHIC northwest of the Arbuckle Dam, a small area in the floodplain of Rock Creek near the middle of the north boundary line of Section 16, T. 1 S, R. 3 E, and south of the Simpson Group in the south-central part of Section 21, T. 1 S, R. 3 E. The Sylvan Shale is mapped by itself on the north flank of the Tishomingo Anticline along the southern boundary of the park (Blome et al. 2013). The upper contact with the Keel Formation is conformable (Playford and Wicander 2006), but if the Keel Formation is absent, as appears to be the case for at least part of CHIC (Amsden 1960), the upper contact is disconformable. Deposition of the Sylvan Shale occurred during the middle Late Ordovician (Richmondian) (Playford and Wicander 2006), about 445 Ma.

The Sylvan Shale was deposited during a marine transgression (Eriksson and Leslie 2003). During this event, the clays that became the Sylvan Shale were deposited over the rocks of the Viola Group (Denison 1997). Deposition was under low-energy conditions, and the water depth may have been greater than for other pre-Mississippian formations in the Arbuckle Mountains (Jenkins 1970). The water is interpreted as anoxic, explaining the low fossil content (Playford and Wicander 2006).

It is unclear if the Sylvan Shale is fossiliferous within CHIC. Koch and Santucci (2003) reported that graptolites were known from the Sylvan Shale, although it is not clear from the context of the statement or the original communication if this refers to a site within CHIC or to the formation in general. There does not appear to be any other references to fossils in the Sylvan Shale from a site within CHIC. Overall, the Sylvan Shale is not as fossiliferous as the formations above and below, at least not at the macroscopic level. The most common fossils tend to be very small to microscopic: acritarchs, chitinozoans, microphytoplankton, scolecodonts (worm jaws), graptolites, and conodonts (Playford and Wicander 2006). Most fossils are found in the lower part of the formation, and the upper part may be devoid of macrofossils (Jenkins 1970). Types of fossils reported from the Sylvan Shale include acritarchs (including reports of hystrichospheres) (Loeblich and Tappan 1971a),

chitinozoans (Wilson 1958; Wilson and Hedlund 1964; Jenkins 1970), microphytoplankton (possibly chlorophyte blue algae) (Playford and Wicander 2006), foraminifera (Conkin and Conkin 1965), conulatans, brachiopods (Taff 1903), scolecodonts (Eriksson and Leslie 2003; Eriksson et al. 2005), graptolites (Decker 1935a), and conodonts (Taff 1903).

Hunton Group: Cochrane Formation (lower Silurian)

The Cochrane Formation is one of a series of formations included in the Hunton Group. At CHIC, it is the lowest unit of the Hunton Group because the formation that underlies it elsewhere, the Keel Formation, does not appear to be present in the vicinity of the recreation area (Amsden 1960). The Keel, Cochrane, and Clarita formations are sometimes identified as members of the Chimneyhill Formation in older works (Amsden 1967). The Cochrane Formation was initially known as the "glauconitic member" of the Chimneyhill Limestone (Reeds 1911). In the CHIC area, the Cochrane Formation is composed of white to bluish- or greenish-gray limestone, 4 to 5 m (12 to 15 ft) thick (Blome et al. 2013). In CHIC, it is mapped undivided with the rest of the Hunton Group, except for a small area of the southeastern Tishomingo Anticline where lower and upper Hunton Group sections are mapped separately. The Hunton Group is mapped along the north flank of the Tishomingo Anticline in the southeastern part of the recreation area, northwest of the Arbuckle Dam, and in the south-central part of Section 21, T. 1 S, R. 3 E (Blome et al. 2013).

The Hunton Group formations represent a series of shallow-water carbonates deposited on a gently inclined ramp. Changes in sea level resulted in multiple hiatuses separating most of the formations (Al-Shaieb et al. 2001). In some locations, individual formations of the Hunton Group have been eliminated by erosion before the deposition of the next formation (Amsden 1960). The Cochrane Formation has a disconformable upper contact with the overlying Clarita Formation, with the hiatus representing part of the late early Silurian. Where the Keel Formation is present, its contact with the Cochrane Formation is also a disconformity (Al-Shaieb et al. 2001). The Cochrane Formation was deposited during the late early Silurian (late Llandovery) (Al-Shaieb et al. 2001), about 436 Ma.

The Cochrane Formation is fossiliferous within CHIC. Amsden (1960) reported conodonts from this unit in the M10 section, in the SW¼ SE¼ of Section 33, T. 1 S, R. 2 E, just east of a small stream flowing into what had been Little Buckhorn Creek. Relatively little has been published on Cochrane Formation fossils, but a fairly diverse assemblage is known. Fossils reported from the formation over its entire depositional area include sponge spicules (Amsden 1957b), rugose corals (Elias 1992), tabulate corals (extinct colonial "honeycomb" corals) (Reeds 1911), bryozoans (Barrick et al. 1990a), brachiopods, rostroconchs, nautiloids, gastropods, trilobites (Reeds 1911), ostracodes, (Amsden 1957b), crinoids (Reeds 1911), conodonts (Amsden 1957b), and burrows (Stanley 2001). Fossils are difficult to extract because of the hardness of the beds (Barrick et al. 1990a).

Hunton Group: Clarita Formation (lower–middle Silurian)

The Clarita Formation was first described as the "pink crinoidal" member of the Chimneyhill Formation (Reeds 1911), and was also known as the Dillard Member before receiving its current name (Amsden 1967). The Clarita Formation in the CHIC area is generally composed of fine-grained limestone. The lower part is the lower Silurian Prices Falls Member, composed of shale and marl, and the upper part is the middle Silurian Fitzhugh Member, composed of limestone. The formation is

as much as 45 ft (14 m) thick (Blome et al. 2013). Most of this thickness is in the Fitzhugh Member; the Prices Falls Member is never more than 0.5 m (1.6 ft) thick (Amsden et al. 1980). The Clarita Formation is mapped in CHIC with the rest of the Hunton Group as described under the "Cochrane Formation" above. The Clarita Formation spans the early–middle Silurian boundary (Llandovery–Wenlock, about 433 Ma), with the Prices Falls Member deposited during the late early Silurian (Llandovery) and the Fitzhugh Member deposited during the early middle Silurian (Wenlock) (Amsden 1967). The contact with the overlying Henryhouse Formation is disconformable (Amsden 1962a). Deposition of the Clarita Formation occurred in moderately deep water (Amsden et al. 1980).

The Clarita Formation is fossiliferous within CHIC. At the M10 locality (see above under "Cochrane Formation"), Amsden (1958a) reported pelmatozoans (a general term for stalked echinoderms), and Amsden (1960) reported foraminifera, brachiopods, pelmatozoan plates, and conodonts. Within a few km or mi of CHIC, common fossils include foraminifera, brachiopods, ostracodes, crinoids, and conodonts (Blome et al. 2013). Overall, types of fossils reported from the Clarita Formation over its entire depositional area include foraminifera (Parker et al. 2013), rare algae (Amsden et al. 1980), rugose and tabulate corals (Reeds 1911), bryozoans (Amsden et al. 1980), brachiopods (Amsden 1968), hyoliths (Reeds 1911), rostroconchs (Branson and Amsden 1958), bivalves, cephalopods, gastropods (Amsden et al. 1980), trilobites (Holloway 1980), ostracodes, crinoids and other pelmatozoans (Amsden et al. 1980), conodonts (Barrick and Klapper 1976), and trace fossils such as borings on brachiopods (Chatterton and Whitehead 1987). Macroscopic fossils are found in the Fitzhugh Member; the Prices Falls Member has abundant microfossils (Amsden 1968) but lacks macrofossils (Amsden et al. 1980). Northeast of CHIC, the Fitzhugh Member is more abundantly fossiliferous, but in the CHIC area the member was deposited with more mud, which correlates to fewer and less diverse fossils. This may be because muddier bottom conditions were less suitable for immobile filter-feeders. Brachiopods and crinoids are less common in the more mud-rich rocks, whereas gastropods, trilobites, and ostracodes are more common (Amsden et al. 1980).

Hunton Group: Henryhouse Formation (upper Silurian)

The Henryhouse Formation in the CHIC area is composed of variegated limestone, with interbedded yellowish shale in the lower part. It can be as thick as 65 m (220 ft), but more typically is closer to 27 m (90 ft) thick (Blome et al. 2013). The Henryhouse Formation is mapped in CHIC with the rest of the Hunton Group as described under the "Cochrane Formation" section above. The upper contact with the Haragan Formation is disconformable (Lehman 1945; Amsden 1962a; Barrick and Klapper 1992). The Henryhouse and Haragan formations are quite similar lithologically and only differ significantly in fossil content (Barrick and Klapper 1990, 1992). The Henryhouse Formation was deposited during the Ludlow and Pridoli stages of the Silurian (Barrick and Klapper 1992), approximately 425 to 420 Ma. It was deposited in a low-energy, shallow-marine setting. To the northwest, the depositional basin was shallower, while in the Arbuckle Mountains deposition was typically subtidal (Al-Shaieb et al. 2001).

The Henryhouse Formation is fossiliferous within CHIC, with several publications describing fossils from the M10 locality (see more details under "Cochrane Formation" above). These include rugose corals described by Sutherland (1965) and trilobites described by Campbell (1967). Lundin (1968),

describing ostracodes from the Haragan Formation, noted that typical Henryhouse ostracodes appeared to have been reworked into the lower Haragan Formation at M10. Amsden (1960), describing the stratigraphic section from the M10 site, reported no fossils from the lower part of the formation, corals, bryozoans, brachiopods, and trilobites from the middle part, and bryozoans, brachiopods, and trilobites from the upper part. In the Goddard Youth Camp area of CHIC, in Section 33, T. 1 S, R. 3 E, fossils are rare and limited to bits of crinoids (Stanley 2001).

Including areas outside of CHIC, types of fossils recorded from the Henryhouse Formation include acritarchs, prasinophyte algae (Miller 1998), foraminifera (Moreman 1930; Ireland 1939), the enigmatic encruster *Ascodictyon* (Reeds 1911), sponges (Finks 1995), rugose corals (Sutherland 1965), tabulate corals, bryozoans (Reeds 1911), brachiopods (Amsden 1951, 1958a; Boucot and Amsden 1958), bivalves (Reeds 1911), nautiloids (Miller and Collinson 1952), gastropods (Reeds 1911), trilobites (Campbell 1967), ostracodes (Lundin 1965, 1967), blastoids (Reimann and Fay 1961; Fay and Reimann 1962), crinoids (Strimple 1952, 1963; Frest and Strimple 1980), graptolites (Decker 1935b), conodonts (Barrick and Klapper 1976, 1992), and burrows (Al-Shaieb et al. 2001). Fossils described as phylloid crustaceans by Ruedemann (1935) and occasionally cited elsewhere are not crustaceans, cannot be determined to phylum, and may even be plants (Churkin 1966). More fossils are found in the upper part of the formation than in the lower part (Reeds 1911).

Hunton Group: Haragan Formation (Lower Devonian)

The Haragan Formation is one of the most fossiliferous formations of the CHIC area. The Haragan Formation within and near CHIC is composed of alternating bluish to white shale, limestone, and yellow- to tan-weathering mudstone. It can be as much as 51 m (166 ft) thick, but averages 30 m (100 ft) thick (Blome et al. 2013). The Haragan Formation is mapped in CHIC with the rest of the Hunton Group as described under the "Cochrane Formation" above. The upper contact with the Bois d'Arc Formation is gradational (Stanley 2001). The Bois d'Arc Formation is sometimes interpreted as a facies of the Haragan Formation (Lundin 1967; Campbell 1977). Deposition of the Haragan Formation occurred during the early Early Devonian (Lochkovian) (Barrick and Klapper 1992), between 419 and 411 Ma.

Like the Henryhouse Formation, deposition of the Haragan Formation is interpreted as subtidal in the Arbuckle Mountains (Al-Shaieb et al. 2001). The setting was a warm continental sea, somewhat turbid, with a slightly muddy bottom (Amsden 1958a). The rate of sedimentation was slow, as shown by the extensive growth of encrusting animals including corals and bryozoans on empty shells (Cuffey et al. 1995b).

The Haragan Formation is fossiliferous within CHIC. In the Goddard Youth Camp area in CHIC, fossils are common and well-preserved, and include rugose corals, bryozoans, brachiopods, trilobites, crinoids, and burrows (Stanley 2001). Bivalves have also been reported from the Youth Camp area (Koch and Santucci 2003). Several authorities have reported or described fossils from the M10 locality (see under "Cochrane Formation" above for more information), including Amsden (1958a) (brachiopods), Lundin (1968) (ostracodes), Campbell (1977) (trilobites), Barrick and Klapper (1992) (conodonts), and Cuffey et al. (1995a) (bryozoans). Amsden (1960), describing the stratigraphy at M10, reported the presence of rugose corals, brachiopods, mollusks including gastropods, trilobites,

ostracodes, and crinoid holdfasts. Koch and Santucci (2003) include a reference to gastroliths, ammonites, straight cephalopods, and sharks from the Haragan Formation attributed to Wayne Edgar (Goddard Youth Camp), but this appears to be a misinterpretation of the communication; the gastroliths are Cretaceous in age and are not specifically attributed to the Haragan Formation, and the shark appears to be a reference to the Caney Shale acanthodian from CHIC (see below). The locality or localities of the cephalopods are not clear from the original communication.

One of the most notable fossil localities in the Haragan Formation, White Mound, is a few km or mi outside of CHIC in the SW¼ NW¼ NE¼ of Section 20, T. 2 S, R. 3 E. White Mound was first noted by geologists around 1901, and since that time more than 8,000 students from the University of Oklahoma have visited the site, along with groups from many other organizations. The mound has decreased in height over that time from more than 11 m (35 ft) to 6 m (20 ft). More than 100 fossil species have been collected here, representing foraminifera, sponges, corals, bryozoans, brachiopods, bivalves, nautiloids, trilobites, ostracodes, and conodonts, as well as worm burrows (Chaplin 2005). Aside from its paleontological importance, White Mound is also notable as the type locality for the Haragan Formation (Amsden 1958c).

Diverse fossils have been reported from the Haragan Formation including areas outside of CHIC. Types of fossils represented include possible algal microfossils (Loeblich and Wicander 1976), phytoplankton (Wicander et al. 2006), acritarchs (Loeblich and Drugg 1968; Loeblich and Tappan 1970; Wicander 1986), foraminifera (Moreman 1933; Ireland 1939), glass sponges and softer demosponges (Rigby et al. 2009), rugose and tabulate corals, tentaculitids (extinct “tube worms”) (Reeds 1911), bryozoans (Cuffey et al. 1995a), brachiopods (Amsden 1956, 1958c; Amsden and Ventress 1963), rostroconchs (Branson and Amsden 1958), bivalves, nautiloids, gastropods (Reeds 1911), trilobites (Campbell 1967), ostracodes (Roth 1929; Coryell and Cuskley 1934; Lundin 1967, 1968), crinoids (Strimple 1963), graptolites (Decker 1941), conodonts (Barrick et al. 1990a; Barrick and Klapper 1992), and burrows (Stanley 2001).

Hunton Group: Bois d’Arc Formation (Lower Devonian)

In the CHIC area, the Bois d’Arc Formation is composed of limestone with some chert and shale. It is as much as 27 m (90 ft) thick, but averages 20 m (60 ft) thick (Blome et al. 2013). The Bois d’Arc Formation is mapped in CHIC with the rest of the Hunton Group as described under the “Cochrane Formation” above. The Bois d’Arc Formation is commonly divided into two members: the lower Cravatt Member and the upper Fittstown Member. The Cravatt Member is chert-rich, and the Fittstown Member is composed of sand-sized carbonate grains (calcarenite). The two members have a gradational contact and are thought to be facies of each other (Amsden 1958b). As mentioned above, the Bois d’Arc Formation is similar to the Haragan Formation, but they can be distinguished by the greater chert content of the lower Bois d’Arc rocks (Lundin 1967). Deposition occurred toward the end of the early Early Devonian (Lochkovian) (Stanley 2001), about 411 Ma. The upper contact with the Woodford Shale is disconformable (Lehman 1945).

The Bois d’Arc Formation was deposited under somewhat shallower water than the underlying Haragan Formation, with the Cravatt Member deposited closer to storm wave base than the Fittstown Member, which was deposited under shallower water (Stanley 2013). The environmental setting of

the Cravatt Member is thought to have been like the Haragan Formation, and the Fittstown Member is interpreted as having formed primarily from invertebrate remains buried in place (Amsden 1958b).

The Bois d'Arc Formation is fossiliferous within CHIC. At the M10 locality (see under "Cochrane Formation" above for more information), Amsden (1958b) reported brachiopods in the Fittstown Member, Amsden (1960) reported the presence of unspecified fossils in the Cravatt Member and brachiopods in the Fittstown Member, and Campbell (1977) reported finding a trilobite specimen from the Fittstown Member. In the vicinity of the Goddard Youth Camp within the recreation area, Stanley (2001) reported fragments of brachiopods and crinoids in the Cravatt Member and fragments of brachiopods, trilobites, and crinoids in the Fittstown Member. The Bois d'Arc Formation is also fossiliferous just outside of CHIC. The Hunton Anticline Quarry, in the SE¼ SE¼ NW¼ of Section 31, T. 1 S, R. 3 E, is one such documented locality. At this site, the Cravatt Formation includes bryozoans, brachiopods, crinoids, and burrows, and the Fittstown Member includes rugose corals, brachiopods, trilobites, and crinoids (Stanley 2001). The quarry was opened in the mid-1960s to provide riprap and building material for Arbuckle Dam (Stanley 2013). Some of this riprap is fossiliferous; Neil Suneson (Oklahoma Geological Survey, pers. comm., May 2015), observed a trilobite in the riprap before the dam was closed off for security following the September 11th attacks.

Overall, the fossils of the Bois d'Arc Formation are similar to those of the Haragan Formation (Reeds 1911; Amsden 1958b). Brachiopods are common (Amsden 1958b). The Cravatt Member is fossiliferous, but it is difficult to collect fossils from it (Amsden 1957b). Fossils reported from the Cravatt Member including areas outside of CHIC include palynomorphs (organic microfossils, such as spores and pollen) of uncertain affinities (Loeblich and Wicander 1976), sponges, rugose corals (Amsden 1962b), bryozoans (Stanley 2001), brachiopods (Amsden 1958b), machaeridians (extinct armored annelid worms) (Vinther and Briggs 2009), trilobites (Campbell 1977), ostracodes (Lundin 1968), homoiosteleans, stylophorans, rhombiferan cystoids (Parsley and Sumrall 2007), crinoids, and burrows (Stanley 2001). Fossils reported from the Fittstown Member include rugose corals (Stanley 2001), brachiopods (Amsden 1958b), mollusks (Amsden 1957b), trilobites (Campbell 1977), ostracodes (Lundin 1968), and crinoids (Stanley 2001). Fossils reported from the Bois d'Arc Formation with no member specified include microplankton (Loeblich and Wicander 1974; Barrick et al. 1990b), tabulate corals, bivalves, nautiloids, gastropods (Amsden 1958b), conodonts (Barrick et al. 1990a; Barrick and Klapper 1992), and acanthodian fish ("spiny sharks") (Zidek 1972, 1975).

Woodford Shale (Upper Devonian–Lower Mississippian)

The Woodford Shale is a distinctive dark formation above the Hunton Group. In the CHIC area, the Woodford Shale is composed of shale and bedded chert, with chert and phosphate-rich concretions in the lower part. It ranges from 60 to 210 m (200 to 700 ft) thick. In CHIC, it is mapped undivided with the overlying Welden Limestone and Sycamore Limestone. These three units are mapped northwest and southeast of Arbuckle Dam, on the north flank of the Tishomingo Anticline, and in the southern part of Section 21, T. 1 S, R. 3 E (Blome et al. 2013). Deposition of the Woodford Shale occurred over a relatively long time, from the early Early Devonian (Frasnian) into the earliest Mississippian (Becker and Mapes 2010), between about 380 and 355 Ma. The upper contact with the Sycamore Formation is transitional (Pessagno et al. 1983).

The Woodford Shale was deposited during a marine highstand and experienced little sediment input. The water column was strongly stratified and the bottom water was oxygen-poor, but algal productivity was high (Siy 1994). Phosphate beds and nodules near the top represent marine upwelling (Over and Barrick 1990). The water was generally deeper than that present for the preceding Hunton Group (Brown and Grayson 1985).

The Woodford Shale is fossiliferous within CHIC. Wilson and Urban (1963) described microfossils from a locality near Buckhorn Creek in the NE¼ of Section 3, T. 2 S, R. 3 E. Per Richard Lupia (Sam Noble Oklahoma Museum of Natural History, University of Oklahoma, Norman, Oklahoma), this locality is within CHIC (pers. comm., March 2015). Fossils reported by Wilson and Urban from this site include acritarchs ("hystrichospheres"), the prasinophyte alga *Tasmanites* (a variety of chlorophyte green algae), plant spores, and the new genus and species of palynomorph *Quisquilites buckhornensis*, which came from the lower part of the formation.

Macroscopic fossils are not common in the Woodford Shale, although microfossils are. The patchy distribution of fossils suggests the possibility of concentrations being vertebrate feces or regurgitations (Becker and Mapes 2010). Two extinction events may be represented in the formation (Nowaczewski and Marshall 2011). Types of fossils reported from the Woodford Shale include acritarchs (Wilson and Urban 1963; Sullivan 1985), foraminifera (Nowaczewski and Marshall 2011), radiolarians (protozoans that make "shells" of silica) (Pessagno et al. 1983; Schwartzapfel and Holdsworth 1996), *Tasmanites*, plant spores, other palynomorphs (*Quisquilites*) (Wilson and Urban 1963), brown-algae-like microfossils (Nowaczewski and Marshall 2011), the early tree-like plant *Archaeopteris* (identified as *Callixylon*) (Arnold 1934; Wilson 1958), wood (Wilson 1958), sponge spicules, conulatans, brachiopods, nautiloids, ammonites (Becker and Mapes 2010), scolecodonts (Marshall et al. 2013), phyllocarid crustaceans (Cooper 1932; Feldmann and Schweitzer 2010), an early shrimp (Feldmann and Schweitzer 2010), crinoids (Becker and Mapes 2010), conodonts (Cooper 1931a, 1931b; Barrick and Klapper 1990), the enigmatic possible conodont *Conchodontus* (Donoghue and Chauffe 1998), arthrodire fish (Wilson 1958), sharks and other fish (Becker and Mapes 2010), and burrows (Brown and Grayson 1985). The "pteropod" *Idiotheca rugosa*, named from the ?Woodford Chert by Girty (1909), and sometimes identified as a crustacean (*Spathiocaris woodfordi*; Cooper 1932), is actually a cephalopod mandible (Mapes 1987). Similarly, a report of the plant *Foerstia* turned out to be a cephalopod mandible (Hannibal 1994).

Caney Shale (Middle–Upper Mississippian)

The Caney Shale is a Mississippian unit with a complicated nomenclatural history, in which the original definition was superseded. A particular issue was confusion involving exotic fossiliferous boulders in the original type locality, now assigned to the Johns Valley Formation (Elias and Branson 1959). The Caney Shale in the CHIC area is composed of dark gray to black shale with concretions, often poorly exposed. It is as much as 120 m (400 ft) thick southwest of CHIC. In CHIC, it is mapped just south of Arbuckle Dam and at the southeast end of the recreation area, south of the Reagan Fault (Blome et al. 2013). The Caney Shale of the northern Arbuckles is divisible into as many as three members, in ascending order the Ahloso, Delaware Creek, and Sand Branch members (Chenoweth et al. 1959). The contacts of three members are arbitrary. The Ahloso Member has more

sand-sized and silt-sized grains than the other two members, and the Sand Branch Member can be distinguished by the presence of phosphatic concretions (Elias and Branson 1959). The Ahloso Member is thought to be equivalent to the Sycamore Limestone, at least in part, with the Ahloso Member predominant in the northern Arbuckles and the Sycamore Limestone predominant in the southern Arbuckles (Champlin 1959; Chenoweth et al. 1959).

The Caney Shale is another marine formation that formed in a basin on the site of the aulacogen (Donovan 2001). It was deposited during the Middle and Late Mississippian (Meramecian and Chesterian) (Elias and Branson 1959), between about 335 and 323 Ma. The upper contact with the Springer Formation is sometimes described as involving a hiatus (Wilson 1966) and sometimes as conformable (Boardman et al. 2009).

The Caney Shale is fossiliferous within CHIC. Girty (1909) described fossils from USGS locality 3981, 5 km (3 mi) northeast of Dougherty, at a bluff on Sandy Creek. This appears to be on Guy Sandy Creek just northeast of the dam, in an area currently submerged. Girty (1909) reported brachiopods and ostracodes from the site, and named an ostracode species, *Entomis unicornis*. Elias and Branson (1959) assigned this site to the Ahloso Member. The U.S. Geological Survey's Invertebrate Permian–Carboniferous Catalog has two localities with three specimen records identified as coming from the Caney Shale within CHIC. The sites were visited by J. A. Taff on September 14, 1922. Specimen 8903, an unidentified slab, came from locality 3914, in the center of Section 33, T. 1 S, R. 3 E. Specimens 8904 (brachiopod *Productus*) and 8905 (the foraminifera *Fusulina*) came from locality 3915, in the NE¼ SW¼ of Section 34, T. 1 S, R. 3 E (K. McKinney, pers. comm., November 2014). Locality 3915 may actually be a Deese Group locality; *Fusulina* is a Pennsylvanian genus, implying either a taxonomic or geologic misidentification, and Blome et al. (2013) map the Pennsylvanian Deese Group in that area. Finally, an indeterminate specimen of an acanthodian was recovered from the Delaware Creek Member in the NE¼ SE¼ of Section 32, T. 1 S, R. 3 E, now under water. The specimen is in the collections of the American Museum of Natural History as AMNH 425 (Zidek 1972, 1975).

Omitting reports from units no longer included in the Caney Shale, a variety of fossils have been described from the formation. Cephalopods have received a great deal of attention, including nautiloids (Miller and Furnish 1955; Niko and Mapes 2004, 2011; Kröger and Mapes 2007) and ammonites (Branson et al. 1959; Gordon 1962; Branson 1964b, 1964c). Other groups of fossils reported from the formation include acritarchs ("hystrichospheres"), chitinozoans (Wilson 1966), radiolarians (Pessagno et al. 1983), plant fossils assigned to *Sphenopteris* and *Medullosa* (Elias and Branson 1959), spores, pollen, reworked microfossils from several older formations (Wilson 1966), sponge spicules (Branson et al. 1959) brachiopods, rostroconchs (*Conocardium*), bivalves, bactritidan cephalopods (related to the ancestry of ammonites and many modern cephalopod groups), gastropods, scaphopods (Girty 1909; Elias and Branson 1959), hoplocaridan malacostracans (the group including modern mantis shrimps) (Schram 1979), ostracodes (Girty 1909; Elias and Branson 1959), conodonts (Branson and Mehl 1940; Elias 1956), sharks, acanthodians, and palaeoniscids (early ray-finned fish) (Zidek 1993).

Deese Group (Middle Pennsylvanian)

The Deese Group is a heterogeneous unit. A variety of different divisions have been proposed (Lang 1966; Parker 1966; Billingsley et al. 1996). In the CHIC area, the Deese Group consists of beds of sandstone, gray and red shale, limestone, conglomerate, and limestone, and can be over 2,740 m (9,000 ft) thick. Internal divisions include, in ascending order, the West Arm Formation, Milsap Lake Formation, and Devils Kitchen Conglomerate. In CHIC, it is mapped on the north side of the Reagan Fault on the north side of the southeast arm of the recreation area, and in a small area east of Arbuckle Dam (Blome et al. 2013). The Deese Group is of late Middle Pennsylvanian age (Desmoinesian) (Blome et al. 2013), about 310 Ma. The upper contact with the Vanoss Formation is a disconformity (Blome et al. 2013).

A variety of depositional settings are represented in the Deese Formation, ranging from braidplains to rivers, deltas, and coastal flats, to lagoons, estuaries, and shallow-marine environments. Conglomerate beds correspond to pulses of tectonic activity (Billingsley et al. 1996). Marine deposition took place under shallow equatorial water, of typical marine salinity (Brand 1987), with a tropical and probably monsoonal climate (Seuss et al. 2012a).

The Deese Group may be fossiliferous within CHIC. As noted under the Caney Shale section, USGS locality 3915, from the NE¼ SW¼ of Section 34, T. 1 S, R. 3 E, is described as from the Caney Shale, but actually plots within an area mapped as the Deese Group, and has yielded a Pennsylvanian genus of foraminifera (*Fusulina*). The brachiopod *Productus* has also been found at USGS 3915.

The Deese Group does not appear to be abundantly fossiliferous with the exception of the Buckhorn Asphalt Quarry described below. Fossils seem to be common only in certain limestone and shale beds (Tomlinson 1929). Types of fossils reported from the Deese Group exclusive of the Buckhorn Asphalt Quarry include foraminifera, rugose corals (Tomlinson 1929), bryozoans (Billingsley et al. 1996), brachiopods (Tomlinson 1929), rostroconchs (Hoare et al. 1982), bivalves, nautiloids, gastropods, scaphopods, crinoids (Tomlinson 1929), conodonts (Pieracocos et al. 1993), the unusual cartilaginous fish *Edestus* (Branson 1964d), invertebrate burrows (Brown and Grayson 1985; Billingsley et al. 1996), and reworked Ordovician and Cambrian fossils including stromatolites, brachiopods, and trilobites (Dunham 1955).

The Buckhorn Asphalt Quarry, just outside of CHIC, has the best-preserved Paleozoic mollusk fauna in the world (Seuss et al. 2008). The fossils included some of the most ancient mollusk shells to retain their original aragonitic composition (Chaplin 1989). Asphalt was extracted from a number of quarries in a small area just east of CHIC for many decades, beginning in 1890 (Gorman et al. 1945). Bitumen, mostly from the Oil Creek Formation, was quarried until 1958 (Chaplin 1989). The quarry is located in the SE¼ of Section 23, T. 1 S, R. 3 E, and is often attributed to the Boggy Formation of the Deese Group (Ham 1973; Chaplin 1989; Yancey and Heaney 2000; confusingly, the Boggy Formation is generally assigned to the Krebs Group instead of the Deese Group, with the notable exception of publications on the asphalt quarry). The site has been interpreted as storm deposits laid down between fair weather wave base and storm wave base, in about 10 to 20 m (33 to 67 ft) of water (Yancey and Heaney 2000). Deposition occurred on a shallow-marine shelf near land (Sadd 1991). Shells found here retain their original aragonite and nacreous luster (Squires 1976), and some

still show color patterns (Squires 1976; Wisshak et al. 2008). The exceptional preservation is due to early impregnation with hydrocarbons migrating out of adjacent Ordovician rocks (Wisshak et al. 2008), probably the Oil Creek Formation (Sadd 1991). More than 120 genera and 155 species are present, dominated by mollusks (Seuss et al. 2008). Straight-shelled (orthoconic) nautiloids are particularly abundant (Chaplin 1989). Some nautiloids show evidence of predation (Seuss et al. 2012b). Types of fossils reported from the Buckhorn Asphalt Quarry include foraminifera, calcareous algae (Wisshak et al. 2008), plants (Mapes et al. 2000), chaetetid sponges (Seuss et al. 2014), rugose corals (Souraf and Webb 2003), bryozoans, brachiopods (Ham 1973), bivalves (Yancey and Heaney 2000), nautiloids (Crick 1982; Brand 1987), ammonites (Ham 1973), gastropods (Squires 1976; Bandel et al. 2002), scaphopods (Wisshak et al. 2008), ostracodes, echinoids and other echinoderms (Ham 1973), fish, and microborings attributed to cyanobacteria, chlorophytes, and possibly foraminifera, red algae, and fungi (Wisshak et al. 2008). Plant fossils include abraded or coalified pieces of plants (cordaitaleans and calamitaleans) that lived in the vicinity and reworked pieces of Late Devonian silicified wood (Mapes et al. 2000). More diverse fish may be found; coal balls from the Boggy Formation elsewhere have yielded fossils of several types of fish, including sharks, other cartilaginous fish like *Edestus*, acanthodians, and palaeoniscid ray-finned fish (Zidek 1972).

Potential Sources of Paleontological Resources

Fossils have not yet been documented from the following rock units within CHIC. However, they are known to preserve fossils elsewhere, and future field investigations within the recreation area may result in the discovery of fossils from one or more of these units.

Simpson Group: Joins Formation (Middle Ordovician)

The Joins Formation is the lowermost unit of the Simpson Group. This formation is composed of thin-bedded limestone and shale with a thin basal conglomerate. It can be as much as 90 m (300 ft) thick on the south side of the Arbuckle Mountains. The Joins Formation is mapped with the overlying Oil Creek Formation in the CHIC area. Within the recreation area, the two undivided formations are mapped only in a small area east of the lake, in the central part of Section 21, T. 1 S, R. 3 E (Blome et al. 2013). It may or may not actually be present in or around the recreation area; it is of limited extent, and the areas reported by Decker and Merritt (1931) are generally south of the recreation area. The Joins Formation was deposited at the beginning of the Middle Ordovician (Whiterockian) (Bauer 2010), about 470 Ma. The contact with the underlying Arbuckle Group is variously described as transitional (Shaw 1974) and disconformable (Mound 1965a; Bauer 2010). The contact may involve a minor hiatus (Derby 1969). The upper contact with the Oil Creek Formation varies from conformable to disconformable depending on location (Decker and Merritt 1931).

The Joins Formation is marine in origin, interpreted as having been deposited in a sublittoral shelf to outer shelf setting (Shaw and Fortey 1977). The limestones are interpreted as nearshore and the shale as possibly lagoonal (Shaw 1974). Geographically, it is the least widespread of the five Simpson Group units (Bauer 2010) and is found mostly within the aulacogen (Denison 1997).

The Joins Formation is not reported to be fossiliferous in CHIC. Elsewhere, fossils known from the Joins Formation include stromatolites (McHargue 1982), acritarchs (Derby et al. 1991), brachiopods (Cooper 1956), gastropods (Harris and Harris 1965), ostracodes (Harris 1957), trilobites (Shaw 1974), crinoids (Harris and Harris 1965), graptolites (Amsden 1957a), and conodonts (Harris 1962; Mound 1965a, 1965b; McHargue 1982; Bauer 2010). Most fossils are from the limestone beds (Shaw 1974). The fossils in the lowest part of the formation, including stromatolites and conodonts, appear to represent a distinct shallow subtidal assemblage (McHargue 1982).

Simpson Group: Oil Creek Formation (Middle Ordovician)

The Oil Creek Formation, like the rest of the Simpson Group formations above the Joins Formation, is composed of a primarily carbonate member over a sandstone member (Gorman et al. 1945). In the Criner Hills, the uppermost part is an oolitic limestone known as the Pruitt Ranch Member (Bauer 2010); this unit is not present in the CHIC area (Harris and Harris 1965). In the CHIC area, the Oil Creek Formation is composed of a basal quartz-rich sandstone and an overlying section of limestone, shale, and occasionally sandstone cemented by calcite. On average, it is about 230 m (750 ft) thick, of which as much as 120 m (400 ft) is the lower sandstone. The sandstone is sometimes petroliferous and was once mined as tar sand east of CHIC. As noted, it is mapped with the underlying Joins Formation, and within CHIC the two formations are only mapped in a small area of the central part of Section 21, T. 1 S, R. 3 E (Blome et al. 2013). The history of the asphalt mining is covered briefly in Gorman et al. (1945). Like the underlying Joins Formation, the Oil Creek Formation was deposited during the early Middle Ordovician (Whiterockian) (Bauer 2010). The contact with the overlying McLish Formation varies by location (Decker and Merritt 1931) and may involve a hiatus eliminating part of the early Middle Ordovician (Derby et al. 1991).

The Oil Creek Formation is a shallow-marine unit, with deposition becoming generally shallower to the east-northeast (Brown and Grayson 1985). Before deposition began, a sea level lowstand early in the Middle Ordovician left what had been a marine carbonate platform around the aulacogen exposed above sea level, and a sandy dune-beach complex formed on the new carbonate plain. When sea level rose again, water reworked the dune-beach complex into what became the basal sandstone of the Oil Creek Formation (McPherson et al. 1988). Deposition of the Oil Creek Formation took place during a single marine transgression-regression cycle (Bauer 2010). The setting passed from upper shoreface in the lower, transgressional part of the formation, to offshore marine at the greatest part of the transgression, and back to nearshore shallow deposition during the upper, regressional part. In some places, the depositional setting shallowed to lagoons and tidal flats (Lewis 1978).

The Oil Creek Formation is not known to be fossiliferous within CHIC at this time. Fossils reported elsewhere from the formation include microbial (“algal”) structures (Lewis 1978), acritarchs (Derby et al. 1991), receptaculitids, bryozoans (Brown and Grayson 1985), brachiopods (Cooper 1956), monoplacophorans (Decker and Merritt 1931), scenellids (enigmatic cap-like fossils, possibly mollusks), bivalves, nautiloids, gastropods, trilobites, ostracodes (Brown and Grayson 1985), eocrinoids (Lewis et al. 1987), crinoids (Sprinkle and Kolata 1982), conodonts (Bauer 2010), and burrows (McPherson et al. 1988). The types of fossils vary by depositional setting (Lewis 1978).

Most fossils are found in the upper beds (Brown and Grayson 1985), with only rare burrows reported from the lower sandstone section (McPherson et al. 1988).

Simpson Group: McLish Formation (Middle Ordovician)

The McLish Formation is the middle unit of the Simpson Group. In the CHIC area, the McLish Formation is composed of a basal sandstone and an overlying section of interbedded limestone and shale (Blome et al. 2013). The McLish Formation is as much as 140 m (460 ft) to 150 m (490 ft) thick. In the CHIC area, it is mapped undivided with the other two units of the upper Simpson Group, the Tulip Creek and Bromide formations. In CHIC, the undivided upper Simpson Group is mapped only in the central part of Section 21, T. 1 S, R. 3 E (Blome et al. 2013). The McLish Formation was deposited during the early Middle Ordovician (Chazyan) (Derby et al. 1991), about 460 Ma. The upper contact with the Tulip Creek Formation is conformable (Bauer 1987; Suhm 1997) or involves a brief hiatus (Decker and Merritt 1931; Harris 1957).

Like the other units of the Simpson Group, the McLish Formation is a shallow-marine unit. It was deposited during a marine transgression-regression cycle (Bauer 1990a). The McLish Formation is generally similar to the underlying Oil Creek Formation, albeit showing more influence from currents and waves. Deposition of the upper part was shallow enough for microbial mats, at least in the northeastern Arbuckles (Shaw 1974).

Fossils have not been reported from the McLish Formation within CHIC to date. Fossils known from the McLish Formation elsewhere include microbial structures (Shaw 1974), acritarchs (Derby et al. 1991), cyanobacteria (e.g., *Girvanella*, *Spongiostroma*) (Ham 1954), red algae ("*Tetradium*") (Harris 1957), sponges (Decker and Merritt 1931), tabulate corals (Harris 1957), bryozoans (Farmer 1975; Key 1990), brachiopods (Cooper 1956), bivalves, gastropods (Harris 1957), nautiloids (Harris and Harris 1965), trilobites (Shaw 1974), ostracodes (Harris 1957), cystoids (Amsden 1957a), eocrinoids (Harris 1957), crinoids (Harris and Harris 1965), conodonts (Harris 1964; Bauer 1987), and burrows ("fucoids") in the basal sandstone (Decker and Merritt 1931).

Simpson Group: Tulip Creek Formation (Middle Ordovician)

The Tulip Creek Formation is the second-highest formation of the Simpson Group, and the least studied (Denison 1997). In the CHIC area, the Tulip Creek Formation is composed mostly of sandstone and shale, and some limestone. Sandstone predominates in the lower part, and shale predominates in the upper part, grading into the basal sandstone of the overlying Bromide Formation. The formation is between 90 and 120 m (300 and 400 ft) thick in the I-35 corridor west of CHIC (Blome et al. 2013). Like the Joins Formation, the Tulip Creek Formation has a limited distribution and may not be present at CHIC. Decker and Merritt (1931) reported that it was found in two narrow belts, the nearest being from west of Dougherty to Colbert Creek, west of CHIC. In the CHIC area, it is mapped undivided with the other two units of the upper Simpson Group, the underlying McLish Formation and overlying Bromide Formation. In CHIC, the undivided upper Simpson Group is mapped only in the central part of Section 21, T. 1 S, R. 3 E (Blome et al. 2013). The Tulip Creek Formation was deposited during the late early Middle Ordovician (Chazyan) (Derby et al. 1991). The upper contact with the Bromide Formation is conformable and slightly gradational, with a shift from mud-sized to sand-sized sediments and low energy to higher energy (Longman 1981).

The Tulip Creek Formation is another shallow-marine formation. It was deposited during a transgression-regression cycle (Bauer 1990a), reaching shallow subtidal depths (Bauer 1987). It is one of the more geographically limited of the Simpson Group formations, being restricted to the aulacogen and immediate vicinity (Denison 1997).

Fossils have not been reported from the Tulip Creek Formation within CHIC to date. Fossils reported from the Tulip Creek Formation elsewhere include acritarchs ("hystrichospheres") (Wilson and Dolly 1964; Derby et al. 1991), chitinozoans (Wilson and Dolly 1964), bryozoans (Farmer 1975; Key 1990), brachiopods (Cooper 1956), bivalves, nautiloids, gastropods (Harris 1957), trilobites (Shaw 1974), ostracodes (Harris 1957), conodonts (Bauer 1987), cystoids, crinoids (Wilson and Dolly 1964), and general bioturbation, which is reported from the sandstone interval (Bauer 1990b). Bryozoans, ostracodes, and conodonts are the most common fossils (Shaw 1974).

Sycamore Limestone (Lower–Middle Mississippian)

The Sycamore Limestone in the CHIC area is composed of gray shale, cherty and silty limestone, and lime-rich siltstone overlain by gray shale and tan-weathering marlstone. It is between 40 and 110 m (130 and 350 ft) thick (Blome et al. 2013). It is mapped undivided with the underlying Woodford Shale and Welden Limestone as described above in the "Woodford Shale" section. It is discontinuous in the CHIC area (Jackson 1969). The nomenclature of the stratigraphic interval representing the Lower and Middle Mississippian in the Arbuckle Mountains and vicinity is complicated, involving the Woodford Shale, the Welden Formation, the Sycamore Limestone, the Caney Shale, and various equivalents and informally named units, as discussed in Braun (1959), Champlin (1959), and Chenoweth et al. (1959).

The age of the Sycamore Limestone varies from author to author, probably due in part to the nomenclatural differences mentioned above and the relative paucity of fossils. Deposition began during the Early Mississippian (Kinderhookian or Osagean) and ended during the middle Mississippian (Meramecian) (Ormiston and Lane 1976; Pessagno et al. 1983; Donovan 2001), by approximately 335 Ma. There seems to have been little deposition during the Osagean (Donovan 2001), between about 348 and 340 Ma. The upper contact with the Caney Shale (Ahloso Member) is gradational (Chenoweth et al. 1959) to disconformable (Donovan 2001).

The Sycamore Limestone was deposited during a marine transgression (Braun 1959). Several facies are apparent, from shallow-marine shale formed after the initial transgression, to deeper-water limestone, to deep-water shale (Cole 1988). The sediment source was to the north. Carbonates are more common in the lower part of the Sycamore stratigraphic interval on the south side of the mountains, where they are assigned to the Welden Limestone (Donovan 2001).

The Sycamore Limestone is not known to be fossiliferous in CHIC. It has few fossils in general (Braun 1959). Most of the fossils are in the limestone beds. There is little evidence of life in the shale, and the marly beds have only some burrows and brachiopod shells (Donovan 2001). Fossils reported from the Sycamore Limestone include radiolarians (Ormiston and Lane 1976; Pessagno et al. 1983; Schwartzapfel and Holdsworth 1996), calcispheres (enigmatic microfossils), calcareous algae, sponge spicules, bryozoans, brachiopods (Cole 1988), fragments of gastropods and trilobites

(Prestidge 1959), ostracodes, crinoids (Cole 1988), echinoids (Donovan 2001), conodonts (Ormiston and Lane 1976; Pessagno et al. 1983), and burrows, trails, and general bioturbation (Cole 1988).

Springer Formation (Upper Mississippian–Lower Pennsylvanian)

The Springer Formation of the CHIC area is composed of beds of dark bituminous shale containing concretions and separated by sandstone and limestone beds. It can be as much as 1,830 m (6,000 ft) thick, but is typically much thinner due to post-depositional Middle Pennsylvanian erosion. The Springer Formation is mapped in CHIC only in the center of Section 34, T. 1 S, R. 3 E (Blome et al. 2013). The Springer Formation is typically raised to group rank and includes a number of internal divisions. These members, or formations when the Springer is a group, are usually persistent sandstone beds separated by unnamed intervals of dark shale (Tomlinson 1929; Lang 1966; Wilson 1966; Meek et al. 1988). An exception to this rule of named sandstone beds and unnamed shale intervals is the Goddard Shale Member, found at the base of the Springer Formation in the CHIC area (Jackson 1969; Blome et al. 2013). The Goddard Shale Member is sometimes excluded from the Springer Formation and described as a formation in its own right (Lang 1966; Wilson 1966; Straka 1972). Deposition of the Springer Formation took place from the Late Mississippian to the Early Pennsylvanian (Chesterian to Morrowan) (Blome et al. 2013), sometime between 331 and 315 Ma, with the Goddard Shale Member limited to the Late Mississippian (Chesterian) (Wilson 1966), between 331 and 323 Ma. The upper contact with the Deese Group is disconformable (Blome et al. 2013).

The Springer Formation was deposited in coastal and nearshore settings, and exhibits deltaic, fluvial, and tidal influences (Keighin and Flores 1989). Sediment arrived from the northwest and was transported southeast along the length of the aulacogen (Sutherland and Grayson 1992), toward a marine basin on the southeast (Meek et al. 1988).

Fossils are not common in the Springer Formation (Tomlinson 1929), and none have been reported from the formation within CHIC. Burrows and indeterminate debris are the only common fossils (Meek et al. 1988). Both terrestrial and marine fossils have been reported. Terrestrial fossils reported from the Springer Formation include plant fossils such as wood (Meek et al. 1988), *Calamites* (Tomlinson 1929), *Sigillaria* (Felix and Burbridge 1967), root casts (Keighin and Flores 1989), and palynomorphs (Wilson 1966; Felix and Burbridge 1967). Marine fossils of the Springer Formation include foraminifera (Tomlinson 1929), rugose corals, bryozoans, brachiopods, bivalves (Bennison 1954), ammonites (Furnish et al. 1964), ostracodes, crinoids (Bennison 1954), conodonts (Straka 1972; Sutherland and Grayson 1992), *Bascomella* (apparently a barnacle boring trace) (Bennison 1954), and burrows (Meek et al. 1988). Fossils reported from the Goddard Shale Member include chitinozoans (Wilson and Clarke 1960), radiolarians (Holdsworth et al. 1982; Schwartzapfel and Holdsworth 1996), spores (some reworked from Ordovician and Devonian formations) (Wilson 1966), and conodonts (Straka 1972).

Vanoss Formation (Upper Pennsylvanian)

The Vanoss Formation is the formation at or nearest the surface for most of CHIC (Blome et al. 2013). Unlike the heavily folded formations beneath it, it is relatively flat-lying, showing that it postdates most of the tectonic activity of the area (Lang 1966; Donovan and Heinlen 1988); this

geometry can be seen in the geologic cross-sections of Blome et al. (2013). The Vanoss Formation of the CHIC area includes a lower limestone conglomeratic facies and an upper shale facies. The limestone conglomeratic facies is composed of gray conglomerate with limestone cobbles in a lime-rich matrix, and can be as much as 150 m (500 ft) thick, but is more typically about 30 m (100 ft) thick. This facies is mapped at the surface over much of central and northeastern CHIC. It grades into the overlying shale facies, which is composed of shale and silty shale with some sandstone and local beds of conglomerate. This facies is between 9 and 24 m (30 and 80 ft) thick and is mapped beneath most of the northern arm of CHIC and the western side of the northeastern arm (Blome et al. 2013).

The Vanoss Formation was deposited during the Late Pennsylvanian (Virgilian) (Donovan and Heinlen 1988; Blome et al. 2013), about 300 Ma. It is composed of alluvial deposits on the north side of the Arbuckle Mountains, shed from the newly formed mountains. The climate is thought to have been stable for long periods of time, as shown by the many calcrete horizons, and occasionally semiarid (Donovan and Heinlen 1988). There are few reports of fossils from this formation, and none have been reported from CHIC. Fossils include plants such as the conifer *Walchia*, brachiopods, bivalves, gastropods (Morgan 1924), and pebbles or nodules that may be "algal" in origin (Tomlinson 1929; Dunham 1955). Morgan's fossils came from shale, limestone, and sandstone beds in the upper half of the formation about 35 km (22 mi) north-northwest of CHIC in the vicinity of Ada, and may pertain to facies not present in CHIC.

Quaternary sediments (Pleistocene–Holocene)

The Quaternary sediments of CHIC are undifferentiated alluvium and colluvium, composed of sand, silt, clay, and gravel. These deposits are typically 1 to 15 m (3 to 50 ft) thick. Quaternary sediments are mapped in the floodplains of the streams in the northern and northeastern arms of the recreation area, and below Arbuckle Dam (Blome et al. 2013).

Fossils have not yet been reported from CHIC's Quaternary deposits, but similar deposits have yielded fossils within about 100 km (60 mi) of the recreation area. Useful online paleontological resources for this region include the Neotoma paleoecology database (http://www.neotomadb.org/), and Faunmap, which is the vertebrate element of Neotoma (http://www.ucmp.berkeley.edu/faunmap/). Numerous sites are reported in Neotoma, although the great majority of these sites are archeological sites yielding bison remains dating back approximately 1,000 years or less (Baugh 1986).

Inventories of Quaternary vertebrates including the CHIC area have been produced by Hay (1924) and Smith and Cifelli (2000). Hay (1924) included eight reports of Quaternary mammals within about 100 km of CHIC, all of mastodons, mammoths, or bison. Mastodon remains were reported from the vicinity of Citra, Oklahoma, about 60 km (40 mi) northeast of CHIC; between Lexington and Noble, Oklahoma, about 72 km (45 mi) north-northwest of CHIC; and Gainesville, Texas, about 90 km (55 mi) south of CHIC. Mammoth remains (assigned to Columbian and Imperial mammoths, now generally considered the same species) were reported from near Kinlock, Oklahoma, 47 km (29 mi) south-southeast of CHIC; just south of Norman, Oklahoma, about 90 km (55 mi) north-northwest of CHIC; and near Tulip, Texas, just over 100 km (60 mi) southeast of CHIC. A neck vertebra of an extinct bison was reported from 10 km (6 mi) north of Sherman, Texas, about 85 km (53 mi) south-

southeast of CHIC. Finally, a modern or extinct bison molar was reported from 13 km (8 mi) north of Denison, Texas, about 70 km (45 mi) south-southeast of CHIC (Hay 1924). Smith and Cifelli (2000) reported that several gravel pits and other sites on terraces of the Washita River in Grady County have yielded vertebrate remains. Animals represented include turtles, turkeys and other birds, sloths, rodents, felids, skunks, mastodons, mammoths, horses, peccaries, camels, cervids, shrubox, and bison.

Additional relevant fossil reports not included in those surveys include the Ward Quarry Local Faunule from the vicinity of Muenster and Marysville in Cooke County, Texas, over 80 km (50 mi) south-southwest of CHIC, which has yielded catfish, other fish, frogs, turtles, lizards, snakes, rodents, mammoths, horses, and the extinct bison *Bison latifrons* (Dalquest 1961), and dire wolf material from Marlow, Oklahoma, about 85 km (53 mi) west-northwest of CHIC (Cifelli et al. 2002). Pleistocene bivalves and gastropods are also common near rivers in the CHIC area (Frye and Leonard 1963). Finally, if bog or lake deposits were found in CHIC, they would be of interest because of their potential to include fossils useful for paleoecology and paleoclimatology, such as spores and pollen. An example is Ferndale Bog in Atoka County (Albert 1981; Holloway and Ferring 1985). However, the creation of the Lake of the Arbuckles has submerged the low-lying areas in CHIC that were probably the most likely areas to find such sites.

Park Collections

At one time, CHIC had at least 36 cataloged paleontological specimens from a variety of locations and formations around the world, from ammonites of Upper Jurassic rocks of Germany to snail-bearing Eocene rocks of Wyoming. The majority of these specimens were deaccessioned in 1988. Five catalogued specimens are retained in storage: CHIC 137, a Devonian trilobite; CHIC 145, a trilobite from the Viola Group; CHIC 156, a specimen identified as crustacean shells; CHIC 175, a fossiliferous asphaltic rock which probably derived from the asphalt quarries just east of CHIC; and CHIC 184, Viola Group graptolites from the Arbuckle Mountains. Noel Osborn (CHIC chief of resource management, pers. comm., April 2015) reported that the CHIC museum currently has a drawer of uncatalogued and unlabeled fossils. Among the specimens are rugose corals, bryozoans, brachiopods, bivalves, nautiloids, ammonites, crinoids, “hash slabs” of mixed fossils, and a larger object that resembles some microbial structures (CHIC Figure 6, 7). These specimen appear to be typical of the Simpson and Hunton groups of the CHIC area, and Cretaceous rocks from the south (N. Osborn, pers. comm., April 2015). CHIC also exhibits a small group of fossils at the Travertine Nature Center, including an example of the trilobite *Cryptolithus ulrichi* from the Viola Limestone; a block of specimens of the paracrinoid *Oklahomacystis tribrachiatus*, a common Bromide Formation fossil; a large cut specimen of *Callixylon* (wood of the early tree-like plant *Archaeopteris*) from Devonian rocks; a Devonian nautiloid (*Rayonnoceras*); the common local Devonian crinoid structure *Camarocrinus*; post-Paleozoic bivalves (*Gryphaea* and *Pecten*); and a Cretaceous ammonite (CHIC Figure 8, 9) (N. Osborn, pers. comm., April 2015). In addition to the recreation area’s holdings, the Goddard Youth Camp’s Children’s Museum, located within CHIC boundaries, exhibits a variety of fossils, including skeletons of dinosaurs known from Oklahoma such as *Acrocanthosaurus*.



CHIC Figure 6. Specimens in CHIC collections. Left: brachiopods and bivalves. Right: rugose corals (N. Osborn/CHIC, NPS).



CHIC Figure 7. An ammonite and a “hash slab” of mixed fossils in CHIC collections (N. Osborn/CHIC, NPS).



CHIC Figure 8. *Callixylon* on display at the Travertine Nature Center, CHIC (M. Sander/CHIC, NPS).



CHIC Figure 9. *Oklahomacystis tribtrachiatus* on display at the Travertine Nature Center, CHIC (M. Sander/CHIC, NPS).

Three institutions are known to hold fossils from localities within CHIC. The Sam Noble Oklahoma Museum of Natural History (SNOMNH; University of Oklahoma, Norman, Oklahoma) probably has the most fossils. It is the repository of the fossils collected from the M10 locality (e.g., Amsden 1958b; Sutherland 1965; Campbell 1977), as well as other fossils collected for the Oklahoma Geological Survey. The type specimen of the palynomorph *Quisquilites buckhornensis* Wilson and Urban (1963) was initially given as holotype slide OPC 35OD-3-2, from the Oklahoma Geological Survey palynology collections. It is currently reposited in the Sam Noble Oklahoma Museum of Natural History as OPC 7026-19036 on slide OPC 7026-19083 (R. Lupia, pers. comm., March 2015) (CHIC Table 2). The National Museum of Natural History (USNM; Washington, D.C.) is the repository for the fossils described by Girty (1909), including the holotype of the ostracode *Entomis unicornis* (USNM PAL 120749). Other specimens collected for the U.S. Geological Survey, such as the Caney Shale material collected by Taff, are probably at the USNM as well. Finally, the Caney Shale acanthodian discussed by Zidek (1972, 1975) is in the collections of the American Museum of Natural History (AMNH; New York, New York) as AMNH 425. It is likely that the Oklahoma Geological Survey and U.S. Geological Survey maintain records of interest as well.

In addition to the above, the Goddard Youth Camp has historically permitted fossil collecting from a site within CHIC (N. Osborn, pers. comm., April 2015). This activity should be evaluated.

CHIC Table 2. Fossil taxa named from specimens found within CHIC.

Taxon	Publication	Catalog Number	Provenance	Notes
Entomis unicomis	Girty 1909	USNM PAL 120749	Mississippian, Caney	Ostracode
Quisquilites buckhornensis	Wilson and Urban 1963	OPC 7026-19036	Devonian, Woodford	Palynomorph

Cultural Resources Connections

There is at least one example of fossils in a cultural context at CHIC: a Goddard Youth Camp building, constructed of rock from various places in Oklahoma, includes some large ammonites perhaps from Cretaceous rocks of the Lake Texoma area (N. Osborn, pers. comm., April 2015) (CHIC Figure 10). Additional fossils in cultural resource contexts at CHIC would not be unusual. A common type of cultural association for this region would be fossiliferous stone used for artifacts. For example, in the Southwest, petrified wood from the Upper Triassic Chinle Formation was often used for artifacts. The majority of parks in the neighboring Southern Colorado Plateau Network have examples (Tweet et al. 2009). Another common association is the remains of contemporaneous flora and fauna at archeological sites. As mentioned in the “Quaternary sediments” section, there are many archeological sites in south-central Oklahoma that have yielded remains of contemporaneous fauna, such as fish, rodents, rabbits, deer, and bison. Many also have yielded artifacts of bone and shell, or artifacts of stone that may prove fossiliferous. Most of these sites are younger than 2,000 years. Some examples are described in Ray (1960), Sharrock (1961), Pillaert (1962), Dalquest and Hibbard (1965), Richard (1971), Drass (1979), Penman (1979), Baugh (1986), and Drass and Flynn (1990). Kenworthy and Santucci (2006) presented an overview and cited selected examples of National Park Service fossils found in cultural resource contexts.



CHIC Figure 10. This building, in the Goddard Youth Camp, has several large ammonites included in its masonry (NPS photo from the geologic scoping session, October 2007).

Paleontological Resource Management, Preliminary Recommendations

- CHIC is paleontologically rich, but a systematic ground study of its fossils has not been done. A ground survey of its paleontological resources is recommended to document fossil sites and evaluate them for monitoring needs.

- Bringing in a GeoCorps intern who is familiar with invertebrate paleontology to assist with CHIC paleontology needs is recommended.

- A technical assistance request should be submitted through STAR for a Geologic Resources Division site visit to evaluate paleontological resources, conduct field inventories and assessments, provide staff training, and train the paleontological intern if one is present.

- The reported fossil collecting activity at the Goddard Youth Camp should be evaluated.

- The fossil collections of the recreation area should be evaluated, and uncatalogued specimens should be documented. In addition, given the fossiliferous nature of many of the formations,

if it is ever desired to obtain additional fossils, making a good collection should not be difficult.

- Staff should be encouraged to observe exposed rocks and sedimentary deposits for fossil material while conducting their usual duties. To promote this, staff should also receive guidance regarding how to recognize common local fossils. When opportunities arise to observe paleontological resources in the field and take part in paleontological field studies with trained paleontologists, staff should take advantage of them, if funding and time permit.

- Staff should photodocument and monitor any occurrences of paleontological resources that may be observed in situ. Fossils and their associated geologic context (surrounding rock) should be documented but left in place unless they are subject to imminent degradation by artificially accelerated natural processes or direct human impacts. A Geologic Resource Monitoring Manual by the Geological Society of America and NPS Geologic Resources Division includes a section on paleontological resource monitoring (Santucci et al. 2009). Santucci and Koch (2003) present information on paleontologic resource monitoring.

- Fossils found in a cultural context should be documented like other fossils, but will also require the input of an archeologist or a cultural resource specialist. Any fossil which has a cultural context may be culturally sensitive as well (e.g., subject to NAGPRA) and should be regarded as such until otherwise established. The Geologic Resources Division can coordinate additional documentation/research of such material.

- It may be of interest to refer to the nearby Bromide Formation bryozoan reef, White Mound, and Buckhorn Asphalt Quarry sites for educational purposes. If expansion is considered for CHIC, the unique Buckhorn Asphalt Quarry site should be looked at.

- Contact the NPS Geologic Resources Division for technical assistance with paleontological resource management issues.

References Cited

Alberstadt, L. P. 1967. Brachiopod biostratigraphy of the Viola and “Fernvale” formations (Ordovician), Arbuckle Mountains, south-central Oklahoma. Dissertation. University of Oklahoma, Norman, Oklahoma. Available at http://hdl.handle.net/11244/2268 (accessed April 2015).

Alberstadt, L. P. 1973. Articulate brachiopods of the Viola Formation (Ordovician) in the Arbuckle Mountains, Oklahoma. Oklahoma Geological Survey, Norman, Oklahoma. Bulletin 117. Available at http://www.ogs.ou.edu/pubsscanned/BULLETINS/Bulletin117.pdf (accessed March 2015).

Albert, L. E. 1981. Ferndale Bog and Natural Lake: five thousand years of environmental change in southeastern Oklahoma. Oklahoma Archeological Survey, Norman, Oklahoma. Studies in Oklahoma's Past 7.

Al-Shaieb, Z., J. Puckette, and P. Blubaugh. 2001. The Hunton Group: sequence stratigraphy, facies, dolomitization, and karstification. Pages 17–29 *in* K. S. Johnson, editor. Silurian, Devonian, and Mississippian geology and petroleum in the southern midcontinent, 1999 symposium. Oklahoma Geological Survey, Norman, Oklahoma. Circular 105. Available at http://www.ogs.ou.edu/pubsscanned/Circulars/Circular105.pdf (accessed March 2015).

Amati, L., and S. R. Westrop. 2006. Sedimentary facies and trilobite biofacies along an Ordovician shelf to basin gradient, Viola Group, south-central Oklahoma. Palaios 21(6):516–529.

Amsden, T. W. 1951. Brachiopods of the Henryhouse Formation (Silurian) of Oklahoma. Journal of Paleontology 25(1):69–96.

Amsden, T. W. 1956. Notes on *Parmorthis brownsportensis* and *Isorthis arcuaria* from the Henryhouse and Brownsport formations. Oklahoma Geology Notes 16(8):78–85. Available at http://www.ogs.ou.edu/pubsscanned/NOTES/1956Vol16P.pdf (accessed March 2015).

Amsden, T. W. 1957a. Catalog of fossils from the Middle and Upper Ordovician of Oklahoma. Oklahoma Geological Survey, Norman, Oklahoma. Circular 43. Available at http://www.ogs.ou.edu/pubsscanned/Circulars/Circular43.pdf (accessed March 2015).

Amsden, T. W. 1957b. Introduction to stratigraphy. Part 1 of Stratigraphy and paleontology of the Hunton group in the Arbuckle Mountain region. Oklahoma Geological Survey, Norman, Oklahoma. Circular 44. Available at http://www.ogs.ou.edu/pubsscanned/Circulars/circular44.pdf (accessed March 2015).

Amsden, T. W. 1958a. Haragan articulate brachiopods. Part 2 of Stratigraphy and paleontology of the Hunton group in the Arbuckle Mountain region. Oklahoma Geological Survey, Norman, Oklahoma. Bulletin 78:9–144. Available at http://www.ogs.ou.edu/pubsscanned/BULLETINS/Bulletin78.pdf (accessed March 2015).

Amsden, T. W. 1958b. Bois d'Arc articulate brachiopods. Part 5 of Stratigraphy and paleontology of the Hunton group in the Arbuckle Mountain region. Oklahoma Geological Survey, Norman, Oklahoma. Bulletin 82. Available at http://www.ogs.ou.edu/pubsscanned/BULLETINS/Bulletin82.pdf (accessed March 2015).

Amsden, T. W. 1958c. White Mound. Oklahoma Geology Notes 18(8–9):131–135.

Amsden, T. W. 1960. Stratigraphy and paleontology of the Hunton Group in the Arbuckle Mountain region. Part VI, Stratigraphy. Oklahoma Geological Survey, Norman, Oklahoma. Bulletin 84. Available at http://www.ogs.ou.edu/pubsscanned/BULLETINS/Bulletin84mm.pdf (accessed March 2015).

Amsden, T. W. 1962a. Silurian and Early Devonian carbonate rocks of Oklahoma. Bulletin of the American Association of Petroleum Geologists 46(8):1502–1519.

Amsden, T. W. 1962b. Additional fossils from the Bois d'Arc Formation in the southeastern part of the Arbuckle Mountains region. Oklahoma Geology Notes 22(8):212–216. Available at http://www.ogs.ou.edu/pubsscanned/NOTES/1962Vol22P.pdf (accessed March 2015).

Amsden, T. W. 1967. Chimneyhill limestone sequence (Silurian), Hunton Group, Oklahoma, revised. American Association of Petroleum Geologists Bulletin 51(6, Part 1):942–945.

Amsden, T. W. 1968. Articulate brachiopods of the Saint Clair Limestone (Silurian), Arkansas, and the Clarita Formation (Silurian), Oklahoma. Paleontological Society Memoir 1.

Amsden, T. W., and W. E. Ham. 1959. A remarkable specimen of the trilobite Isotelus from the Viola limestone. Oklahoma Geology Notes 19(2):18–19.

Amsden, T. W., and W. C. Sweet. 1983. Upper Bromide Formation and Viola Group (Middle and Upper Ordovician) in eastern Oklahoma: Part I, Welling-Fite-Corbin Ranch strata: Part II, Conodont biostratigraphy of Fite Formation and Viola Group: Part III, the Late Ordovician brachiopods. Oklahoma Geological Survey, Norman, Oklahoma. Bulletin 132. Available at http://www.ogs.ou.edu/pubsscanned/BULLETINS/Bulletin132.pdf (accessed March 2015).

Amsden, T. W., and W. P. S. Ventress. 1963. Early Devonian brachiopods of Oklahoma: Part 1, Articulate brachiopods of the Frisco Formation: Part 2, Articulate brachiopods of the Sallisaw Formation: Part 3, Supplement to the Haragan brachiopods. Oklahoma Geological Survey, Norman, Oklahoma. Bulletin 94. Available at http://www.ogs.ou.edu/pubsscanned/BULLETINS/Bulletin94.pdf (accessed March 2015).

Amsden, T. W., D. F. Toomey, and J., E. Barrick. 1980. Paleoenvironment of Fitzhugh Member of Clarita Formation (Silurian, Wenlockian), southern Oklahoma. Oklahoma Geological Survey, Norman, Oklahoma. Circular 83. Available at http://www.ogs.ou.edu/pubsscanned/Circulars/circular83.pdf (accessed March 2015).

Arnold, C. A. 1934. *Callixylon whiteanum* sp. nov., from the Woodford chert of Oklahoma. Botanical Gazette 96(1):180–185.

Bandel, K., A. Nützel, and T. E. Yancey. 2002. Larval shells and shell microstructures of exceptionally well-preserved Late Carboniferous gastropods from the Buckhorn Asphalt deposit (Oklahoma, USA). Senckenbergiana Lethaea 82(2):639–689

Barrick, J. E., and G. Klapper. 1976. Multielement Silurian (late Llandoverian–Wenlockian) conodonts of the Clarita Formation, Arbuckle Mountains, Oklahoma, and phylogeny of *Kockelella*. Geologica et Palaeontologica 10:59–100.

Barrick, J. E., and G. Klapper. 1990. Stop 2: Henryhouse and Haragan formations (Late Silurian–Early Devonian) and Woodford Shale (Late Devonian–Early Mississippian). Pages 11–13 *in* S. M. Ritter, editor. Early to Middle Paleozoic conodont biostratigraphy of the Arbuckle Mountains, southern Oklahoma. Oklahoma Geological Survey, Norman, Oklahoma. Guidebook 27. Available at http://www.ogs.ou.edu/pubsscanned/guidebooks/GB27.pdf (accessed March 2015).

Barrick, J. E., and G. Klapper. 1992. Late Silurian–Early Devonian conodonts from the Hunton Group (upper Henryhouse, Haragan, and Bois d'Arc formations), south-central Oklahoma. Pages 19–65 *in* J. R. Chaplin and J. E. Barrick. Special papers in paleontology and stratigraphy: a tribute to Thomas W. Amsden. Oklahoma Geological Survey, Norman, Oklahoma. Bulletin 145. Available at http://www.ogs.ou.edu/pubsscanned/BULLETINS/Bulletin145.pdf (accessed March 2015).

Barrick, J. E., G. Klapper, and T. W. Amsden. 1990a. Late Ordovician–Early Devonian conodont succession in the Hunton Group, Arbuckle Mountains and Anadarko Basin, Oklahoma. Pages 55–62 *in* S. M. Ritter, editor. Early to Middle Paleozoic conodont biostratigraphy of the Arbuckle Mountains, southern Oklahoma. Oklahoma Geological Survey, Norman, Oklahoma. Guidebook 27. Available at http://www.ogs.ou.edu/pubsscanned/guidebooks/GB27.pdf (accessed March 2015).

Barrick, J. E., G. Klapper, and T. W. Amsden. 1990b. Stop 1: Hunton Group (Late Ordovician–Early Devonian). Pages 5–9 *in* S. M. Ritter, editor. Early to Middle Paleozoic conodont biostratigraphy of the Arbuckle Mountains, southern Oklahoma. Oklahoma Geological Survey, Norman, Oklahoma. Guidebook 27. Available at http://www.ogs.ou.edu/pubsscanned/guidebooks/GB27.pdf (accessed March 2015).

Bassler, R. S. 1943. New Ordovician cystidean echinoderms from Oklahoma. American Journal of Science 241:694–703.

Bates, D. E. B., and N. H. Kirk. 1991. The ultrastructure, mode of construction and functioning of Ordovician retiolitid graptolites from the Viola Springs Limestone, Oklahoma. Modern Geology 15(2–3):131–286.

Bauer, J. A. 1987. Conodonts and conodont biostratigraphy of the McLish and Tulip Creek Formations (Middle Ordovician) of south-central Oklahoma. Oklahoma Geological Survey, Norman, Oklahoma. Bulletin 141. Available at http://www.ogs.ou.edu/pubsscanned/BULLETINS/Bulletin141.pdf (accessed March 2015).

Bauer, J. A. 1990a. Stratigraphy and conodont biostratigraphy of the upper Simpson Group, Arbuckle Mountains, Oklahoma. Pages 39–53 *in* S. M. Ritter, editor. Early to Middle Paleozoic conodont biostratigraphy of the Arbuckle Mountains, southern Oklahoma. Oklahoma Geological Survey, Norman, Oklahoma. Guidebook 27. Available at http://www.ogs.ou.edu/pubsscanned/guidebooks/GB27.pdf (accessed March 2015).

Bauer, J. A. 1990b. Stop 5: Upper Simpson Group (western Arbuckle Facies, Middle Ordovician), Interstate 35 section. Pages 19–21 *in* S. M. Ritter, editor. Early to Middle Paleozoic conodont biostratigraphy of the Arbuckle Mountains, southern Oklahoma. Oklahoma Geological Survey, Norman, Oklahoma. Guidebook 27. Available at http://www.ogs.ou.edu/pubsscanned/guidebooks/GB27.pdf (accessed March 2015).

Bauer, J. A. 1994. Conodonts from the Bromide Formation (Middle Ordovician), south-central Oklahoma. Journal of Paleontology 68(2):358–376.

Bauer, J. A. 2010. Conodonts and conodont biostratigraphy of the Joins and Oil Creek Formations, Arbuckle Mountains, south-central Oklahoma. Oklahoma Geological Survey, Norman, Oklahoma. Bulletin 150. Available at http://www.ogs.ou.edu/pubsscanned/BULLETINS/Bulletin150all.pdf (accessed March 2015).

Baugh, S. T. 1986. Late Prehistoric bison distributions in Oklahoma. Plains Anthropologist Memoir 21:83–96.

Becker, T. R., and R. Mapes. 2010. Uppermost Devonian ammonoids from Oklahoma and their palaeobiogeographic significance. Acta Geologica Polonica 60(2):139–163.

Bennison, A. P. 1954. Target limestone, new member of Springer Formation, Carter County, Oklahoma. Bulletin of the American Association of Petroleum Geologists 38(5):913–915.

Billingsley, P., S. Banerjee, P. K. Sutherland, and R. C. Grayson, Jr. 1996. Fluvial-deltaic facies patterns in the lower Deese Group (Middle Pennsylvanian), Ardmore Basin, Oklahoma. Pages 240–248 *in* K. S. Johnson, editor. Deltaic reservoirs in the southern midcontinent, 1993 symposium. Oklahoma Geological Survey, Norman, Oklahoma. Circular 98. Available at http://www.ogs.ou.edu/pubsscanned/Circulars/Circular98.pdf (accessed March 2015).

Blake, D. B. 2008. A new Ordovician asteroid (Echinodermata) with somasteroid-like skeletal elements. Journal of Paleontology 82(4):645–656.

Blome, C. D., D. J. Lidke, R. R. Wahl, and J. A. Golab. 2013. Geologic map of Chickasaw National Recreation Area, Murray County, Oklahoma. U.S. Geological Survey, Reston, Virginia. Scientific Investigations Map 3258. Scale 1:24,000. Available at http://pubs.er.usgs.gov/publication/sim3258 (accessed March 2015).

Boardman, D., J. Puckette, I. Cemen, L. Watney, and A. Cruse. 2009. High resolution stratigraphy of the Middle and Upper Mississippian Caney Shale (Visean-Serpukhovian) of Oklahoma. Abstracts with Programs - Geological Society of America 41(2):6.

Boucot, A. J., and T. W. Amsden. 1958. New genera of brachiopods. Part 4 of Stratigraphy and paleontology of the Hunton group in the Arbuckle Mountain region. Oklahoma Geological Survey, Norman, Oklahoma. Bulletin 78:159–170. Available at http://www.ogs.ou.edu/pubsscanned/BULLETINS/Bulletin78.pdf (accessed March 2015).

Brand, U. 1987. Biogeochemistry of nautiloids and paleoenvironmental aspects of Buckhorn seawater (Pennsylvanian), southern Oklahoma. Palaeogeography, Palaeoclimatology, Palaeoecology 61(3–4):255–264.

Branson, C. C. 1964a. Sclerites? from Bromide Formation. Oklahoma Geology Notes 24(5):106–107. Available at http://www.ogs.ou.edu/pubsscanned/NOTES/GN-V24N5.pdf (accessed March 2015).

Branson, C. C. 1964b. False color pattern on an Oklahoma goniatite. Oklahoma Geology Notes 24(7):160. Available at http://www.ogs.ou.edu/pubsscanned/NOTES/GN-V24N7.pdf (accessed March 2015).

Branson, C. C. 1964c. Large specimen of *Goniatites*. Oklahoma Geology Notes 24(12):287–288. Available at http://www.ogs.ou.edu/pubsscanned/NOTES/GN-V24N12.pdf (accessed March 2015).

Branson, C. C. 1964d. Record of *Edestus* in Oklahoma. Oklahoma Geology Notes 24(9):210. Available at http://www.ogs.ou.edu/pubsscanned/NOTES/GN-V24N9.pdf (accessed March 2015).

Branson, C. C. 1966. *Conocardium* in the Bromide Formation (Ordovician) of Oklahoma. Oklahoma Geology Notes 26(3):78–79. Available at http://www.ogs.ou.edu/pubsscanned/NOTES/GN-V26N3.pdf (accessed March 2015).

Branson, C. C., and T. W. Amsden. 1958. *Conocardium* from the Hunton group. Oklahoma Geology Notes 18(10):147–151.

Branson, E. B., and M. G. Mehl. 1940. Caney conodonts of Upper Mississippian age. Journal of the Scientific Laboratories, Denison University 35:167–178.

Branson, C. C., M. K. Elias, and T. W. Amsden. 1959. Type of *Goniatites choctawensis*. Oklahoma Geology Notes 19(8):157–164. Available at http://www.ogs.ou.edu/pubsscanned/NOTES/1959Vol19P.pdf (accessed March 2015).

Braun, J. C. 1959. A stratigraphic study of the Sycamore and related formations in the southeastern Anadarko Basin. Shale Shaker 10(1):6–23.

Brett, C. E. 1985. *Tremichnus*: a new ichnogenus of circular-parabolic pits in fossil echinoderms. Journal of Paleontology 59(3):625–635.

Brown, W. G., and R. C. Grayson, Jr., editors. 1985. Tectonism and sedimentation in the Arbuckle Mountain region, Southern Oklahoma Aulacogen. Baylor Geological Society, Waco, Texas. Southwestern Association of Student Geological Societies field trip.

Campbell, K. S. W. 1967. Trilobites of the Henryhouse Formation (Silurian) in Oklahoma. Oklahoma Geological Survey, Norman, Oklahoma. Bulletin 115. Available at http://www.ogs.ou.edu/pubsscanned/BULLETINS/Bulletin115.pdf (accessed March 2015).

Campbell, K. S. W. 1977. Trilobites of the Haragan, Bois d'Arc and Frisco formations (Early Devonian), Arbuckle Mountains region, Oklahoma. Oklahoma Geological Survey, Norman,

Oklahoma. Bulletin 123. Available at http://www.ogs.ou.edu/pubsscanned/BULLETINS/Bulletin123.pdf (accessed March 2015).

Cardott, B. J., and J. R. Chaplin. 1993. Guidebook for selected stops in the western Arbuckle Mountains, southern Oklahoma. Oklahoma Geological Survey, Norman, Oklahoma. Special Publication 93-3. Available at http://www.ogs.ou.edu/pubsscanned/SPs/SP93_3.pdf (accessed May 2015).

Carlucci, J. R., S. R. Westrop, and L. Amati. 2010. Tetralichine trilobites from the Upper Ordovician of Oklahoma and Virginia and phylogenetic systematics of the Tetralichini. Journal of Paleontology 84(6):1099–1120.

Carlucci, J. R., S. R. Westrop, L. Amati, J. M. Adrain, and R. E. Swisher. 2012. A systematic revision of the Upper Ordovician trilobite genus *Bumastoides* (Illaenidae), with new species from Oklahoma, Virginia and Missouri. Journal of Systematic Palaeontology 10(4):679–723.

Cates, S. W. 1989. Fault distribution in the Sulphur, Oklahoma, area based on gravity, magnetic and structural data. Thesis. University of Oklahoma, Norman, Oklahoma.

Cates, S. W. 1991. Study of the Ordovician Arbuckle-Simpson Aquifer in the Sulphur area of south-central Oklahoma. Page 210 *in* K. S. Johnson, editor. Late Cambrian–Ordovician geology of the southern midcontinent, 1989 symposium. Oklahoma Geological Survey, Norman, Oklahoma. Circular 92. Available at http://www.ogs.ou.edu/pubsscanned/Circulars/Circular92.pdf (accessed March 2015).

Champlin, S. C. 1959. The problem of the Welden, Sycamore and lower Caney in the eastern Arbuckle Mountains. Proceedings of the Oklahoma Academy of Science 39:120–124. Available at http://digital.library.okstate.edu/oas/oas_pdf/v39/p120_124.pdf (accessed March 2015).

Chaplin, J. R. 1989. Guidebook for selected geologic stops in the Arbuckle Mountains. Oklahoma Geological Survey, Norman, Oklahoma. Open-File Report 4-89.

Chaplin, J. R. 2005. White Mound: a world famous fossil collecting locality revisited. Shale Shaker 55(5):131–142.

Chatterton, B. D. E., and H. L. Whitehead. 1987. Predatory borings in the inarticulate brachiopod *Artiotreta* from the Silurian of Oklahoma. Lethaia 20(1):67–74.

Chenoweth, P. A., J. C. Braun, S. C. Champlin, and J. W. Prestridge. 1959. Sycamore and related formations of southern Oklahoma. Tulsa Geological Society Digest 27:113–123.

Christenson, S., N. I. Osborn, C. R. Neel, J. R. Faith, C. D. Blome, J. Puckette, and M. P. Pantea. 2011. Hydrogeology and simulation of groundwater flow in the Arbuckle-Simpson aquifer, south-central Oklahoma. U.S. Geological Survey, Reston, Virginia. Scientific Investigations Report 2011-5029. Available at http://pubs.er.usgs.gov/publication/sir20115029 (accessed May 2015).

Churkin, M., Jr. 1966. Morphology and stratigraphic range of the phyllocarid crustacean *Caryocaris* from Alaska and the Great Basin. Palaeontology 9(3):371–380. Available at http://cdn.palass.org/publications/palaeontology/volume_9/pdf/vol9_part3_pp371-380.pdf (accessed April 2015).

Cifelli, R. L., K. S. Smith, and F. von Hofe Grady. 2002. Dire wolf (*Canis dirus*) in the Pleistocene of Oklahoma. Oklahoma Geology Notes 62(3):92–96. Available at http://www.ogs.ou.edu/pubsscanned/NOTES/GN-V62N3.pdf (accessed March 2015).

Colbath, G. K., and S. K. Larson. 1980. On the chemical composition of fossil polychaete jaws. Journal of Paleontology 54(2):485–488.

Cole, T. 1988. A surface to subsurface study of the Sycamore Limestone (Mississippian) along the north flank of the Arbuckle Anticline. Shale Shaker 38(6):98–114.

Conkin, J. E., and B. M. Conkin. 1965. Ordovician (Richmondian) Foraminifera from Oklahoma, Missouri, Illinois, and Kentucky. Oklahoma Geology Notes 25(8):207–221. Available at http://www.ogs.ou.edu/pubsscanned/NOTES/1965Vol25P.pdf (accessed March 2015).

Cooper, C. L. 1931a. Conodonts from the Arkansas novaculite, Woodford Formation, Ohio shale, and Sunbury shale. Journal of Paleontology 5(2):143–151.

Cooper, C. L. 1931b. New conodonts from the Woodford Formation of Oklahoma. Journal of Paleontology 5(3):230–243.

Cooper, C. L. 1932. A crustacean fauna from the Woodford Formation of Oklahoma. Journal of Paleontology 6(4):346–352.

Cooper, G. A. 1956. Chazyan and related brachiopods. Smithsonian Miscellaneous Collections 127. Available at http://archive.org/details/smithsonianmisce12711956smit and http://archive.org/details/smithsonianmisce12721956smit (accessed April 2015).

Coryell, H. N., and V. A. Cuskley. 1934. Some new ostracodes from the “White Mound” section of the Haragan shale, Murray County, Oklahoma. American Museum Novitates 748. Available at http://digitallibrary.amnh.org/dspace/handle/2246/4589?show=full (accessed March 2015).

Crick, R. E. 1982. The mode and tempo of cameral deposit formation: evidence of orthoconic nautiloid physiology and ecology. North American Paleontological Convention Proceedings 3(1):113–118.

Cuffey, C. A., and R. J. Cuffey. 1995. The Chickasaw bryozoan reef in the Middle Ordovician of south-central Oklahoma. Pages 435–438 *in* J. D. Cooper, M. L. Droser, and S. C. Finney, editors. Ordovician odyssey: short papers for the Seventh international symposium on the Ordovician System. Pacific Section, Society of Economic Paleontologists and Mineralogists. Field Trip Guidebook 77.

Cuffey, C. A., R. J. Cuffey, A. J. Robb, III, and J. T. Lembcke. 1995a. Reconnaissance survey of the Haragan Formation bryozoan fauna and its paleoecology, Lower Devonian of south-central Oklahoma. Oklahoma Geology Notes 55(4):128–149. Available at http://www.ogs.ou.edu/pubsscanned/NOTES/GN-V55N4.pdf (accessed March 2015).

Cuffey, C. A., A. J. Robb, III, J. T. Lembcke, and R. J. Cuffey. 1995b. Epizoic bryozoans and corals as indicators of life and post-mortem orientations of the Devonian brachiopod *Meristella*. Lethaia 28(2):139–153.

Dalquest, W. W. 1961. A record of the giant bison (*Bison latifrons*) from Cooke County, Texas. Texas Journal of Science 13(1):41–44.

Dalquest, W.W., and C.W. Hibbard. 1965. 1350-year-old vertebrate remains from Montague County, Texas. Southwestern Naturalist 10(4):315–316.

Decker, C. E. 1933. Viola limestone, primarily of Arbuckle and Wichita Mountain regions. Bulletin of the American Association of Petroleum Geologists 17(12):1405–1435.

Decker, C. E. 1935a. Graptolites of the Sylvan shale of Oklahoma and Polk Creek shale of Arkansas. Journal of Paleontology 9(8):697–708.

Decker, C. E. 1935b. Graptolites from the Silurian of Oklahoma. Journal of Paleontology 9(5):434–446.

Decker, C. E. 1941. Graptolites from the Haragan Formation (Lower Devonian) of Oklahoma: Journal of Paleontology 15(2):164–165.

Decker, C. E., and C. A. Merritt. 1931. The stratigraphy and physical characteristics of the Simpson Group, with a section of descriptions and illustrations of ostracodes and conodonts, by R. W. Harris. Oklahoma Geological Survey, Norman, Oklahoma. Bulletin 55. Available at http://www.ogs.ou.edu/pubsscanned/BULLETINS/Bulletin55mm.pdf (accessed April 2015).

Denison, R. E. 1997. Contrasting sedimentation inside and outside the southern Oklahoma Aulacogen during the Middle and Late Ordovician. Pages 39–47 *in* K. S. Johnson, editor. Simpson and Viola groups in the southern midcontinent, 1994 symposium. Oklahoma Geological Survey, Norman, Oklahoma. Circular 99. Available at http://www.ogs.ou.edu/pubsscanned/Circulars/Circular99.pdf (accessed March 2015).

Derby, J. R. 1969. Revision of Lower Ordovician–Middle Ordovician boundary in western Arbuckle Mountains, Oklahoma. Pages 35–37 *in* W. E. Ham. Regional geology of the Arbuckle Mountains, Oklahoma. Oklahoma Geological Survey, Norman, Oklahoma. Guidebook 17. Available at http://www.ogs.ou.edu/pubsscanned/guidebooks/GB17.pdf, http://www.ogs.ou.edu/pubsscanned/guidebooks/GBill/GB17%20FIG16.pdf, http://www.ogs.ou.edu/pubsscanned/guidebooks/GBill/GB17%20Geo%20Map.pdf (accessed March 2015).

Derby, J. R., J. A. Bauer, W. B. Creath, R. I. Dresbach, R. L. Ethington, J. D. Loch, J. H. Stitt, T. R. McHargue, J. F. Miller, M. A. Miller, J. E. Repetski, W. C. Sweet, J. F. Taylor, and M. Williams. 1991. Biostratigraphy of the Timbered Hills, Arbuckle, and Simpson groups, Cambrian and Ordovician, Oklahoma: a review of correlation tools and techniques available to the explorationist. Pages 15–41 *in* K. S. Johnson, editor. Late Cambrian–Ordovician geology of the southern midcontinent, 1989 symposium. Oklahoma Geological Survey, Norman, Oklahoma. Circular 92. Available at http://www.ogs.ou.edu/pubsscanned/Circulars/Circular92.pdf (accessed March 2015).

Donoghue, P. C. J., and K. M. Chauffe. 1998. *Conchodontus*, *Mitrellataxis* and *Fungulodus*: conodonts, fish or both? Lethaia 31(4):283–292.

Donovan, R. N. 2001. Field study of the Sycamore Formation on Interstate Highway 35 in the Arbuckle Mountains, Oklahoma. Pages 139–149 *in* K. S. Johnson, editor. Silurian, Devonian, and Mississippian geology and petroleum in the southern midcontinent, 1999 symposium. Oklahoma Geological Survey, Norman, Oklahoma. Circular 105. Available at http://www.ogs.ou.edu/pubsscanned/Circulars/Circular105.pdf (accessed March 2015).

Donovan, R. N., and W. D. Heinlen. 1988. Pennsylvanian conglomerates in the Arbuckle Mountains, southern Oklahoma. Pages 159–164 *in* O. T. Hayward, editor. South-central section of the Geological Society of America. Geological Society of America, Boulder, Colorado. Centennial field guide 4.

Drass, R. R. 1979. Roulston-Rogers: a stratified Plains Woodland and Late Archaic site in the Cross Timbers. Bulletin of the Oklahoma Anthropological Society 28:1–136.

Drass, R. R., and P. Flynn. 1990. Temporal and geographic variations in subsistence practices for Plains villagers in the Southern plains. Plains Anthropologist 35:175–190.

Dunham, R. J. 1955. Pennsylvanian conglomerates, structure, and orogenic history of Lake Classen area, Arbuckle Mountains, Oklahoma. Bulletin of the American Association of Petroleum Geologists 39(1):1–30.

Elias, M. K. 1956. Upper Mississippian and Lower Pennsylvanian formations of south-central Oklahoma. Pages 56–134 *in* I. C. Hicks, J. Westheimer, C. W. Tomlinson, D. M. Putnam, and E. L. Selk, editors. Petroleum geology of southern Oklahoma: a symposium. Volume 1. Ardmore Geological Society and American Association of Petroleum Geologists, Tulsa, Oklahoma. Special Volume 16.

Elias, R. J. 1992. New information on latest Ordovician to earliest Silurian solitary rugose corals of the east-central United States. Pages 113–125 *in* J. R. Chaplin and J. E. Barrick. Special papers in paleontology and stratigraphy: a tribute to Thomas W. Amsden. Oklahoma Geological Survey, Norman, Oklahoma. Bulletin 145. Oklahoma Geological Survey, Norman, Oklahoma. Bulletin 145. Available at http://www.ogs.ou.edu/pubsscanned/BULLETINS/Bulletin145.pdf (accessed March 2015).

Elias, M. K., and C. C. Branson. 1959. Type section of the Caney shale. Oklahoma Geological Survey, Norman, Oklahoma. Circular 52. Available at http://www.ogs.ou.edu/pubsscanned/Circulars/circular52.pdf (accessed March 2015).

Eriksson, M., and S. A. Leslie. 2003. Microfossils from the upper Sylvan Shale (Late Ordovician), Oklahoma, USA. Serie Correlacion Geologica 17:295–296. Available at http://insugeo.org.ar/publicaciones/docs/scg_17/50.htm (accessed March 2015).

Eriksson, M. E., S. A. Leslie, and C. F. Bergman. 2005. Jawed polychaetes from the upper Sylvan Shale (Upper Ordovician), Oklahoma, USA. Journal of Paleontology 79(3):486–496.

Faith, J. R., C. D. Blome, M. P. Pantea, J. O. Puckette, T. Halihan, N. Osborn, S. Christenson, and S. Pack. 2010. Three-dimensional geologic model of the Arbuckle-Simpson aquifer, south-central Oklahoma. U.S. Geological Survey, Reston, Virginia. Open-File Report 2010-1123. Available at http://pubs.er.usgs.gov/publication/ofr20101123 (accessed May 2015).

Farmer, G. T., Jr. 1975. New bifoliate tubular bryozoan genera from the Simpson Group (middle Ordovician), Arbuckle Mountains, Oklahoma. Bulletins of American Paleontology 67(287):123–138. Available at http://biodiversitylibrary.org/page/10896281 (accessed March 2015).

Fay, R. O., and A. A. Graffham. 1982. Stratigraphic studies. Pages 11–16 *in* J. Sprinkle, editor. Echinoderm faunas from the Bromide Formation (Middle Ordovician) of Oklahoma. University of Kansas Paleontological Institute, Lawrence, Kansas. University of Kansas Paleontological Contributions. Monograph 1. Available at http://hdl.handle.net/1808/3841 (accessed January 2015),

Fay, R. O., and I. G. Reimann. 1962. The paradeltoid plates of *Polydeltoideus*. Oklahoma Geology Notes 22(2):50–52. Available at http://www.ogs.ou.edu/pubsscanned/NOTES/1962Vol22P.pdf (accessed March 2015).

Fay, R. O., A. A. Graffham, and J. Sprinkle. 1982. Appendix: Measured sections and other collecting localities. Pages 335–369 *in* J. Sprinkle, editor. Echinoderm faunas from the Bromide Formation (Middle Ordovician) of Oklahoma. University of Kansas Paleontological Institute, Lawrence, Kansas. University of Kansas Paleontological Contributions. Monograph 1. Available at http://hdl.handle.net/1808/3841 (accessed January 2015).

Feldmann, R. M., and C. E. Schweitzer. 2010. The oldest shrimp (Devonian, Famennian) and remarkable preservation of soft tissue. Abstracts with Programs - Geological Society of America 42(2):83.

Felix, C. J., and P. P. Burbridge. 1967. Palynology of the Springer Formation of southern Oklahoma, U.S.A. Palaeontology 10(3):349–425. Available at http://cdn.palass.org/publications/palaeontology/volume_10/pdf/vol10_part3_pp349-425.pdf (accessed March 2015).

Finks, R. M. 1995. Some new genera of Paleozoic calcareous sponges. University of Kansas Paleontological Contributions 6. Available at http://hdl.handle.net/1808/3769 (accessed March 2015).

Finney, S. C. 1988. Middle Ordovician strata of the Arbuckle and Ouachita mountains, Oklahoma: contrasting lithofacies and biofacies deposited in southern Oklahoma Aulacogen and Ouachita Geosyncline. Pages 171–176 *in* O. T. Hayward, editor. South-central section of the Geological Society of America. Geological Society of America, Boulder, Colorado. Centennial field guide 4.

Frest, T. J., and H. L. Strimple. 1980. New diminutive camerate crinoids from the Ludlow of Oklahoma. Geological Magazine 117(3):255–266.

Frest, T. J., H. L. Strimple, and B. J. Witzke. 1980. New Comarocystitida (Echinodermata: Paracrinoidea) from the Silurian of Iowa and Ordovician of Oklahoma. Journal of Paleontology 54(1):217–228.

Frye, J. C., and A. B. Leonard. 1963. Pleistocene geology of Red River basin in Texas. Bureau of Economic Geology, University of Texas at Austin, Austin, Texas. Report of Investigations 49. Available at http://www.lib.utexas.edu/books/landscapes/detail.php?work_id=288520 (accessed March 2015).

Furnish, W. M., J. H. Quinn, and J. A. McCaleb. 1964. The Upper Mississippian ammonoid *Delepinoceras* in North America. Palaeontology 7(2):173–180. Available at http://cdn.palass.org/publications/palaeontology/volume_7/pdf/vol7_part2_pp173-180.pdf (accessed March 2015).

Girty, G. H. 1909. The fauna of the Caney Shale of Oklahoma. U.S. Geological Survey, Washington, D.C. Bulletin 377. Available at http://pubs.er.usgs.gov/publication/b377 (accessed March 2015).

Glaser, G. C. 1965. Lithostratigraphy of carbonate petrology of the Viola group (Ordovician), Arbuckle Mountains, south-central Oklahoma. Dissertation. University of Oklahoma, Norman, Oklahoma. Available at http://hdl.handle.net/11244/1964 (accessed April 2015).

Gordon, M., Jr. 1962. Species of *Goniatites* in the Caney Shale of Oklahoma. Journal of Paleontology 36(2):355–357.

Gorman, J. M., and G. M. Flint, Jr. 1944. Geologic map of the Dougherty asphalt area, Murray County, Oklahoma. U.S. Geological Survey, Washington, D.C. Oil and Gas Investigation Map 15. Scale 1:3,600. Available at http://ngmdb.usgs.gov/Prodesc/proddesc_5298.htm (accessed May 2015).

Gorman, J. M., C. E. Decker, G. M. Flint, Jr., and W. E. Ham. 1945. Geologic map of the Sulphur asphalt area, Murray County, Oklahoma, 1944. U.S. Geological Survey, Washington, D.C. Oil and Gas Investigations Map 22. Scale 1:3,600. Available at http://pubs.er.usgs.gov/publication/om22 (accessed March 2015).

Gould, C. N., and S. L. Schoff. 1939. Geological report on water conditions at Platt National Park, Oklahoma. U.S. Geological Survey, Washington, D.C. Open-File Report 39-14.

Graham, J. 2008. Geologic resource evaluation scoping summary: Chickasaw National Recreation Area, Oklahoma. National Park Service, Geologic Resources Division, Denver, Colorado. Available at http://www.nature.nps.gov/geology/inventory/publications/s_summaries/CHIC_scoping_summary_2008-0131.pdf (accessed March 2015).

Grahn, Y., and M. A. Miller. 1986. Chitinozoa from the Middle Ordovician Bromide Formation, Arbuckle Mountains, Oklahoma, U.S.A. Neues Jahrbuch für Geologie und Palaeontologie. Abhandlungen 172(3):381–403.

Hacker, S. M. 2001. Sources, types, and mixing of ground water in the Chickasaw National Recreation Area. Thesis. Illinois State University, Normal, Illinois.

Ham, W. E. 1954. Algal origin of the "birdseye" limestone in the McLish Formation. Proceedings of the Oklahoma Academy of Science 33:200–203. Available at http://digital.library.okstate.edu/oas/oas_pdf/v33/v200_203.pdf (accessed March 2015).

Ham, W. E. 1973. Regional geology of the Arbuckle Mountains. Oklahoma Geological Survey, Norman, Oklahoma. Special Paper 73-3. Available at http://www.ogs.ou.edu/pubsscanned/SPs/SP73_3.pdf (accessed March 2015).

Ham, W. E., M. E. McKinley, and others (unnamed). 1954. Geologic map of the Arbuckle Mountains, Oklahoma. Oklahoma Geological Survey, Norman, Oklahoma. Miscellaneous Map A-2. Scale 1:72,000. Available at http://www.ogs.ou.edu/geolmapping/Arbuckle_Map.pdf (accessed April 2015).

Hannibal, J. T. 1994. Methods for distinguishing carbonized specimens of the presumed cephalopod aptychus *Sidetes* (*Spathiocaris*) from the plant *Protosalvinia* (*Foerstia*). Journal of Paleontology 68(3):671–673.

Hanson, R. L., and S. W. Cates. 1994. Hydrogeology of the Chickasaw National Recreation Area, Murray County, Oklahoma. U.S. Geological Survey, Reston, Virginia. Water-Resources Investigations 94-4102. Scale 1:24,000. Available at http://pubs.er.usgs.gov/publication/wri944102 (accessed March 2015).

Hanson, R. E., R. E. Puckett, Jr., R. G. Keller, M. E. Brueseke, C. L. Bulen, S. A. Mertzman, S. A. Finegan, and D. A. McCleery. 2013. Intraplate magmatism related to opening of the southern Iapetus Ocean; Cambrian Wichita igneous province in the Southern Oklahoma rift zone. Lithos 174:57–70.

Harris, R. W. 1957. Ostracoda of the Simpson Group of Oklahoma. Oklahoma Geological Survey, Norman, Oklahoma. Bulletin 75. Available at http://www.ogs.ou.edu/pubsscanned/BULLETINS/bulletin75mm.pdf (accessed March 2015).

Harris, R. W. 1962. New conodonts from Joins (Ordovician) Formation of Oklahoma. Oklahoma Geology Notes 22(8):199–211. Available at http://www.ogs.ou.edu/pubsscanned/NOTES/1962Vol22P.pdf (accessed March 2015).

Harris, R. W. 1964. Erismodid conodonts in Simpson (Ordovician) of Oklahoma. Oklahoma Geology Notes 24(8):171–177. Available at http://www.ogs.ou.edu/pubsscanned/NOTES/GN-V24N8.pdf (accessed March 2015).

Harris, R. W., and R. W. Harris, Jr. 1965. Pruitt Ranch, new member of the Oil Creek (Simpson) in Criner Hills, Oklahoma. Tulsa Geological Society Digest 33:144–161.

Hay, O. P. 1924. The Pleistocene of the middle region of North America and its vertebrated animals. Carnegie Institute of Washington Publication 322A. Available at https://archive.org/details/pleistoceneofmid00hayo (accessed January 2015).

Hoare, R. D., R. H. Mapes, and C. J. Brown. 1982. Some Mississippian and Pennsylvanian rostroconchs from the Midcontinent region. Journal of Paleontology 56(1):123–131.

Holdsworth, B. K., E. A. Pessagno, Jr., Y. Cheng, and J. Schwartz-Apfel. 1982. Biostratigraphic investigations of Paleozoic (Upper Devonian to Middle Pennsylvanian) Radiolaria in Wichita and Ouachita orogenic belts. Abstracts with Programs - Geological Society of America 14(3):114.

Holloway, D. J. 1980. Middle Silurian trilobites from Arkansas and Oklahoma, U.S.A.: Part 1. Palaeontographica. Abteilung A: Paläozoologie-Stratigraphie 170(1–3):1–85.

Holloway, R. G., and C. R. Ferring. 1985. A 12,000-year pollen and vegetational record from the Southern plains. Palynology 9:244.

Hollrah, T. L. 1978. Subsurface lithostratigraphy of the Hunton Group, in parts of Payne, Lincoln and Loga counties, Oklahoma: Part 2. Shale Shaker 28(8):168–175.

Ireland, H. A. 1939. Devonian and Silurian foraminifera from Oklahoma. Journal of Paleontology 13:190–202.

Jackson, J. L. 1969. Geologic studies at Arbuckle Dam, Murray County, Oklahoma. Bulletin of the Association of Engineering Geologists 5(2):79–99.

Jenkins, W. A. M. 1969. Chitinozoans from the Ordovician Viola and Fernvale Limestones of the Arbuckle Mountains, Oklahoma. Palaeontological Association of London, London, United Kingdom. Special Papers in Palaeontology 5. Available at http://cdn.palass.org/publications/special_papers_in_palaeontology/spp_5/pdf/spp5_pp1-44.pdf (accessed April 2015).

Jenkins, W. A. M. 1970. Chitinozoa from the Ordovician Sylvan shale of the Arbuckle mountains, Oklahoma. Palaeontology 13(2):261–288. Available at

http://cdn.palass.org/publications/palaeontology/volume_13/pdf/vol13_part2_pp261-288.pdf (accessed March 2015).

Johnson, K. S. 1990. Geologic map and sections of the Arbuckle Mountains. Revised (original W. E. Ham, M. E. McKinley, et al., 1954). Included in Oklahoma Geological Survey Circular 91. Scale 1:100,000. Available at http://www.ogs.ou.edu/pubsscanned/CircularsPlates/C91P1.pdf (accessed April 2015).

Johnson, K. S. 1991. Geologic overview and economic importance of Late Cambrian and Ordovician rocks in Oklahoma. Pages 3–14 *in* K. S. Johnson, editor. Late Cambrian–Ordovician geology of the southern midcontinent, 1989 symposium. Oklahoma Geological Survey, Norman, Oklahoma. Circular 92. Available at http://www.ogs.ou.edu/pubsscanned/Circulars/Circular92.pdf (accessed March 2015).

Johnson, K. S., M. R. Burchfield, and W. E. Harrison. 1984. Guidebook for Arbuckle Mountain field trip, southern Oklahoma. Oklahoma Geological Survey, Norman, Oklahoma. Special Publication 84-1. Available at http://www.ogs.ou.edu/pubsscanned/SPs/SP84_1.pdf (accessed March 2015).

Karim, T., and S. R. Westrop. 2002. Taphonomy and paleoecology of Ordovician trilobite clusters, Bromide Formation, south-central Oklahoma. Palaios 17(4):394–402.

Keighin, C. W., and R. M. Flores. 1989. Depositional facies, petrofacies, and diagenesis of siliciclastics of Morrow and Springer rocks, Anadarko Basin, Oklahoma. Pages 147–161 *in* K. S. Johnson, editor. Anadarko Basin symposium, 1988. Oklahoma Geological Survey, Norman, Oklahoma. Circular 90. Available at http://www.ogs.ou.edu/pubsscanned/Circulars/Circular90.pdf (accessed March 2015).

Kenworthy, J. P., and V. L. Santucci. 2006. A preliminary investigation of National Park Service paleontological resources in cultural resource contexts, Part 1: general overview. New Mexico Museum of Natural History and Science Bulletin 34:70–76. Available at http://nature.nps.gov/geology/paleontology/pub/fossil_conference_7/9%20Kenworthy.pdf (accessed December 2014).

Key, M. M., Jr. 1990. A new family of trepostome bryozoans from the Ordovician Simpson Group of Oklahoma. Journal of Paleontology 64(5):700–724.

Key, M. M., Jr. 1991. The halloporid trepostome bryozoans from the Ordovician Simpson Group of Oklahoma. Journal of Paleontology 65(2):200–212.

Koch, A. L., and V. L. Santucci. 2003. Chickasaw National Recreation Area. Pages 9–12 *in* A. L. Koch and V. L. Santucci. Paleontological resource inventory and monitoring: Southern Plains Network. TIC# D-107. National Park Service, Denver, Colorado.

Kröger, B., and R. Mapes. 2007. Carboniferous actinoceratoid Nautiloidea (Cephalopoda): a new perspective. Journal of Paleontology 81(4):714–724.

Lang, R. C. 1966. The Pennsylvanian rocks of the Lake Murray area. Pages 13–18 *in* Pennsylvanian of the Ardmore Basin, southern Oklahoma. Ardmore Geological Society, Ardmore, Oklahoma. Field conference guidebook.

Lehman, R. P. 1945. Thrust faulting in Arbuckle Mountains, Oklahoma. Bulletin of the American Association of Petroleum Geologists 29(2):187–209.

Leslie, S. A., S. M. Bergström, and W. D. Huff. 2008. Ordovician K-bentonites discovered in Oklahoma. Oklahoma Geology Notes 68(1–2):4–14. Available at http://www.ogs.ou.edu/pubsscanned/NOTES/2008Vol68N1_2.pdf (accessed March 2015).

Lewis, R. D. 1978. Environments of deposition and paleoecology of the Oil Creek Formation (Middle Ordovician), Arbuckle Mountains and Criner Hills, Oklahoma. Page 88 *in* R. L. Gilbertson, editor. Energy quest for the Southwest. West Texas Geological Society, Midland, Texas. Publication 78-69 SWS.

Lewis, R. D., J. Sprinkle, J. B. Bailey, J. Moffit, and R. L. Parsley. 1987. *Mandalacystis*, a new rhipidocystid eocrinoid from the Whiterockian Stage (Ordovician) in Oklahoma and Nevada. Journal of Paleontology 61(6):1222–1235.

Loeblich, A. R., Jr. 1942. Bryozoa from the Ordovician Bromide Formation, Oklahoma. Journal of Paleontology 16(4):413–436.

Loeblich, A. R., Jr., and W. S. Drugg. 1968. New acritarchs from the Early Devonian (Late Gedinnian) Haragan Formation of Oklahoma, U.S.A. Tulane Studies in Geology 6(4):129–137.

Loeblich, A. R., Jr., and H. Tappan. 1970. *Thysanoprobolus*, a new acritarch genus from the early Devonian (late Gedinnian) Haragan Formation of Oklahoma, U.S.A. Proceedings of the Biological Society of Washington 83(24):261–266. Available at http://biodiversitylibrary.org/page/34572891 (accessed March 2015).

Loeblich, A. R., Jr., and H. Tappan. 1971a. New observations of the ultrastructure of *Asketopalla*, an Ordovician acritarch. Journal of Paleontology 45(5):899–901.

Loeblich, A. R., Jr., and H. Tappan. 1971b. Two new *Orthosphaeridium* (Acritarcha) from the middle and upper Ordovician. Transactions of the American Microscopical Society 90(2):182–188.

Loeblich, A. R., Jr., and E. R. Wicander. 1974. New early Devonian (late Gedinnian) microphytoplankton: *Demorhethium lappaceum* n.g., n. sp., from the Bois d'Arc Formation of Oklahoma, U.S.A. Neues Jahrbuch für Geologie und Paläontologie. Monatshefte 12:707–711.

Loeblich, A. R., Jr., and E. R. Wicander. 1976. Organic-walled microplankton from the lower Devonian late Gedinnian Haragan and Bois d'Arc formations of Oklahoma, U.S.A., Part I. Palaeontographica. Abteilung B: Paläophytologie 159(1–3):1–39.

Longman, M. W. 1981. Deposition of the Bromide Formation, Arbuckle Mountains, Oklahoma: ontogeny of an ancient carbonate shelf. Shale Shaker 32(2):1–18.

Longman, M. W. 1982. Depositional environments. Pages 17–30 *in* J. Sprinkle, editor. Echinoderm faunas from the Bromide Formation (Middle Ordovician) of Oklahoma. University of Kansas Paleontological Institute, Lawrence, Kansas. University of Kansas Paleontological Contributions. Monograph 1. Available at http://hdl.handle.net/1808/3841 (accessed January 2015).

Lundin, R. F. 1965. Ostracodes of the Henryhouse Formation (Silurian) in Oklahoma. Oklahoma Geological Survey, Norman, Oklahoma. Bulletin 108. Available at http://www.ogs.ou.edu/pubsscanned/BULLETINS/Bulletin108.pdf (accessed March 2015).

Lundin, R. F. 1967. Ostracoda and stratigraphy of the Henryhouse and Haragan formations in southcentral Oklahoma. Tulsa Geological Society Digest 35:198–208.

Lundin, R. F. 1968. Ostracodes of the Haragan Formation (Devonian) in Oklahoma. Oklahoma Geological Survey, Norman, Oklahoma. Bulletin 116. Available at http://www.ogs.ou.edu/pubsscanned/BULLETINS/Bulletin116.pdf (accessed March 2015).

Mapes, R. H. 1987. Upper Paleozoic cephalopod mandibles: frequency of occurrence, modes of preservation, and paleoecological implications. Journal of Paleontology 61(3):521–538.

Mapes, R. H., G. Mapes, T. E. Yancey, and Z. H. Liu. 2000. Fossil plants from the Buckhorn Lagerstaette (Late Carboniferous–Desmoinesian) in southern Oklahoma. Abstracts with Programs - Geological Society of America 32(7):15.

Marshall, A. O., V. Nowaczewski, and C. P. Marshall. 2013. Microchemical differentiation of conodont and scolecodont microfossils. Palaios 28(7):433–437.

Matthews, F. D., and Z. Al-Shaieb. 1993. Paleokarstic features and reservoir characteristics of the Hunton Group in central and western Oklahoma. Pages 140–162 *in* K. S. Johnson and J. A. Campbell, editors. Petroleum-reservoir geology in the southern midcontinent, 1991 symposium. Oklahoma Geological Survey, Norman, Oklahoma. Circular 95. Available at http://www.ogs.ou.edu/pubsscanned/Circulars/Circular95.pdf (accessed March 2015).

McHargue, T. R. 1982. Ontogeny, phylogeny, and apparatus reconstruction of the conodont genus *Histiodella*, Joins Fm., Arbuckle Mountains, Oklahoma. Journal of Paleontology 56(6):1410–1433.

McPherson, J. G., R. E. Denison, D. W. Kirkland, and D. W. Summers. 1988. Basal sandstone of the Oil Creek Formation in the quarry of the Pennsylvania Glass Sand Corporation, Johnston County, Oklahoma. Pages 165–170 in O. T. Hayward, editor. South-central section of the Geological Society of America. Geological Society of America, Boulder, Colorado. Centennial field guide 4.

Meek, F. B., R. D. Elmore, and P. K. Sutherland. 1988. Lithostratigraphy and depositional environments of the Springer and lower Golf Course formations, Ardmore Basin, Oklahoma. Pages 189–194 *in* O. T. Hayward, editor. South-central section of the Geological Society of America. Geological Society of America, Boulder, Colorado. Centennial field guide 4.

Miller, M. A. 1998. Palynological characterization of a Silurian transgressive event. Palynology 22:249–250.

Miller, A. K., and C. W. Collinson. 1952. A trochoceratoid nautiloid from the Henryhouse shale (Silurian) of Oklahoma. Journal of Paleontology 26(4):622–623.

Miller, A. K., and W. M. Furnish. 1955. The Carboniferous guide fossil, *Tylonautilus*, in America. Journal of Sedimentary Petrology 25(2):143.

Moreman, W. L. 1930. Arenaceous foraminifera from Ordovician and Silurian limestones of Oklahoma. Journal and Paleontology 4:42–59.

Moreman, W. L. 1933. Arenaceous foraminifera from the Lower Paleozoic rocks of Oklahoma. Journal of Paleontology 7:393–397.

Morgan, G. D. 1924. Geology of the Stonewall quadrangle, Oklahoma. Oklahoma Bureau of Geology, Norman, Oklahoma. Bulletin 2.

Mound, M. C. 1965a. A conodont fauna from the Joins Formation (Ordovician), Oklahoma. Tulane Studies in Geology 4(1):1–46.

Mound, M. C. 1965b. Two new conodont genera from the Joins Formation (lower Middle Ordovician) of Oklahoma. Proceedings of the Biological Society of Washington 78:193–200. Available at http://biodiversitylibrary.org/page/34562545 (accessed March 2015).

National Park Service Geologic Resources Inventory Program. 2014. Unpublished Digital Geologic Map of Chickasaw National Recreation Area and Vicinity, Oklahoma (NPS, GRD, GRI, CHIC, CHIC digital map). NPS Geologic Resources Inventory Program. Lakewood, Colorado. Geospatial Dataset-2165116. Available at https://irma.nps.gov/App/Reference/Profile/2165116 (accessed March 2015).

Nicholl, M., T. Wikle, T. Brown, J. Nord, and R. Parker. 1999. Water quantity issues at Chickasaw National Recreation area. Park Science 19(2):30–32. Available at http://www.nature.nps.gov/ParkScience/archive/PDF/ParkScience19%282%29December1999.pdf (accessed March 2015).

Niko, S., and R. H. Mapes. 2004. A new Early Carboniferous nautilid from the Caney Formation of Oklahoma, central North America. Paleontological Research 8(4):341–344.

Niko, S., and R. H. Mapes. 2011. *Caneycycloceras*, a new brachycycloceratid cephalopod genus from the Early Carboniferous in Oklahoma, Midcontinent North America. Paleontological Research 15(4):292–295.

Nowaczewski, V. S., and A. O. Marshall. 2011. Biomarker and paleontologic investigation of the upper and lower Woodford Shale, south-central Oklahoma. Abstracts with Programs - Geological Society of America 43(5):52.

Ormiston, A. R., and H. R. Lane. 1976. A unique radiolarian fauna from the Sycamore Limestone (Mississippian) and its biostratigraphic significance. Palaeontographica. Abteilung A: Paläozoologie-Stratigraphie 154(4–6):158–180.

Ossian, C. R., and M. A. Halseth. 1976. Discovery of Ordovician vertebrates in the Arbuckle Mountains of Oklahoma. Journal of Paleontology 50(5):773–777.

Over, D. J. 1992. Conodonts and the Devonian-Carboniferous boundary in the upper Woodford Shale, Arbuckle Mountains, south-central Oklahoma. Journal of Paleontology 66(2):293–311.

Over, D. J., and J. E. Barrick. 1990. The Devonian/Carboniferous boundary in the Woodford Shale, Lawrence Uplift, south-central Oklahoma. Pages 63–73 *in* S. M. Ritter, editor. Early to Middle Paleozoic conodont biostratigraphy of the Arbuckle Mountains, southern Oklahoma. Oklahoma Geological Survey, Norman, Oklahoma. Guidebook 27. Available at http://www.ogs.ou.edu/pubsscanned/guidebooks/GB27.pdf (accessed March 2015).

Parker, E. C. 1966. The Pennsylvanian rocks north of Ardmore. Pages 29–37 *in* Pennsylvanian of the Ardmore Basin, southern Oklahoma. Ardmore Geological Society, Ardmore, Oklahoma. Field conference guidebook.

Parker, M. J., G. P. Nestell, M. K. Nestell, and J. E. Barrick. 2013. Foraminifers of the Clarita Formation (late Llandovery–early Ludlow, Silurian) from the Arbuckle Mountains, Oklahoma. Abstracts with Programs - Geological Society of America 45(3):76.

Parsley, R. L., and C. D. Sumrall. 2007. New recumbent echinoderm genera from the Bois d'Arc Formation: Lower Devonian (Lochkovian) of Coal County, Oklahoma. Journal of Paleontology 81(6):1486–1493.

Penman, J. T. 1979. Faunal remains from the Pate site, Oklahoma. Bulletin of the Oklahoma Anthropological Society 28:148–151.

Pessagno, E. A., B. K. Holdsworth, J. A. Schwartzapfel, and Y. N. Cheng. 1983. Preliminary biostratigraphic investigations of Paleozoic (Upper Devonian to Middle Pennsylvanian) Radiolaria in the Wichita and Ouachita orogenic belts, Arkansas and Oklahoma. Pages 17–23 *in* K. C. Nielson, editor. Structural styles of the Ouachita Mountains, southeastern Oklahoma. Earth Enterprises, Austin, Texas.

Pieracacos, N. J., R. C. Grayson, Jr., R. D. Elmore, and P. K. Sutherland. 1993. Desmoinesian conodont biostratigraphy of the Deese Group, Ardmore Basin, Oklahoma. Abstracts with Programs - Geological Society of America 25(3):73.

Pillaert, E. E. 1962. Test excavations at the Lee II site, Gv-4, Garvin County, Oklahoma. Bulletin of the Oklahoma Anthropological Society 10:79–103.

Playford, G., and R. Wicander. 2006. Organic-walled microphytoplankton of the Sylvan Shale (Richmondian, Upper Ordovician), Arbuckle Mountains, southern Oklahoma, U.S.A. Oklahoma Geological Survey, Norman, Oklahoma. Bulletin 148. Available at http://www.ogs.ou.edu/pubsscanned/BULLETINS/Bulletin148.pdf (accessed March 2015).

Prestridge, J. W. 1959. Subdivisions of Sycamore Formation. Pages 156–164 in Petroleum geology of southern Oklahoma—a symposium, volume 2. Ardmore Geological Society, Ardmore, Oklahoma.

Ray, M. A. 1960. The James site, Br-11, an archeological site in Bryan County, Oklahoma. Bulletin of the Oklahoma Anthropological Society 8:53–74.

Reeds, C. A. 1911. The Hunton Formation of Oklahoma. American Journal of Science 32(190):256–268.

Reimann, I. G., and R. O. Fay. 1961. *Polydeltoideus*, a new Silurian blastoid from Oklahoma. Oklahoma Geology Notes 21(3):86–89. Available at http://www.ogs.ou.edu/pubsscanned/NOTES/1961Vol21P.pdf (accessed March 2015).

Renne, P. R., R. Mundil, G. Balco, K. Min, and K. R. Ludwig. 2010. Joint determination of ^{40}K decay constants and $^{40}Ar^*/^{40}K$ for the Fish Canyon sanidine standard, and improved accuracy for $^{40}Ar/^{39}Ar$ geochronology. Geochimica et Cosmochimica Acta 74:5349–5367.

Reso, A., and K. Wegner. 1964. Echinoderm (holothurian?) sclerites from the Bromide Formation (Black Riverian) of southern Oklahoma. Journal of Paleontology 38(1):89–94.

Richard, M. K. 1971. The Lee site, a late Prehistoric manifestation in Garvin County, Oklahoma. Bulletin of the Oklahoma Anthropological Society 20:1–82.

Rigby, J. K., and R. C. Gutschick. 1976. Two new lower Paleozoic hexactinellid sponges from Utah and Oklahoma. Journal of Paleontology 50(1):79–85.

Rigby, J. K., G. P. Hansen, W. J. Rushlau, and L. K. Burgener. 2009. Sponges from the Devonian Haragan Formation, Coal County, Oklahoma. Oklahoma Geology Notes 69(2):43–55. Available at http://www.ogs.ou.edu/pubsscanned/NOTES/2009Vol69N2.pdf (accessed March 2015).

Rohr, D. M., and R. A. Johns. 1990. First occurrence of *Oriostoma* (Gastropoda) from the Middle Ordovician. Journal of Paleontology 64(5):732–735.

Rosenau, N. A., A. D. Herrmann, and S. A. Leslie. 2012. Conodont apatite $\delta^{18}O$ values from a platform margin setting, Oklahoma, USA: implications for initiation of Late Ordovician icehouse conditions. Palaeogeography, Palaeoclimatology, Palaeoecology 315–316:172–180.

Roth, R. I. 1929. Some ostracodes from the Haragan marl, Devonian, of Oklahoma. Journal of Paleontology 3(4):327–372.

Ruedemann, R. 1935. Silurian phyllocarid crustaceans from Oklahoma. Journal of Paleontology 9(5):447–448.

Ruedemann, R., and C. E. Decker. 1934. The graptolites of the Viola limestone. Journal of Paleontology 8(3):303–327.

Sadd, J. L. 1991. Tectonic influences on carbonate deposition and diagenesis, Buckhorn Asphalt, Deese Group (Desmoinesian), Arbuckle Mountains, Oklahoma. Journal of Sedimentary Petrology 61(1):28–42.

Santucci, V. L., and A. L. Koch. 2003. Paleontological resource monitoring strategies for the National Park Service. Park Science 22(1):22–25. Available at http://www.nature.nps.gov/ParkScience/archive/PDF/ParkScience22%281%29Fall2003.pdf (accessed January 2015).

Santucci, V. L., J. P. Kenworthy, and A. L. Mims. 2009. Monitoring in situ paleontological resources. Pages 189–204 *in* R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado.

Scheirer, D. S., and A. H. Scheirer. 2006. Gravity investigations of the Chickasaw National Recreation Area, south-central Oklahoma. U.S. Geological Survey, Reston, VA. Open-File Report 2006-1083. Available at http://pubs.er.usgs.gov/publication/ofr20061083 (accessed March 2015).

Schram, F. R. 1979. The genus *Archaeocaris*, and a general review of the Palaeostomatopoda (Hoplocarida: Malacostraca). Transactions of the San Diego Society of Natural History 19(5):57–65. Available at http://biodiversitylibrary.org/page/5784863 (accessed March 2015).

Schwartzapfel, J. A., and B. K. Holdsworth. 1996. Upper Devonian and Mississippian radiolarian zonation and biostratigraphy of the Woodford, Sycamore, Caney and Goddard formations, Oklahoma. Cushman Foundation for Foraminiferal Research Special Publication 33.

Seuss, B., A. Nützel, R. Mapes, and T. E. Yancey. 2008. The Buckhorn asphalt deposit: an unique fossil Lagerstaette from the Pennsylvanian of Oklahoma. Abstracts with Programs - Geological Society of America 40(6):503.

Seuss, B., J. Titschack, S. Seifert, J. Neubauer, and A. Nützel. 2012a. Oxygen and stable carbon isotopes from a nautiloid from the Middle Pennsylvanian (Late Carboniferous) impregnation

Lagerstätte “Buckhorn asphalt quarry”—primary paleo-environmental signals versus diagenesis. Palaeogeography, Palaeoclimatology, Palaeoecology 319–320:1–15.

Seuss, B., R. H. Mapes, C. Klug, and A. Nützel. 2012b. Exceptional cameral deposits in a sublethally injured Carboniferous orthoconic nautiloid from the Buckhorn Asphalt Lagerstätte in Oklahoma, USA. Acta Palaeontologica Polonica 57(2):375–390. Available at https://www.app.pan.pl/article/item/app20110008.html (accessed March 2015)

Seuss, B., B. Senowbari-Daryan, A. Nützel, S. Dittrich, and J. Neubauer. 2014. A chaetetid sponge assemblage form the Desmoinesian (Upper Moscovian) Buckhorn asphalt quarry Lagerstätte in Oklahoma, USA. Rivista Italiana di Paleontologia e Stratigrafia 120(1):3–26.

Sharrock, F. W. 1961. The Grant site of the Washita River focus. Bulletin of the Oklahoma Anthropological Society 9:1–66.

Shaw, F. C. 1974. Simpson Group (middle Ordovician) trilobites of Oklahoma. Paleontological Society Memoir 5(48).

Shaw, F. C. 1991. Viola Group (Ordovician, Oklahoma) cryptolithinid trilobites: biogeography and taxonomy. Journal of Paleontology 65(6):919–935.

Shaw, F. C., and R. A. Fortey. 1977. Middle Ordovician facies and trilobite faunas in N America. Geological Magazine 114(6):409–443.

Siy, S. E. 1994. The Woodford Shale (Upper Devonian–Lower Mississippian) and associated phosphate nodules, south-central and southeastern Oklahoma. Pages 85–98 *in* D. R. Keller and C. L. Reed, editors. Paleokarst, karst-related diagenesis, reservoir development, and exploration concepts: examples from the Paleozoic section of the southern mid-continent. Society of Economic Paleontologists and Mineralogists, Permian Basin Section, Midland, Texas. Fielld Trip Guidebook 93-34.

Smith, K. S., and R. L. Cifelli. 2000. A synopsis of the Pleistocene vertebrates of Oklahoma. Oklahoma Geological Survey Bulletin 147. Available at http://www.ogs.ou.edu/pubsscanned/BULLETINS/Bulletin147.pdf (accessed January 2015).

Sorauf, J. E., and G. E. Webb. 2003. The origin and significance of zigzag microstructure in late Paleozoic Lophophyllidium (Anthozoa, Rugosa). Journal of Paleontology 77(1):16–30.

Sprinkle, J., editor. 1982a. Echinoderm faunas from the Bromide Formation (Middle Ordovician) of Oklahoma. University of Kansas Paleontological Institute, Lawrence, Kansas. University of Kansas Paleontological Contributions. Monograph 1. Available at http://hdl.handle.net/1808/3841 (accessed January 2015).

Sprinkle, J. 1982b. Echinoderm zones and faunas. Pages 47–56 *in* J. Sprinkle, editor. Echinoderm faunas from the Bromide Formation (Middle Ordovician) of Oklahoma. University of Kansas

Paleontological Institute, Lawrence, Kansas. University of Kansas Paleontological Contributions. Monograph 1. Available at http://hdl.handle.net/1808/3841 (accessed January 2015).

Sprinkle, J. 1982c. Holothurians. Page 315 *in* J. Sprinkle, editor. Echinoderm faunas from the Bromide Formation (Middle Ordovician) of Oklahoma. University of Kansas Paleontological Institute, Lawrence, Kansas. University of Kansas Paleontological Contributions. Monograph 1. Available at http://hdl.handle.net/1808/3841 (accessed January 2015).

Sprinkle, J., and D. R. Kolata. 1982. "Rhomb-bearing" camerate. Pages 206–211 *in* J. Sprinkle, editor. Echinoderm faunas from the Bromide Formation (Middle Ordovician) of Oklahoma. University of Kansas Paleontological Institute, Lawrence, Kansas. University of Kansas Paleontological Contributions. Monograph 1. Available at http://hdl.handle.net/1808/3841 (accessed January 2015).

Squires, R. L. 1976. Color pattern of *Naticopsis* (*Naticopsis*) *wortheniana*, Buckhorn asphalt deposit, Oklahoma. Journal of Paleontology 50(2):349–350.

Stanley, T. M. 2001. Stratigraphy and facies relationships of the Hunton Group, northern Arbuckle Mountains and Lawrence Uplift, Oklahoma. Oklahoma Geological Survey, Norman, Oklahoma. Guidebook 33. Available at http://www.ogs.ou.edu/pubsscanned/guidebooks/GB33mm.pdf, http://www.ogs.ou.edu/pubsscanned/guidebooks/GBill/GB33%20P%20I.pdf (accessed March 2015).

Stanley, T. M. 2013. The Hunton Anticline Quarry. Shale Shaker 64(3):228–237.

Straka, J. J., II. 1972. Conodont evidence of age of Goddard and Springer formations, Ardmore Basin, Oklahoma. American Association of Petroleum Geologists Bulletin 56(6):1087–1099.

Strimple, H. L. 1952. Some new species of crinoids from the Henryhouse Formation of Oklahoma. Journal of the Washington Academy of Sciences 42(3):75–79. Available at http://biodiversitylibrary.org/page/39697409 (accessed March 2015).

Strimple, H. L. 1963. Crinoids of the Hunton Group (Devonian–Silurian) of Oklahoma. Oklahoma Geological Survey, Norman, Oklahoma. Bulletin 100. Available at http://www.ogs.ou.edu/pubsscanned/BULLETINS/Bulletin100.pdf (accessed March 2015).

Suhm, R. W. 1997. Simpson stratigraphy of the southern Midcontinent. Pages 3–38 *in* K. S. Johnson, editor. Simpson and Viola groups in the southern Midcontinent, 1994 symposium. Oklahoma Geological Survey, Norman, Oklahoma. Circular 99. Available at http://www.ogs.ou.edu/pubsscanned/Circulars/Circular99.pdf (accessed March 2015).

Sullivan, K. L. 1985. Organic facies variation of the Woodford Shale in western Oklahoma. Shale Shaker 35(4):76–89.

Sutherland, P. K. 1965. Rugose corals of the Henryhouse formation (Silurian) in Oklahoma. Oklahoma Geological Survey, Norman, Oklahoma. Bulletin 109. Available at http://www.ogs.ou.edu/pubsscanned/BULLETINS/Bulletin109.pdf (accessed March 2015).

Sutherland, P. K., and R. C. Grayson, Jr. 1992. Morrowan and Atokan (Pennsylvanian) biostratigraphy in the Ardmore Basin, Oklahoma. Pages 81–99 *in* P. K. Sutherland and W. L. Manger, editors. Recent advances in middle Carboniferous biostratigraphy—a symposium. Oklahoma Geological Survey, Norman, Oklahoma. Circular 94. Available at http://www.ogs.ou.edu/pubsscanned/Circulars/circular94.pdf (accessed March 2015).

Sykes, M., J. Puckette, A. Abdalla, and Z. Al-Shaieb. 1997. Karst development in the Viola Limestone in southern Oklahoma. Pages 66–75 *in* K. S. Johnson, editor. Simpson and Viola groups in the southern midcontinent, 1994 symposium. Oklahoma Geological Survey, Norman, Oklahoma. Circular 99. Available at http://www.ogs.ou.edu/pubsscanned/Circulars/Circular99.pdf (accessed March 2015).

Taff, J. A. 1903. Description of the Tishomingo Quadrangle, Indian Territory (Oklahoma). U.S. Geological Survey, Washington, D.C. Geological Atlas Folio 98. Available at http://pubs.er.usgs.gov/publication/gf98 (accessed March 2015).

Tappan, H., and A. R. Loeblich, Jr. 1972. Surface sculpture of the wall in Lower Paleozoic acritarchs. Micropaleontology 17(4):385–410.

Tomlinson, C. W. 1929. The Pennsylvanian system in the Ardmore Basin. Oklahoma Geological Survey, Norman, Oklahoma. Bulletin 46. Available at http://www.ogs.ou.edu/pubsscanned/BULLETINS/Bulletin46.pdf (accessed March 2015).

Tweet, J., V. L. Santucci, J. P. Kenworthy, and A. L. Mims. 2009. Paleontological resource inventory and monitoring: Southern Colorado Plateau Network. Natural Resource Technical Report NPS/NRPC/NRTR—2009/245. TIC# D-59. National Park Service, Fort Collins, Colorado.

Vinther, J., and D. E. G. Briggs. 2009. Machaeridian locomotion. Lethaia 42(3):357–364.

Werts, S. P., R. J. Cuffey, and C. A. Cuffey. 2001. Bryozoan species in the Chickasaw bryozoan reef (Ordovician, Oklahoma). Abstracts with Programs - Geological Society of America 33(5):54–55.

Wicander, R. 1986. Lower Devonian (Gedinnian) acritarchs from the Haragan Formation, Oklahoma, U. S. A. Review of Palaeobotany and Palynology 47(3–4):327–365.

Wicander, R., A. Le Herisse, K. J. Dorning, and G. L. Mullins. 2006. Acritarch and prasinophyte biodiversity changes through the Late Silurian to Earliest Devonian: an overview. Palynology 30:231.

Williams, M., and D. J. Siveter. 1996. Lithofacies-influenced ostracod associations in the Middle Ordovician Bromide Formation, Oklahoma, USA. Journal of Micropalaeontology 15(1):69–81.

Wilson, L. R. 1958. A chitinozoan faunule from the Sylvan shale of Oklahoma. Oklahoma Geology Notes 18(4):67–71. Available at http://www.ogs.ou.edu/pubsscanned/NOTES/1958Vol18P.pdf (accessed March 2015).

Wilson, L. R. 1966. Palynological evidence for Mississippian age of the Springer Formation. Pages 20–24 *in* Pennsylvanian of the Ardmore Basin, southern Oklahoma. Ardmore Geological Society, Ardmore, Oklahoma. Field conference guidebook.

Wilson, L. R., and R. T. Clarke. 1960. A Mississippian chitinozoan from Oklahoma. Oklahoma Geology Notes 20(6):148–150. Available at http://www.ogs.ou.edu/pubsscanned/NOTES/1960Vol20P.pdf (accessed March 2015).

Wilson, L. R., and E. D. Dolly. 1964. Chitinozoa in the Tulip Creek Formation, Simpson Group (Ordovician), of Oklahoma. Oklahoma Geology Notes 24(10):224–230. Available at http://www.ogs.ou.edu/pubsscanned/NOTES/GN-V24N10.pdf (accessed March 2015).

Wilson, L. R., and R. W. Hedlund. 1964. *Calpichitina scabiosa*, a new chitinozoan from the Sylvan Shale (Ordovician) of Oklahoma. Oklahoma Geology Notes 24(7):161–164. Available at http://www.ogs.ou.edu/pubsscanned/NOTES/GN-V24N7.pdf (accessed March 2015).

Wilson, L. R., and J. B. Urban. 1963. An Incertae sedis palynomorph from the Devonian of Oklahoma. Oklahoma Geology Notes 23(1):16–19. Available at http://www.ogs.ou.edu/pubsscanned/NOTES/GN-V23N1.pdf (accessed March 2015).

Wisshak, M., B. Seuss, and A. Nützel. 2008. Evolutionary implications of an exceptionally preserved Carboniferous microboring assemblage in the Buckhorn Asphalt Lagerstätte (Oklahoma, USA). Pages 21–54 *in* M. Wisshak and L. Tapanila, editors. Current developments in bioerosion. Erlangen earth conference series. Springer-Verlag, Berlin, Germany.

Yancey, T. E., and M. J. Heaney, III. 2000. Carboniferous praecardioid bivalves from the exceptional Buckhorn Asphalt biota of south-central Oklahoma, USA. Pages 291–301 *in* E. M. Harper, J. D. Taylor, and J. A. Crame, editors. The evolutionary biology of the Bivalvia. Geological Society of London, London, United Kingdom. Special Publication 177.

Zidek, J. 1972. Oklahoma paleoichthyology, pt. 1, a review and commentary. Oklahoma Geology Notes 32(6):171–187. Available at http://www.ogs.ou.edu/pubsscanned/NOTES/GN-V32N6.pdf (accessed March 2015).

Zidek, J. 1975. Oklahoma paleoichthyology: Part IV, Acanthodii. Oklahoma Geology Notes 35(4):135–146. Available at http://www.ogs.ou.edu/pubsscanned/NOTES/GN-V35N4.pdf (accessed March 2015).

Zidek, J. 1993. A large stethacanthid shark (Elasmobranchii: Symmoriida) from the Mississippian of Oklahoma. Oklahoma Geology Notes 53(1):4–15. Available at http://www.ogs.ou.edu/pubsscanned/NOTES/GN-V53N1.pdf (accessed March 2015).

Additional References

Adrain, J. M. 1996. A new otarionine trilobite from the Henryhouse Formation (Silurian, Ludlow) of Oklahoma. Journal of Paleontology 70(4):611–614.

Adrain, J. M., B. D. E. Chatterton, and G. J. Kloc. 2008. Systematics of the koneprusiine trilobites, with new taxa from the Silurian and Devonian of Laurentia. Journal of Paleontology 82(4):657–675.

Adrian, J. M., and G. J. Kloc. 1997. Lower Devonian aulacopleuroidean trilobites from Oklahoma. Journal of Paleontology 71(4):703–712.

Al-Shaieb, Z., R. D. Fritz, J. E. Barrick, P. L. Medlock, and J. Puckette. 1993. Hunton Group field trip to the Arbuckle Mountains, Oklahoma. Pages 183–212 *in* K. S. Johnson, editor. Hunton Group core workshop and field trip. Oklahoma Geological Survey Norman, Oklahoma. Special Publication 93-4. Available at http://www.ogs.ou.edu/pubsscanned/SPs/SP93_4.pdf (accessed March 2015).

Amati, L. 2014. Isoteline trilobites of the Viola Group (Ordovician: Oklahoma): systematics and stratigraphic occurrence. Oklahoma Geological Survey, Norman, Oklahoma. Bulletin 151. Available at http://www.ogs.ou.edu/pubsscanned/BULLETINS/Bulletin151.pdf (accessed March 2015).

Amsden, T. W. 1949. Two new genera of brachiopods from the Henryhouse Formation (Silurian) of Oklahoma. Journal of the Washington Academy of Sciences 39(6):202–203. Available at http://biodiversitylibrary.org/page/39703502 (accessed March 2015).

Amsden, T. W. 1956. Catalog of fossils from the Hunton group, Oklahoma. Oklahoma Geological Survey, Norman, Oklahoma. Circular 38. Available at http://www.ogs.ou.edu/pubsscanned/Circulars/circular38.pdf (accessed March 2015).

Amsden, T. W. 1958. Supplement to the Henryhouse brachiopods. Part 3 of Stratigraphy and paleontology of the Hunton Group in the Arbuckle Mountain region. Oklahoma Geological Survey Bulletin 78:145–157. Available at http://www.ogs.ou.edu/pubsscanned/BULLETINS/Bulletin78.pdf (accessed March 2015).

Amsden, T. W. 1959. *Chilidiopsis* Boucot: a recently described brachiopod genus, with some remarks on the Hunton Orthotetacea. Oklahoma Geology Notes 19(4):74–77. Available at http://www.ogs.ou.edu/pubsscanned/NOTES/1959Vol19P.pdf (accessed March 2015).

Amsden, T. W., and J. E. Barrick. 1988. Late Ordovician through Early Devonian annotated correlation chart and brachiopod range charts for the southern Midcontinent region, U.S.A., with a discussion of Silurian and Devonian conodont faunas. Oklahoma Geological Survey, Norman, Oklahoma. Bulletin 143. Available at http://www.ogs.ou.edu/pubsscanned/BULLETINS/Bulletin143wm.pdf (accessed March 2015).

Ausich, W. I. 2003. Developmental breakdown during the early evolution of the Codiacrinidae: *Parazophocrinus callosus* Strimple, 1963 (class Crinoidea). Journal of Paleontology 77(3):471–475.

Babcock, L. E. 1985. A new Ordovician conulariid from Oklahoma? Oklahoma Geology Notes 45(2):66–70. Available at http://www.ogs.ou.edu/pubsscanned/NOTES/GN-V45N2.pdf (accessed March 2015).

Barrick, J. E. 1977. Multielement simple-cone conodonts from the Clarita Formation (Silurian), Arbuckle Mountains, Oklahoma. Geologica et Palaeontologica 11:47–68.

Blake, D. F., D. R. Peacor, and B. H. Wilkinson. 1982. The sequence and mechanism of low-temperature dolomite formation: calcian dolomites in a Pennsylvanian echinoderm. Journal of Sedimentary Petrology 52(1):59–70.

Blome, C. D., and D. V. Smith. 2010. Geology of the Chickasaw National Recreation Area, south-central Oklahoma: a multidisciplinary geologic approach. Abstracts with Programs - Geological Society of America 42(5):562.

Blome, C. D., J. R. Faith, R. R. Wahl, D. J. Lidke, D. W. Moore, and D. V. Smith. 2009. Geologic mapping of the Chickasaw National Recreation area, south-central Oklahoma. Abstracts with Programs - Geological Society of America 41(7):150.

Bordeau, K. V. 1972. *Ptiloncodus harrisi*: a new species of conodont from the Viola Limestone (Ordovician) of Oklahoma. Journal of the Tennessee Academy of Science 47(3):118–120.

Branson, C. C. 1958. Notes on a rare cystoid from Oklahoma. Oklahoma Geology Notes 18(11):178–179.

Branson, C. C. 1965. New specimens of *Homotelus* from the Bromide Formation. Oklahoma Geology Notes 25(11):294–296.

Branson, C. C. 1967. *Caryocaris* removed from Oklahoma faunal list. Oklahoma Geology Notes 27(3):44. Available at http://www.ogs.ou.edu/pubsscanned/NOTES/1967Vol27P.pdf (accessed March 2015).

Brooks, R. L., R. R. Drass, and F. E. Swenson. 1985. Prehistoric farmers of the Washita River valley: settlement and subsistence patterns during the Plains Village period. Oklahoma Archeological Survey, Archaeological Resource Survey Report 23.

Brower, J. C. 1977. Calceocrinids from the Bromide Formation (Middle Ordovician) of southern Oklahoma. Oklahoma Geological Survey, Norman, Oklahoma. Circular 78. Available at http://www.ogs.ou.edu/pubsscanned/Circulars/circular78.pdf (accessed March 2015).

Brower, J. C. 1987. The relations between allometry, phylogeny, and functional morphology in some calceocrinid crinoids. Journal of Paleontology 61(5):999–1032.

Campbell, K. S. W. 1967. Geographic and stratigraphic implications of a study of the Henryhouse trilobite fauna. Tulsa Geological Society Digest 35:253–258.

Campbell, K. S. W. 1982. A note on the Haragan trilobite *Dicranurus hamatus elegantus*. Oklahoma Geology Notes 42(1):4–6. Available at http://www.ogs.ou.edu/pubsscanned/NOTES/GN-V42N1.pdf (accessed March 2015).

Cuffey, C. A., and R. J. Cuffey. 1994. Discovery of the Chickasaw bryozoan reef in the Middle Ordovician of south-central Oklahoma. Abstracts with Programs - Geological Society of America 26(5):11.

Decker, C. E. 1924. A preliminary list giving the distribution of Proboscidea in Oklahoma. Proceedings of the Oklahoma Academy of Science 4:123–124.

Decker, C. E. 1936. Some tentative correlations on the basis of graptolites of Oklahoma and Arkansas. Bulletin of the American Association of Petroleum Geologists 20(3):301–311.

Decker, C. E. 1955. A new Devonian species of *Dictyonema* from Oklahoma. Journal of Paleontology 29(4):699–701.

Eastman, C. R. 1913. Brain structures of fossil fishes from the Caney shales. Geological Society of America Bulletin 24:119–120. Available at http://biodiversitylibrary.org/page/36323514 (accessed March 2015).

Elias, S. A. 1997. The Ice Age history of southwestern National Parks. Smithsonian Institution Press, Washington, D.C.

Ellwood, B. B. 1996. Geology and America's National Park areas. Prentice Hall, Upper Saddle River, New Jersey.

Eschberger, A. M., and R. E. Hanson. 2014. Stop 3: Mafic-felsic igneous breccia in the West Timbered Hills. Pages 15–20 *in* N. Suneson, editor. Igneous and tectonic history of the Southern Oklahoma Aulacogen. Oklahoma Geological Survey, Norman, Oklahoma. Guidebook 38.

Eschberger, A. M., R. E. Hanson, and R. E. Puckett, Jr. 2014. Stop 2: Carlton Rhyolite and diabase intrusions in the East Timbered Hills. Pages 7–14 *in* N. Suneson, editor. Igneous and tectonic history of the Southern Oklahoma Aulacogen. Oklahoma Geological Survey, Norman, Oklahoma. Guidebook 38.

Esker, G. C., III. 1964. New species of trilobites from the Bromide Formation (Pooleville Member) of Oklahoma. Oklahoma Geology Notes 24(9):195–209. Available at http://www.ogs.ou.edu/pubsscanned/NOTES/GN-V24N9.pdf (accessed March 2015).

Finney, S. C., L. F. Gentile, and R. Asbery. 1984. The Viola Springs Formation (Ordovician) of Oklahoma, a heaven for graptolite specialists. Oklahoma Geology Notes 44(4):116–120.

Available at http://www.ogs.ou.edu/pubsscanned/NOTES/GN-V44N4.pdf (accessed March 2015).

Frederickson, E. A. 1960. New evidence concerning *Dolmanites oklahomae*. Oklahoma Geology Notes 20(3):53–54. Available at http://www.ogs.ou.edu/pubsscanned/NOTES/1960Vol20P.pdf (accessed March 2015).

Frederickson, E. A. 1964. Two Ordovician trilobites from southern Oklahoma. Oklahoma Geology Notes 24(4):71–75. Available at http://www.ogs.ou.edu/pubsscanned/NOTES/GN-V24N4.pdf (accessed March 2015).

Frest, T. J., and H. L. Strimple. 1977. Three new camerates (Echinodermata: Crinoidea) from the Silurian of Oklahoma and Tennessee. Journal of Paleontology 51(2):272–281.

Frest, T. J., H. L. Strimple, and M. R. McGinnis. 1976. A new species of *Platycystites* (Echinodermata, Paracrinoidea) from the Middle Ordovician of Oklahoma. Journal of the Washington Academy of Sciences 66(4):211–221. Available at http://biodiversitylibrary.org/page/39803071 (accessed March 2015).

Frest, T. J., H. L. Strimple, and M. R. McGinnis. 1979. Two new crinoids from the Ordovician of Virginia and Oklahoma, with notes on pinnulation in the Disparida. Journal of Paleontology 53(2):399–415.

Graham, R. W. 1987. Late Quaternary mammalian faunas and paleoenvironments of the southwestern Plains of the United States. Pages 24–86 *in* R. W. Graham, H. A. Semken, Jr., and M. A. Graham, editors. Late Quaternary mammalian biogeography and environments of the Great Plains and prairies. Illinois State Museum, Springfield, Illinois. Scientific Papers 22.

Gregoire, C., and C. Teichert. 1965. Conchiolin membranes in shell and cameral deposits of Pennsylvanian cephalopods, Oklahoma. Oklahoma Geology Notes 25(7):175–201. Available at http://www.ogs.ou.edu/pubsscanned/NOTES/1965Vol25P.pdf (accessed March 2015).

Harris, A. H. 1985. Late Pleistocene vertebrate paleoecology of the west. University of Texas Press, Austin, Texas.

Hass, W. H., and J. W. Huddle. 1965. Late Devonian and Early Mississippian age of the Woodford Shale in Oklahoma, as determined from conodonts. Pages D125–D132 *in* Geological Survey research 1965, Chapter D. U.S. Geological Survey, Washington, D.C. Professional Paper 525-D. Available at http://pubs.er.usgs.gov/publication/pp525D (accessed March 2015).

Holliday, V. T. 1997. Paleoindian geoarchaeology of the southern High Plains. University of Texas Press, Austin, Texas.

Johnson, K. S., T.W. Amsden, R. E. Denison, S. P. Dutton, A. G. Goldstein, B. Rascoe, P. K. Sutherland, and D.M. Thompson. 1989. Geology of the southern Midcontinent. Oklahoma Geological Survey, Norman, Oklahoma. Special Publication 89-2.

Laudon, L. R. 1939. Unusual occurrence of *Isotelus gigas* DeKay in the Bromide Formation (Ordovician) of southern Oklahoma. Journal of Paleontology 13(2):211–213.

Leslie, S. A., and O. Lehnert. 2005. Middle Ordovician (Chazyan) sea-level changes and the evolution of the Ordovician conodont genus *Cahabagnathus* Bergström, 1983. Journal of Paleontology 79(6):1131–1142.

Levinson, S. A. 1961. New genera and species of Bromide (Middle Ordovician) ostracodes of Oklahoma. Micropaleontology 7(3):359–364.

Loeblich, A. R., Jr. 1940. An occurrence of *Isotelus gigas* DeKay in the Arbuckle Mountains, Oklahoma. Journal of Paleontology 14(2):161–162.

Lundin, R., and H. W. Scott. 1963. Morphology and ontogeny of *Phanassymetria* Roth. Journal of Paleontology 37(6):1272–1283.

Lundin, R. F. 1964. Dimorphism in the thlipsurid ostracode *Thlipsuroides striatopunctatus* (Roth). Journal of Paleontology 38(6):1099–1104.

Lundin, R. F., M. Williams, and D. J. Siveter. 1995. Domatial dimorphism occurs in leperditellid and monotiopleurid ostracodes. Journal of Paleontology 69(5):886–896.

Mayor, A. 2005. Fossil legends of the first Americans. Princeton University Press, Princeton, New Jersey.

McKinley, M. E. 1954. Stratigraphy of the Vanoss Formation in the western Arbuckle Mountains. Proceedings of the Oklahoma Academy of Science 33:205–207. Available at http://digital.library.okstate.edu/oas/oas_pdf/v33/v205_207.pdf (accessed March 2015).

Moss, D. K., and S. R. Westrop. 2014. Systematics of some Late Ordovician encrinurine trilobites from Laurentian North America. Journal of Paleontology 88(6):1095–1119.

Nazarov, B. B., and A. R. Ormiston. 1986. Origin and biostratigraphic potential of the stauraxon polycystine Radiolaria. Marine Micropaleontology 11(1–3):33–54.

Nicholl, M., and J. Nord. 2000. Sustaining aquifer discharge as a cultural and historic resource. Abstracts with Programs - Geological Society of America 32(7):141.

Nützel, A., T. E. Yancey, and R. H. Mapes. 2000. Exceptional preservation of gastropods in the Buckhorn Lagerstatte, (Late Carboniferous, Desmoinesian) Buckhorn asphalt quarry, Oklahoma. Abstracts with Programs - Geological Society of America 32(7):97.

Olsen, S. J. 1971. Zooarchaeology: animal bones in archaeology and their interpretation. Addison-Wesley Publishing Company, New York City, New York.

Parmley, D. 1990. A late Holocene herpetofauna from Montague County, Texas. Texas Journal of Science 42(4):412–415.

Parsley, R. L. 1972. The Belemnocystitidae: solutan homeomorphs of the Anomalocystitidae. Journal of Paleontology 46(3):341–347.

Ross, J. R. P. 1991. Lower/Middle Ordovician bryozoans from the Oil Creek Formation, Arbuckle Mountains, Oklahoma (U.S.A.). Bulletin de la Societe des Sciences Naturelles de l'Ouest de la France Hors 1:383–390.

Scheirer, D. 2007. Gravity and magnetic characterization of faults in the Hunton Anticline area of the Arbuckle Uplift, south-central Oklahoma. Abstracts with Programs - Geological Society of America 39(6):165.

Scheirer, D. S., D. V. Smith, R. Coffee, and J. Cason. 2009. Magnetic, electromagnetic, and bathymetric survey of the Lake of the Arbuckles, south-central Oklahoma. Eos, Transactions, American Geophysical Union 90(supplement to 52):NS23A-1129.

Smith, A. B., and J. J. Savill. 2001. *Bromidechinus*, a new Ordovician echinozoan (Echinodermata), and its bearing on the early history of echinoids. Transactions of the Royal Society of Edinburgh: Earth Sciences 92(2):137–147.

Sprinkle, J., and T. E. Guensburg. 2014. Giant, spiraled, spine-bearing edrioasteroid from the Upper Ordovician Bromide Formation of Oklahoma. Abstracts with Programs - Geological Society of America 46(6):138.

Sprinkle, J., L. Henry, F. S. Zimmer, L. S. Kelley, and J. Whiteley. 1985. New *Pleurocystites* from the Bromide Formation of Oklahoma. Journal of Paleontology 59(6):1476–1480.

Squires, R. L. 1973. Burial environment, diagenesis, mineralogy, and Mg & Sr contents of skeletal carbonates in the Buckhorn asphalt of Middle Pennsylvanian age, Arbuckle Mountains, Oklahoma. Dissertation. California Institute of Technology, Pasadena, California. Available at http://resolver.caltech.edu/CaltechETD:etd-10102006-152318 (accessed May 2015).

Strain, W. S. 1937. The Pleistocene geology of part of the Washita River Valley, Grady County, Oklahoma. Thesis. University of Oklahoma, Norman, Oklahoma.

Strimple, H. L. 1948. *Pleurocystites watkinsi*, n. sp., from the Bromide Formation of Oklahoma. American Journal of Science 246(12):761–764.

Strimple, H. L. 1953. A new carpoid from Oklahoma. Journal of the Washington Academy of Sciences 43(4):105–106. Available at http://biodiversitylibrary.org/page/39744763 (accessed March 2015).

Strimple, H. L. 1953. A new species of *Archaeocrinus* from Oklahoma. Journal of Paleontology 27(4):604–606.

Strimple, H. L. 1955. New Ordovician echinoderms: [Part] 1, (and W. T. Watkins). Three new genera: [Part] 2, (and A. A. Graffham), A new species of *Cyathocystis*. Journal of the

Washington Academy of Sciences 45(11):347–355. Available at http://biodiversitylibrary.org/page/39747225 (accessed March 2015).

Strimple, H. L. 1961. On *Synbathocrinus*? *antiquus*. Oklahoma Geology Notes 21(2):48–49. Available at http://www.ogs.ou.edu/pubsscanned/NOTES/1961Vol21P.pdf (accessed March 2015).

Strimple, H. L. 1972. The genus *Parazophocrinus* from the Henryhouse Formation (Silurian), Pontotoc County, Oklahoma. Oklahoma Geology Notes 32(4):119–121. Available at http://www.ogs.ou.edu/pubsscanned/NOTES/GN-V32N4.pdf (accessed March 2015).

Strimple, H. L. 1974. *Abyssocrinus* from the Haragan Formation (Devonian) of southern Oklahoma. Oklahoma Geology Notes 34(4):160–162. Available at http://www.ogs.ou.edu/pubsscanned/NOTES/GN-V34N4.pdf (accessed March 2015).

Strimple, H. L. 1975. Crowns of *Parapisocrinus* from Oklahoma and Tennessee. Oklahoma Geology Notes 35(5):197–199. Available at http://www.ogs.ou.edu/pubsscanned/NOTES/GN-V35N5.pdf (accessed March 2015).

Strimple, H. L. 1977. Possible commensal relationship between *Edriocrinus* and the bulbous float of *Scyphocrinites* (Crinoidea: Echinodermata). Oklahoma Geology Notes 37(5):171–173. Available at http://www.ogs.ou.edu/pubsscanned/NOTES/GN-V37N5.pdf (accessed March 2015).

Strimple, H. L. 1981. *Thalamocrinus* cf. *elongatus* Springer from the Henryhouse Formation (Silurian) of Oklahoma. Oklahoma Geology Notes 41(4):116–118. Available at http://www.ogs.ou.edu/pubsscanned/NOTES/GN-V41N4.pdf (accessed March 2015).

Suneson, N. H. Petrified wood in Oklahoma. The Shale Shaker 60(6):259–273. Available at http://www.ogs.ou.edu/geology/pdf/PetWoodIS_14,pdf.pdf (accessed May 2015).

Ulrich, E. O. 1927. Fossiliferous boulders in the Ouachita “Caney” shale and the age of the shale containing them. Oklahoma Geological Survey, Norman, Oklahoma. Bulletin 45. Available at http://www.ogs.ou.edu/pubsscanned/BULLETINS/Bulletin45.pdf (accessed March 2015).

Whittington, H. B. 1954. A new Ordovician graptolite from Oklahoma. Journal of Paleontology 28(5):613–621.

Whittington, H. B. 1955. Additional new Ordovician graptolites and a chitinozoan from Oklahoma. Journal of Paleontology 29(5):837–851.

Wilson, L. R. 1958. Oklahoma’s oldest fossil trees. Oklahoma Geology Notes 18(11):172–176.

Wilson, L. R., and J. J. Skvarla. 1967. Electron-microscope study of the wall structure of *Quisquilites* and *Tasmanites*. Oklahoma Geology Notes 27(3):54–63. Available at http://www.ogs.ou.edu/pubsscanned/NOTES/1967Vol27P.pdf (accessed April 2015).

Wilson, L. R., and J. B. Urban. 1971. Electron microscope studies of the marine palynomorph *Quisquilites*. Micropaleontology 19(2):239–243.

Data Sets

Chickasaw National Recreation Area Paleontological Archives
5/1985–present. (hard copy data; reports; electronic data; photographs; maps; publications). Originated by Santucci, Vincent; status: Active.

Chickasaw National Recreation Area Collections
1965–present. (museum specimens; associated specimen notes; collection records; maps; etc.). Originated by PECO staff; status: Active.

Chickasaw National Recreation Area Digital Geologic Map
2014–present. (geologic map data; electronic files; GIS metadata; associated report). Originated by NPS-Geologic Resources Inventory staff; status: Active. Online. https://irma.nps.gov/App/Reference/Profile/2165116.

American Museum of Natural History
1970s–present. (museum specimens; associated specimen notes; collection records; maps; etc.). Originated by AMNH staff; status: Active.

National Museum of Natural History
1900s–present. (museum specimens; associated specimen notes; collection records; maps; etc.). Originated by USNM staff; status: Active.

Oklahoma Geological Survey
1950s–present. (locality notes; collection records; maps; etc.). Originated by OKGS staff; status: Active.

Sam Noble Oklahoma Museum of Natural History
1950s–present. (museum specimens; associated specimen notes; collection records; maps; etc.). Originated by SNOMNH staff; status: Active.

U.S. Geological Survey
1900s–present. (locality notes; collection records; maps; etc.). Originated by USGS staff; status: Active.

Fort Larned National Historic Site

Fort Larned National Historic Site (FOLS) preserves the site of Fort Larned, a military outpost established near the midway point of the Santa Fe Trail (commemorated by the Santa Fe National Historic Trail) (FOLS Figure 1). The fort was in operation from 1859 to 1878, during which time it was also an important base of operation during the Indian Wars. FOLS was authorized August 31, 1964. The historic site encompasses 290.72 ha (718.39 acres), 275.05 ha (679.66 acres) of which are federal. The great majority of the land is in one unit, but there is also a small detached parcel about 5.6 km (3.5 mi) to the south, preserving wagon ruts of the Santa Fe Trail.



FOLS Figure 1. An aerial view of Fort Larned from the east, with the riparian corridor of the Pawnee River (FOLS/NPS).

Geologic Background

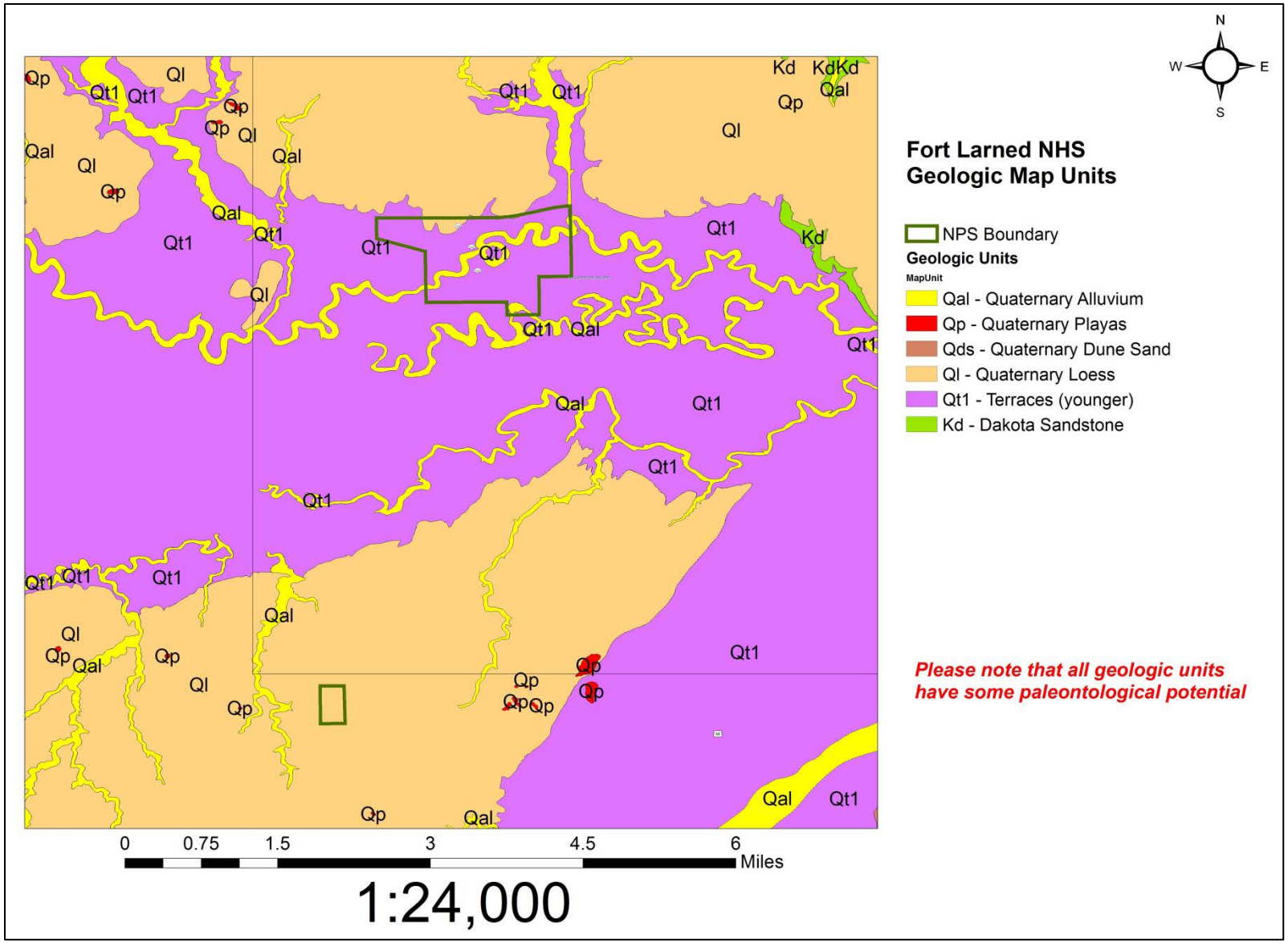
FOLS is located in central Pawnee County, central Kansas. It is about 8 km (5 mi) due west of Larned, 43 km (27 mi) southwest of Great Bend, Kansas, and 85 km (53 mi) northeast of Dodge City, Kansas. The Pawnee River runs through the historic site from west to east, in a meandering course. Publications on the geology and paleontology of the FOLS area include McLaughlin (1949), Scott (1977), Mandel (1991, 1994), Koch and Santucci (2003), KellerLynn (2008), and Johnson and Woodburn (2015). The NPS Geologic Resources Division coordinated a Geologic Resource Evaluation scoping summary for FOLS in May 2008 (KellerLynn 2008), and Koch and Santucci (2003) prepared the original paleontologic resource inventory and summary for FOLS.

Geologic units present at or near the subsurface of FOLS are limited to the Quaternary (see the Appendix for a geologic time scale). However, building stone at the historic site spans a wider stretch of time. Identified types of building stone at FOLS, representing the Dakota Formation and Greenhorn Limestone, were deposited along and within a shallow continental sea known as the Western Interior Seaway or Cretaceous Interior Seaway, which covered much of central North

America from approximately 100 to 70 Ma (million years ago). At its greatest extent, the seaway extended from the Arctic to the Gulf of Mexico, bisecting North America (Elder and Kirkland 1993, 1994). Its advances (transgressions) and retreats (regressions) influenced the geology of numerous NPS units both within and outside of the Southern Plains Network (SOPN). Several major cycles of marine transgressions and regressions occurred (Kauffman et al. 1969; Scott et al. 1998), with smaller sea level rises and falls within them (Scott et al. 1998). Volcanoes to the west of the seaway introduced great quantities of ash, today preserved as bentonite layers (Hattin 1975a). The cycles of transgressions and regressions ended after a mountain-building event toward the end of the Cretaceous, beginning roughly 75 Ma, uplifted the region far above sea level. This event, called the Laramide Orogeny, was the first step in the creation of the modern Rocky Mountains. Erosion wore down these peaks until tectonic activity resulted in renewed uplift during the past few million years (Sayre and Ort 2011).

There is little direct evidence for geologic events that occurred at FOLS during the approximately 70 million years that separate the Cretaceous seaway and the Quaternary, which began about 2.6 Ma. During the Late Pleistocene, western Kansas and the vicinity are interpreted as having had a taiga-like mix of conifer forest and aspen parkland, resembling the subalpine taiga of the modern Rockies. Fire events promoted parklands, which were replaced by forests within a century or two. The climate was more equable than present, with cooler, cloudier, and moister summers, and fewer droughts (Wells and Stewart 1987). The Pawnee River was present by the Pleistocene (McLaughlin 1949), and cut at least three terraces above the modern floodplain during the Pleistocene and Holocene (Mandel 1994). Humans arrived in the region by about the end of the Pleistocene (Hofman 2001).

There are no bedrock units exposed at FOLS. Instead, the surface and nearsurface geology of the historic site is made up primarily of Quaternary sediments (Pleistocene–Holocene) in the Pawnee River floodplain (McLaughlin 1949; Ross 1991; Johnson and Woodburn 2015) (FOLS Figure 2). The outlier, farther from the river, is over a Quaternary deposit mapped as terrace material by McLaughlin (1949) and loess by Ross (1991) and Johnson and Woodburn (2015). Rock from several formations has been used for building stone at FOLS, including the Dakota Formation (Lower–Upper Cretaceous), the Greenhorn Limestone (Upper Cretaceous), and an undetermined limestone that may be the Funston Limestone (lower Permian) (KellerLynn 2008). Fossils have been reported in the building stone, and late Holocene pollen and shells are present in the Quaternary sediments (FOLS Table 1).



FOLS Figure 2. Schematic geologic map of FOLS, based on a digital map derived from Johnson and Woodburn (2015).

FOLS Table 1. Summary of FOLS stratigraphy, fossils, and depositional settings in descending order of age, from youngest to oldest. Details and references can be found in the text.

Formation	Age	Fossils Within FOLS	Depositional Environment
Quaternary sediments	Pleistocene–Holocene	*Ephedra*, conifer, and angiosperm pollen and shells of late Holocene age (~2,000 years)	Alluvial deposition in the Pawnee River valley, and windblown loess
Greenhorn Limestone (building stone)	Late Cretaceous	Inoceramid bivalves in building stone	Marine
Dakota Formation (building stone)	Early–Late Cretaceous	A leaf in sandstone (assumed to be this formation)	Coastal plain and fluvial transitioning to coastal marine over time
Undetermined building stone (possibly the Funston Limestone)	Possibly early Permian	None to date; if it is the Funston Limestone, algae and marine invertebrates would be most likely	Marine

Sources of Paleontological Resources

The fossils of FOLS present opportunities for education, interpretation, and continued or future scientific research in the park.

Dakota Formation (Lower–Upper Cretaceous)

The Dakota Formation is not found in situ within FOLS, but blocks of Dakota Formation sandstone are used throughout FOLS as building stone. The material was quarried from a site at Jenkins Hill, about 0.8 km (0.5 mi) away (KellerLynn 2008). There is a fossil leaf impression in a sandstone block in FOLS collections (G. Elmore, FOLS historian, pers. comm. to VLS, August 2013). Given the geology of the area, the presence of leaves in the Dakota Formation, and the known use of Dakota Formation sandstone at FOLS, the Dakota Formation is the most likely candidate for the source rock.

The Dakota Formation of Pawnee County is composed of varicolored sandy shale and clay with lenticular beds of fine sandstone. It is as much as 69 m (225 ft) thick, and is regarded as fluvial and nearshore marine in origin (McLaughlin 1949). In central Kansas, the formation is sometimes divided into the Terra Cotta Clay and Janssen Clay members, with the Janssen Clay Member being more marine in influence (e.g., Bayne et al. 1971). However, these members are not necessarily mappable (Farley and Dilcher 1986). The Dakota Formation is a lithologically complex formation, reflecting its origin in a variety of depositional settings from terrestrial to shallow marine (Hattin and Cobban 1977; Hattin et al. 1978; Retallack and Dilcher 1981; Arbogast and Johnson 1996). The basic setting was a delta or coastal plain complex with the Western Interior Seaway to the west. As the seaway transgressed over the coast, deposition of the Dakota Formation was replaced by the shallow-marine deposition that became the Graneros Shale (Hattin and Cobban 1977; Hattin et al. 1978). Deposition occurred at approximately the Early–Late Cretaceous boundary (Brenner et al. 2000), currently placed at 100.5 Ma

The Dakota Formation name is used over a wide area of the central and western United States, albeit not necessarily accurately, and fossils have been reported from many of these areas. For the purposes of this report, the discussion will be limited to Kansas. The Dakota Formation of central Kansas is

best known for its plant fossils. Fossil plant remains, particularly angiosperm leaves, but also often other angiosperm body structures and fern and conifer fossils, have been reported from Kansas since the 19th century, and significant discoveries and new taxa are still being found (Popa and Dilcher 2002; Wang and Dilcher 2002; Dilcher et al. 2005; Wang and Dilcher 2006; Wang et al. 2008; Dilcher and Wang 2009). Spores, pollen, and other palynomorphs (organic microfossils) are abundant, and include dinoflagellates (single-celled organisms that move using one or more whip-like flagella) (possibly reworked) (Farley and Dilcher 1986), cysts of chlorophyte algae, spores of ferns, quillworts, clubmoss, and spikemosses, and conifer and angiosperm pollen (Kovach 1988; Kovach and Dilcher 1988). Some leaves show evidence of ancient leaf-mining insects (Labandeira et al. 1994).

The upper part of the Dakota Formation is part of a marine transgression, and it includes a notably brackish to marine assemblage of fossils. Among them are foraminifera ("amoebas with shells"), brachiopods (lamp shells), bivalves, gastropods, scaphopods (tusk shells), serpulid worm tubes, shark teeth, and invertebrate burrows and bioturbation (nonspecific but heavy modification of sediment by organisms), with some plant fragments and angiosperm leaves as well (Hattin and Cobban 1977; Hattin et al. 1978). The most common of these types of fossils are marginal marine bivalves and diverse invertebrate burrows (Arbogast and Johnson 1996). The invertebrates appear to be related to faunas from southern waters, such as those in Texas in slightly older rocks (Hattin 1967). Investigations of microvertebrate fossils are finding a variety of shark, ray, and teleost fish remains (Everhart et al. 2005; Bourdon and Everhart 2010). Tetrapods are uncommon in the Dakota Formation of Kansas. They are represented by a cast of a turtle, a plesiosaur (McAllister 1989), fragments of plesiosaurs and crocodilians (Bourdon and Everhart 2010), the crocodilian *Dakotasuchus* (Mehl 1941), the armored dinosaur *Silvisaurus*, a few other dinosaur specimens, some dinosaur tracks (Liggett 2005a), and bird tracks (McAllister 1989).

Greenhorn Limestone (Upper Cretaceous)

The Greenhorn Limestone is not found in situ at FOLS, but is widely used as a building stone at the historic site, particularly in window sills and thresholds. Inoceramids, a type of large, thick-shelled bivalve, have been observed in this type of stone at FOLS (KellerLynn 2008). In central Kansas, the Greenhorn Limestone consists of, in ascending order, the Lincoln, Hartland, Jetmore, and Pfeifer members (Hattin 1975a). Several beds within the formation have been used for building stone, including the Fencepost Limestone at the top of the Pfeifer Member and the "Shellrock Bed" of the upper Jetmore Member (Muilenburg and Swineford 1975). Beds of the Greenhorn Limestone can be traced over hundreds of miles (Hattin 1975a). This property has allowed the most suitable beds for building stone material to be exploited over large areas of central Kansas (Muilenburg and Swineford 1975) (see also "Cultural Resource Contexts" below).

The Greenhorn Limestone is a shallow-marine formation, deposited under warm temperate waters with normal salinity and poor oxygenation near the sea floor. Water depth was greater than 18 to 24 m (60 to 80 ft) but considerably less than 180 m (600 ft). Generally the energy of deposition was not great, and decreased after an initial period of high energy. The maximum transgression occurred during deposition of the Jetmore and Pfeifer members (Hattin 1975a). Cyclic bedding has been

observed throughout the formation. In the upper part of the formation, the cyclic alternation of limestone and shale beds is attributed to orbital variations comparable to modern Milankovitch cycles (Courtinat 1993; Kennedy et al. 2005), with cycles perhaps 41,000 years long (Courtinat 1993; Scott et al. 1998). Cycles lower in the Greenhorn Limestone may be longer, on the order of 100,000 years (Scott et al. 1998). Based on its fossils (Hattin 1975a; Scott et al. 1998), deposition of the Greenhorn Limestone occurred during the late Cenomanian and middle Turonian stages, beginning after 94.96 ± 0.50 Ma (ammonite *Plesiacanthus wyomingense* and bivalve *Inoceramus prefragilis*) and ending before 92.46 ± 0.58 Ma (ammonite *Collignoniceras woollgari* and bivalve *Mytiloides subhercynicus*) (Cobban et al. 2006). Because the transgression that produced the Greenhorn Limestone spread from west to east, the formation began deposition later and was deposited over a shorter time to the east (Hattin 1975a).

The Greenhorn Formation is heavily fossiliferous, although the diversity of the macroscopic fossils is often limited (Hattin 1975a). Because a significant part of the formation is nannofossils, microfossils, and fragments of bivalve shells (Hattin 1975a), practically any given stone or outcrop can be regarded as fossiliferous, although the fossil content would not necessarily be apparent to the naked eye. Generally, the same types of fossils can be found throughout the formation, although genera and species differ, and vertebrate fossils are mostly found in the lower part of the formation (Hattin 1975a; Everhart and Bell 2009; Miller 2013). Microscopic fossils include nannofossils such as coccoliths (mineralized plates of plankton), foraminifera, algal calcispheres (Hattin 1975a), palynomorphs that may include foraminifera linings, dinoflagellates, lignin and other plant materials, spores, pollen, fungi, and scolecodonts (worm jaws) (Courtinat 1993), and microscopic fecal pellets composed of coccoliths, possibly excreted by copepods or free-swimming tunicates (Hattin 1975b). A few plant fossils have been found, which likely drifted out to sea from the shore. The plant fossils include wood and logs, often with mollusk (“shipworm”) borings. Filled borings left behind from decayed wood have also been found (Hattin 1975a). Invertebrate fossils are mostly limited to mollusks. Major groups include brachiopods (lamp shells), bivalves (mostly the thick-shelled inoceramids), ammonites, gastropods, barnacles, and echinoids (sea urchins) (Hattin 1975a). Rarer groups include corals (Hattin 1975a) and ostracodes (seed shrimp) (Hazel 1969). Invertebrates also produced burrows (Hattin 1975a) and bioturbation (Kennedy et al. 2005). The invertebrate fauna is near the southern limit of the northern temperate assemblage. Generally, the bottom conditions were unfavorable to benthic fauna, although chalky limestones show burrowing, implying amelioration (Hattin 1975a). The Greenhorn Limestone vertebrate assemblage includes chondrichthyans (including sharks, rays, and guitarfish), bony fish, the turtle *Desmatochelys*, diverse plesiosaurs (Arratia and Chorn 1998; Cicimurri 2001), the aquatic lizard *Coniasaurus*, early mosasaur relatives, pterosaurs (flying reptiles) (Cicimurri 2001), and toothed seabirds (Weishampel et al. 2004; Everhart and Bell 2009).

Quaternary rocks and sediments (Pleistocene–Holocene)

The surface and shallow subsurface of FOLS is made up of Quaternary deposits. The deposits near the river, in the main unit of FOLS, are of alluvial origin. They are composed mostly of coarse sand and gravel, with some silt and clay. In the Pawnee River valley, they range from 20 to 42 m (65 to 138 ft) thick, averaging 32 m (105 ft), and are probably Late Pleistocene through Holocene in age

(McLaughlin 1949). The FOLS outlier, away from the river, is over higher terrace sediments composed of silt, as much as 45 m (150 ft) thick (McLaughlin 1949). These deposits are interpreted as loess (Ross 1991). Some of the sampling done by Rolfe Mandel for his dissertation on the Holocene evolution of the Pawnee River valley (Mandel 1994) occurred within FOLS, providing a detailed look at the recent geologic history. The main unit of FOLS is primarily atop the youngest terrace of the river, the T-1 terrace, which is regarded as Holocene in age. This terrace aggraded between approximately 10,500 and 1,600 years before present, with two pauses long enough for the formation of soil horizons between 2,750 and 1,600 years before present. Sampling in the northwest quarter of the northwest quarter of Section 32, T21S, R17W, which is within FOLS, found another paleosol at a depth of about 3.5 m (11 ft). Organic carbon in the ancient soil dates to 10,100 ± 130 radiocarbon years before present (12,140 to 11,240 calibrated years before present) (Mandel 1994). (Note that radiocarbon dates are not the same as calendar dates, and must be calibrated to approximate calendar years. Dates can be calibrated using a calibration program such as Calib 7.1 [http://calib.qub.ac.uk/calib/] if error ranges are provided. “Present” in “before present” is 1950.)

The Holocene sediments of FOLS are fossiliferous. Pollen sampling at FOLS in 1973 included a column of sediment from an eroded river bank (the Reed-Ott samples). Ephedra, conifer, and angiosperm pollen were found in this core, along with shells and artifacts. The cultural objects from 20 to 30 cm (8 to 12 in) indicate a Middle Woodland age, inferred to date back approximately 2,000 years (Scott 1977). The pollen and shells show the presence of late Holocene paleontological materials and illustrate what can be expected if further pollen investigations are undertaken at FOLS.

A variety of other fossils are known from upper Pleistocene and Holocene deposits in central Kansas. Relatively few latest Pleistocene sites have been reported from the region, although there are several significant faunas of older Pleistocene age (Frye and Hibbard 1941; Frye 1945; Hibbard 1976; Hibbard et al. 1978; Zakrzewski and Kolb 1982; Martin et al. 2011). Terrestrial gastropods are a notable exception, with numerous faunas known from the Peorian loess of western Kansas. Small mammals (shrews, rodents) and conifer fragments are also fairly common (Wells and Stewart 1987). Within a 100 km radius of FOLS, finds of large mammals are confined to a handful of isolated remains of proboscideans, horses, muskox, and bison, the nearest being a mammoth tooth found near Rush Center, about 30 km (20 mi) north of FOLS (Hay 1924). A partial skeleton of a mammoth has been found recently at Pratt, about 72 km (45 mi) southeast of FOLS (Liggett 2005b). Within Pawnee and Edwards counties, the alluvium occasionally contains bone fragments and fossil shells, particularly of gastropods (McLaughlin 1949). The most significant site in the vicinity is perhaps the Cheyenne Bottoms pollen site, in the Cheyenne Bottoms Wildlife Refuge about 65 km (40 mi) northeast of FOLS. This site has yielded pollen and spores from two time periods, between about 30,000 and 24,000, and from about 11,000 years ago to the present. The fossils, which include fern, horsetail, and lycopod spores, and ephedra, conifer, and angiosperm pollen, show that drying began before the Holocene, and that the grasslands are older than previously thought (Fredlund 1992, 1995). Useful online paleontological resources for the area include the Neotoma paleoecology database (http://www.neotomadb.org/), and Faunmap, which is the vertebrate element of Neotoma (http://www.ucmp.berkeley.edu/faunmap/).

Potential Sources of Paleontological Resources

Fossils have not yet been documented from the following geologic unit within FOLS. However, this unit is known to preserve fossils elsewhere, and future field investigations within the historic site may result in the discovery of fossils within it.

Undetermined building stone (lower Permian?)

There is at least one additional type of stone in use at FOLS. It is a limestone used mostly for thresholds, and is denser than the Greenhorn Limestone. Bob Sawin (Kansas Geological Survey) has speculated that it is Funston Limestone (KellerLynn 2008). The Funston Limestone, found in eastern Kansas, was deposited during the early Permian (Zeller 1968). It is a marine formation, deposited during a marine transgression within a larger transgressional episode (Schultze 1985). The Funston Limestone is fossiliferous, with typical fossils including bryozoans, brachiopods, bivalves, and ostracodes (Condra and Upp 1931). Fossils of chondrichthyans and bony fish have also been found (Schultze 1985). Part of the formation is made up of an algal reef or biostrome (Mudge and Burton 1959). If the building stone is indeed from the Funston Limestone, it would not be surprising to observe examples of these fossils in it.

Park Collections

The probable Dakota Formation sandstone block with the leaf fossil is in FOLS collections (G. Elmore, pers. comm. to V. L. Santucci, August 2013). No FOLS fossils are currently reported to be in the collections of other institutions.

Cultural Resource Connections

As described above, FOLS has multiple occurrences of fossils preserved in building stone. Aside from this basic fact, there is also a broader cultural story of interest here. FOLS, and Pawnee County, are within a section of central Kansas known as “Fencepost County”, due to the use of stone from the upper bed of the Greenhorn Limestone as distinctive, durable fenceposts. The upper bed is now known as the Fencepost Limestone because of this usage. In situ, it is between 20 and 30 cm (8 and 12 in) thick, and is a grayish chalky limestone. The general absence of trees in much of central Kansas forced settlers to turn to other building materials than wood. The Greenhorn Limestone is widely exposed in this area, and the Fencepost Limestone was found to be a high-quality building material. Use of the Fencepost Limestone was greatest from about 1884 to 1920, when not only was it used for fenceposts, but also in buildings, for statues, for lime, and so on. Fossils are often seen in Fencepost Limestone which has been used for buildings and other structures. Common fossils include inoceramids, the ammonite *Collignoniceras woolgari*, shark teeth, and fish scales; some driftwood has also been seen (Muilenburg and Swineford 1975). It is probable that the Greenhorn Limestone in use at FOLS came from the Fencepost Limestone, which would link it directly to this cultural tradition. Kenworthy and Santucci (2006) presented an overview and cited selected examples of National Park Service fossils found in cultural resource contexts, including in building stone.

Paleontological Resource Management, Preliminary Recommendations

- Staff from the historic site should be encouraged to observe exposed rocks and sedimentary deposits for fossil material while conducting their usual duties. To promote this, staff should also receive guidance regarding how to recognize common local fossils. When opportunities

arise to observe paleontological resources in the field and take part in paleontological field studies with trained paleontologists, staff should take advantage of them, if funding and time permit.

- Staff should photodocument and monitor any occurrences of paleontological resources that may be observed in situ. Fossils and their associated geologic context (surrounding rock) should be documented but left in place unless they are subject to imminent degradation by artificially accelerated natural processes or direct human impacts. A Geologic Resource Monitoring Manual by the Geological Society of America and NPS Geologic Resources Division includes a section on paleontological resource monitoring (Santucci et al. 2009). Santucci and Koch (2003) present information on paleontologic resource monitoring.

- Fossils found in a cultural context should be documented like other fossils, but will also require the input of an archeologist or a cultural resource specialist. Any fossil which has a cultural context may be culturally sensitive as well (e.g., subject to NAGPRA) and should be regarded as such until otherwise established. The Geologic Resources Division can coordinate additional documentation/research of such material.

- Contact the NPS Geologic Resources Division for technical assistance with paleontological resource management issues.

References Cited

Arbogast, A. F., and W. C. Johnson. 1996. Surficial geology and stratigraphy of Russell County, Kansas. Kansas Geological Survey, Lawrence, Kansas. Technical Series 7. Available at http://www.kgs.ku.edu/Publications/Bulletins/TS7/gifs/ts7.pdf (accessed January 2015).

Arratia, G,. and J. Chorn. 1998. A new primitive acanthomorph fish from the Greenhorn Formation (Late Cretaceous) of Nebraska. Journal of Vertebrate Paleontology 18(2):301–314.

Bayne, C. K., P. C. Franks, and W. Ives, Jr. 1971. Geology and ground-water resources of Ellsworth County, central Kansas. Kansas Geological Survey, Lawrence, Kansas. Bulletin 201. Available at http://www.kgs.ku.edu/General/Geology/Ellsworth/index.html (accessed January 2015).

Bourdon, J., and M. J. Everhart. 2010. Occurrence of the extinct carpet shark, *Orectoloboides*, in the Dakota Formation (Late Cretaceous, middle Cenomanian) of Kansas. Transactions of the Kansas Academy of Science 113(3–4):237–242.

Brenner, R. L., G. A. Ludvigson, B. J. Witzke, A. N. Zawistoski, E. P. Kvale, R. L. Ravn, and R. M. Joeckel. 2000. Late Albian Kiowa-Skull Creek marine transgression, lower Dakota Formation, eastern margin of Western Interior Seaway, U.S.A. Journal of Sedimentary Research 70(4):868–878.

Cicimurri, D. J. 2001. Cretaceous elasmobranchs of the Greenhorn Formation (middle Cenomanian-middle Turonian), western South Dakota. Pages 27–43 *in* V. L. Santucci, and L. McClelland, editors. Proceedings of the 6th fossil resource conference: 2001 a fossil odyssey. Technical

Report - National Park Service, Geological Resource Division. Available at http://www.nature.nps.gov/geology/paleontology/pub/fossil_conference_6/cicimurri.htm (accessed January 2015).

Cobban, W. A., I. Walaszczyk, J. D. Obradovich, and K. C. McKinney. 2006. A USGS zonal table for the Upper Cretaceous Middle Cenomanian-Maastrichtian of the Western Interior of the United States based on ammonites, inoceramids, and radiometric ages. U.S. Geological Survey, Reston, Virginia. Open-File Report 2006-1250. Available at http://pubs.usgs.gov/of/2006/1250/ (accessed January 2015).

Condra, G. E., and J. E. Upp. 1931. Correlation of the Big Blue series in Nebraska. Nebraska Geological Survey, Lincoln, Nebraska. Bulletin, 2nd series, 6.

Courtinat, B. 1993. The significance of palynofacies fluctuations in the Greenhorn Formation (Cenomanian-Turonian) of the Western Interior Basin, USA. Marine Micropaleontology 21(1–3):249–257.

Dilcher, D. L., and Wang H. 2009. An Early Cretaceous fruit with affinities to Ceratophyllaceae. American Journal of Botany 96(12):2256–2269.

Dilcher, D. L., Wang H., and E. Kowalski. 2005. Dakota Formation paleoclimate estimates from late Albian angiosperm leaves. Abstracts with Programs - Geological Society of America 37(5):85–86.

Elder, W. P., and J. I. Kirkland. 1993. Cretaceous paleogeography of the Colorado Plateau and adjacent areas. Museum of Northern Arizona Bulletin 59:129–151.

Elder, W. P., and J. I. Kirkland. 1994. Cretaceous paleogeography of the southern Western Interior region. Pages 415–440 *in* M. V. Caputo, J. A. Peterson, and K. J. Franczyk, editors. Mesozoic System of the Rocky Mountain region, USA. Rocky Mountain Section, Society for Sedimentary Geology, Denver, Colorado.

Everhart, M. J., and A. Bell. 2009. A hesperornithiform limb bone from the basal Greenhorn Formation (Late Cretaceous, middle Cenomanian) of north central Kansas. Journal of Vertebrate Paleontology 29(3):952–956.

Everhart, M. J., P. A. Everhart, and K. Ewell. 2005. A marine ichthyofauna from the upper Dakota Sandstone (Late Cretaceous). Transactions of the Kansas Academy of Science 108(1–2):71.

Farley, M. B., and D. L. Dilcher. 1986. Correlation between miospores and depositional environments of the Dakota Formation (Mid-Cretaceous) of north-central Kansas and adjacent Nebraska, U.S.A. Palynology 10:117–133.

Fredlund, G. G. 1992. Analysis of Quaternary pollen from Cheyenne Bottoms, Kansas: evidence for late Quaternary vegetation and climates in the Central Great Plains. Dissertation. University of Kansas, Lawrence, Kansas.

Fredlund, G. G. 1995. Late Quaternary pollen record from Cheyenne Bottoms, Kansas. Quaternary Research 43(1):67–79.

Frye, J. C. 1945. Problems of Pleistocene stratigraphy in central and western Kansas. Journal of Geology 53(2):73–93.

Frye, J. C., and C. W. Hibbard. 1941. Pliocene and Pleistocene stratigraphy and paleontology of the Meade Basin, southwestern Kansas. Kansas Geological Survey, Lawrence, Kansas. Bulletin 38, Part 13. Available at http://www.kgs.ku.edu/Publications/Bulletins/38_13/index.html (accessed January 2015).

Hattin, D. E. 1967. Stratigraphic and paleoecologic significance of macroinvertebrate fossils in the Dakota Formation (Upper Cretaceous) of Kansas. University of Kansas, Department of Geology Special Publication 2:570–589.

Hattin, D. E. 1975a. Stratigraphy and depositional environment of Greenhorn Limestone (Upper Cretaceous) of Kansas. Kansas Geological Survey, Lawrence, Kansas. Bulletin 209. Available at http://www.kgs.ku.edu/Publications/Bulletins/209/index.html (accessed January 2015).

Hattin, D. E. 1975b. Petrology and origin of fecal pellets in upper Cretaceous strata of Kansas and Saskatchewan. Journal of Sedimentary Petrology 45(3):686–696.

Hattin, D. E., and W. A. Cobban. 1977. Upper Cretaceous stratigraphy, paleontology and paleoecology of western Kansas. Mountain Geologist 14(3–4):175–217.

Hattin, D. E., C. T. Siemers, and G. F. Stewart. 1978. Upper Cretaceous stratigraphy and depositional environments of western Kansas. Kansas Geological Survey, Lawrence, Kansas. Guidebook Series 3. Available at http://www.kgs.ku.edu/Publications/Bulletins/GB3/ (accessed January 2015).

Hay, O. P. 1924. The Pleistocene of the middle region of North America and its vertebrated animals. Carnegie Institute of Washington Publication 322A. Available at https://archive.org/details/pleistoceneofmid00hayo (accessed January 2015).

Hazel, J. E. 1969. *Cythereis eaglefordensis* Alexander, 1929: a guide fossil for deposits of latest Cenomanian age in the Western Interior and Gulf Coast regions of the United States. Pages D155–D158 *in* Geological Survey research 1969, Chapter D. U.S. Geological Survey, Washington, D.C. Professional Paper 650-D. Available at http://pubs.er.usgs.gov/usgspubs/pp/pp650D (accessed January 2015).

Hibbard, C. W. 1976. The localities of the Cudahy fauna, with a new ground squirrel (Rodentia, Sciuridae) from the fauna of Kansas (late Kansan). Life Sciences Miscellaneous Publications 1976:278–286. Available at https://archive.org/details/athlonessaysonpa00chur (accessed January 2015).

Hibbard, C. W., R. J. Zakrzewski, R. E. Eshelman, G. Edmund, C. D. Griggs, and C. Griggs. 1978. Mammals from the Kanopolis local fauna, Pleistocene (Yarmouth) of Ellsworth County, Kansas. Contributions from the Museum of Paleontology, University of Michigan 25(2):11–44. Available at http://hdl.handle.net/2027.42/48492 (accessed January 2015).

Hofman, J. L. 2001. Human occupations across the Pleistocene-Holocene transition on the Great Plains: geomorphic and regional patterns. Abstracts with Programs - Geological Society of America 33(6):287.

Johnson, W. C., and T. L. Woodburn. 2015. Surficial geology of Pawnee County, Kansas; text, geologic-unit descriptions, and cross section geology by C. M. Phillips-Lander. Kansas Geological Survey, Lawrence, Kansas. Map M-114. Scale 1:50,000.

Kauffman, E. G., J. D. Powell, and D. E. Hattin. 1969. Cenomanian-Turonian facies across the Raton Basin. The Mountain Geologist 6(3):93–118.

KellerLynn, K. 2008. Geologic resource evaluation scoping summary: Fort Larned National Historic Site, Kansas. National Park Service, Geologic Resources Division, Denver, Colorado. Available at http://www.nature.nps.gov/geology/inventory/publications/s_summaries/FOLS_GRE_scoping_summary_2008-0919.pdf (accessed January 2015).

Kennedy, W. J., I. Walaszczyk, and W. A. Cobban. 2005. The global boundary stratotype section and point for the base of the Turonian stage of the Cretaceous: Pueblo, Colorado, U. S. A. Episodes 28(2):93–104. Available at http://www.stratigraphy.org/GSSP/Turonian.pdf (accessed January 2015).

Kenworthy, J. P., and V. L. Santucci. 2006. A preliminary investigation of National Park Service paleontological resources in cultural resource contexts, Part 1: general overview. New Mexico Museum of Natural History and Science Bulletin 34:70–76. Available at http://nature.nps.gov/geology/paleontology/pub/fossil_conference_7/9%20Kenworthy.pdf (accessed December 2014).

Koch, A. L., and V. L. Santucci. 2003. Fort Larned National Historic Site. Page 13 *in* A. L. Koch and V. L. Santucci. Paleontological resource inventory and monitoring: Southern Plains Network. TIC# D-107. National Park Service, Denver, Colorado.

Kovach, W. L. 1988. Quantitative palaeoecology of megaspores and other dispersed plant remains from the Cenomanian of Kansas, USA. Cretaceous Research 9(3):265–283.

Kovach, W. L., and D. L. Dilcher. 1988. Megaspores and other dispersed plant remains from the Dakota Formation (Cenomanian) of Kansas, U.S.A. Palynology 12:89–119.

Labandeira, C. C., D. L. Dilcher, D. R. Davis, and D. L. Wagner. 1994. Ninety-seven million years of angiosperm-insect association: paleobiological insights into the meaning of coevolution.

Proceedings of the National Academy of Sciences of the United States of America 91(25):12278–12282.

Liggett, G. A. 2005a. A review of the dinosaurs from Kansas. Transactions of the Kansas Academy of Science 108(1–2):1–14.

Liggett, G. A. 2005b. Pratt mammoth site: use of GIS in paleontology. Transactions of the Kansas Academy of Science 108(3–4):171–172.

Mandel, R. 1991. Holocene landscape evolution in the Pawnee River valley, southwestern Kansas. Dissertation. University of Kansas, Lawrence, Kansas.

Mandel, R. D. 1994. Holocene landscape evolution in the Pawnee River valley, southwestern Kansas. Kansas Geological Survey, Lawrence, Kansas. Bulletin 236.

Martin, R. A., P. Pelaez-Campomanes, J. G. Honey, F. Marcolini, and W. A. Akersten. 2011. Five million years of pocket gopher history in the Meade Basin of southwestern Kansas and northwestern Oklahoma. Journal of Vertebrate Paleontology 31(4):866–884.

McAllister, J. A. 1989. Subaqueous vertebrate footmarks from the upper Dakota Formation (Cretaceous) of Kansas, U.S.A. Occasional Papers of the Museum of Natural History, University of Kansas 127. Available at http://biodiversitylibrary.org/page/6251353 (accessed January 2015).

McLaughlin, T. G. 1949. Geology and ground-water resources of Pawnee and Edwards counties, Kansas. Kansas Geological Survey, Lawrence, Kansas. Bulletin 80. Available at http://www.kgs.ku.edu/General/Geology/Pawnee/index.html (accessed January 2015).

Mehl, M. G. 1941. *Dakotosuchus kingi*, a crocodile from the Dakota of Kansas. Journal of the Scientific Laboratories, Denison University 36(3):47–65.

Miller, S. 2013. Fossils and geology of the Greenhorn Cyclothem in the Comanche National Grassland, Colorado. Pages 269–278 *in* L. D. Abbott and G. S. Hancock, editors. Classic concepts and new directions: exploring 125 years of GSA discoveries in the Rocky Mountain Region. Geological Society of America, Boulder, Colorado. Field Guide 33.

Mudge, M. R., and R. H. Burton. 1959. Geology of Wabaunsee County, Kansas. U.S. Geological Survey, Washington, D.C. Bulletin 1068. Available at http://pubs.er.usgs.gov/publication/b1068 (accessed January 2015).

Muilenburg, G., and A. Swineford. 1975. Land of the post rock: its origins, history, and people. The University Press of Kansas, Lawrence, Kansas.

Popa, M. E., and D. L. Dilcher. 2002. Mid-Cretaceous conifers of the Dakota Formation, Kansas. Abstracts with Programs - Geological Society of America 34(2):93.

Retallack, G. J., and D. L. Dilcher. 1981. Early angiosperm reproduction: *Prisca reynoldsii*, gen. et. sp. nov. from Mid-Cretaceous coastal deposits in Kansas, U.S.A. Palaeontographica. Abteilung B: Palaeophytologie 179(5–6):103–137.

Ross, J. A. 1991. Geological map of Kansas. Kansas Geological Survey, Lawrence, Kansas. Map 23. Scale 1:500,000.

Santucci, V. L., and A. L. Koch. 2003. Paleontological resource monitoring strategies for the National Park Service. Park Science 22(1):22–25. Available at http://www.nature.nps.gov/ParkScience/archive/PDF/ParkScience22%281%29Fall2003.pdf (accessed January 2015).

Santucci, V. L., J. P. Kenworthy, and A. L. Mims. 2009. Monitoring in situ paleontological resources. Pages 189–204 *in* R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado.

Sayre, W. O., and M. H. Ort. 2011. A geologic study of the Capulin Volcano National Monument and surrounding areas, Union and Colfax counties, New Mexico. New Mexico Bureau of Geology and Mineral Resources, Socorro, New Mexico. Open File Report 541. Available at http://geoinfo.nmt.edu/publications/openfile/details.cfml?Volume=541 (accessed January 2015).

Schultze, H.-P. 1985. Marine to onshore vertebrates in the Lower Permian of Kansas and their paleoenvironmental Implications. University of Kansas Paleontological Contributions 113. Available at http://hdl.handle.net/1808/3666 (accessed January 2015).

Scott, L. J. 1977. Pollen analysis at Fort Larned, Kansas. Appendix F In Scott, D. D. Historical fact vs. archaeological reality—a test in environmental reconstruction. Dissertation. University of Colorado at Boulder, Boulder, Colorado. tDAR ID: 376351; doi:10.6067/XCV8MK6C59. Available at https://core.tdar.org/document/376351/pollen-analysis-at-fort-larned-kansas (accessed January 2015).

Scott, R. W., P. C. Franks, M. J. Evetts, J. A. Bergen, and J. A. Stein. 1998. Timing of Mid-Cretaceous relative sea level changes in the Western Interior: Amoco No. 1 bounds core. Concepts in Sedimentology and Paleontology 6:11–34.

Wang H., and D. L. Dilcher. 2002. Cenomanian angiosperm leaf megafossils, Dakota Formation, Hoisington III locality, Barton County, Kansas. Abstracts with Programs - Geological Society of America 34(2):A-93.

Wang H., and D. L. Dilcher. 2006. Early Cretaceous angiosperm leaves from the Dakota Formation, Braun Ranch locality, Kansas, USA. Palaeontographica. Abteilung B: Palaeophytologie 273(4–6):101–137.

Wang X., D. L. Dilcher, T. A. Lott, and Li Y. 2008. *Parapodocarpus* gen. nov. and its implications for interpreting the ovulate organ in the Podocarpaceae. Geophytology 37(1–2):1–8.

Weishampel, D. B., P. M. Barrett, R. A. Coria, J. Le Loueff, Xu X., Zhao X., A. Sahni, E. M. P. Gomani, and C. N. Noto. 2004. Dinosaur distribution. Pages 517–606 *in* D. B. Weishampel, P. Dodson, and H. Osmólska, editors. The Dinosauria (2nd edition). University of California Press, Berkeley, California.

Wells, P. V., and J. D. Stewart. 1987. Spruce charcoal, conifer macrofossils, and landsnail and small-vertebrate faunas in Wisconsinan sediments on the High Plains of Kansas. Pages 129–140 in W. C. Johnson, editor. Quaternary environments of Kansas. Kansas Geological Survey, Lawrence, Kansas. Guidebook Series 5. Available at http://www.kgs.ku.edu/Publications/Bulletins/GB5/ (accessed January 2015).

Zakrzewski, R. J., and K. K. Kolb. 1982. Late Kansan faunas from central Kansas. Transactions of the Kansas Academy of Science 85(4):200–215.

Zeller, D. E., editor. 1968. The stratigraphic succession in Kansas. Kansas Geological Survey, Lawrence, KS. Bulletin 189. http://www.kgs.ku.edu/Publications/Bulletins/189/ (accessed January 2015).

Additional References

Baldridge, W. S. 2004. Geology of the American Southwest: a journey through two billion years of plate-tectonic history. Cambridge University Press, Cambridge, United Kingdom.

Cummings, L. S., and K. Puseman. 1995. Pollen, phytolith, and macrofloral analysis of sod from Ft. Larned National Historic Site, central Kansas. Paleo Research Labs Technical Report 95-60, prepared for Midwest Regional Office, National Park Service, Omaha, Nebraska. tDAR ID: 377411; doi:10.6067/XCV8J965P3. Available at https://core.tdar.org/document/377411/pollen-phytolith-and-macrofloral-analysis-of-sod-from-ft-larned-national-historic-site-central-kansas (accessed January 2015).

Elias, S. A. 1997. The Ice Age history of southwestern National Parks. Smithsonian Institution Press, Washington, D.C.

Ellwood, B. B. 1996. Geology and America's National Park areas. Prentice Hall, Upper Saddle River, New Jersey.

Everhart, M. J. 2005. Oceans of Kansas: a natural history of the Western Interior Sea. Indiana University Press, Bloomington and Indianapolis, Indiana.

Graham, R. W. 1987. Late Quaternary mammalian faunas and paleoenvironments of the southwestern Plains of the United States. Pages 24–86 *in* R. W. Graham, H. A. Semken, Jr., and M. A. Graham, editors. Late Quaternary mammalian biogeography and environments of the Great Plains and prairies. Illinois State Museum, Springfield, Illinois. Scientific Papers 22.

Hattin, D. E. 1957. Depositional environment of the Wreford Megacyclothem (Lower Permian) of Kansas. Kansas Geological Survey, Lawrence, Kansas. Bulletin 124. Available at http://www.kgs.ku.edu/Publications/Bulletins/124/ (accessed January 2015).

Harris, A. H. 1985. Late Pleistocene vertebrate paleoecology of the west. University of Texas Press, Austin, Texas.

Hay, O. P. 1927. The Pleistocene of the western region of North America and its vertebrated animals. Carnegie Institute of Washington Publication 322B.

Johnson, W. C. 2003. Preliminary geologic field maps of portions of Pawnee County, Kansas. Kansas Geological Survey, Lawrence, Kansas. Open-File Report 2003-24. Scale 1:24,000.

Mayor, A. 2005. Fossil legends of the first Americans. Princeton University Press, Princeton, New Jersey.

Merriam, D. 2013. Kansas historic frontier military forts building stone. Transactions of the Kansas Academy of Science 116(1–2):47–53.

Olsen, S. J. 1971. Zooarchaeology: animal bones in archaeology and their interpretation. Addison-Wesley Publishing Company, New York City, New York.

Arbogast, A. F., and W. C. Johnson. 1998. Late-Quaternary landscape response to environmental change in south-central Kansas. Annals of the Association of American Geographers 88(1):126–145.

Feng Z.-D., W. C. Johnson, D. R. Sprowl, and Lu Y. 1994. Loess accumulation and soil formation in central Kansas, United States, during the past 400,000 years. Earth Surface Processes and Landforms 19(1):55–67.

McMullen, T. L. 1978. Mammals of the Duck Creek local fauna, late Pleistocene of Kansas. Journal of Mammalogy 59(2):374–386.

McMullen, T. L. 1975. Shrews from the late Pleistocene of central Kansas, with the description of a new species of *Sorex*. Journal of Mammalogy 56(2):316–320.

Siemers, C. T. 1976. Sedimentology of the Rocktown channel sandstone, upper part of the Dakota Formation (Cretaceous), central Kansas. Journal of Sedimentary Petrology 46(1):97–123.

Kurmann, M. H. 1985. An opal phytolith and palynomorph study of extant and fossil soils in Kansas (U.S.A.). Palaeogeography, Palaeoclimatology, Palaeoecology 49(3–4):217–235.

Grisafe, D. A. 1983. Geology and characteristics of building limestone of Kansas. Pages 91–112 *in* C. H. Ault and G. S. Woodard, editors. Proceedings of 18th forum on geology of industrial minerals: Theme: Construction materials. Indiana Geological Survey, Bloomington, Indiana. Occasional Paper 37.

Dilcher, D. L., W. L. Crepet, C. D. Beeker, and H. C. Reynolds. 1976. Reproductive and vegetative morphology of a Cretaceous angiosperm. Science 191(4229):854–856.

Mandel, R. D. 1992. Soils and Holocene landscape evolution in central and southwestern Kansas. Pages 41–100 *in* V. T. Holliday, editor. Soils in archaeology: landscape evolution and human occupation. Smithsonian Institution, Washington, D.C.

Gress, E. M. 1922. An annotated list of fossil plants of the Dakota Formation (Cretaceous) in the collections at the Carnegie Museum, including descriptions of three new species. Annals of Carnegie Museum 13(3–4):274–332. Available at http://biodiversitylibrary.org/page/9958243 (accessed January 2015).

Eaton, T. H., Jr. 1960. A new armored dinosaur from the Cretaceous of Kansas. University of Kansas Paleontological Contributions, Paper 25(8). Available at http://kuscholarworks.ku.edu/handle/1808/3799 (accessed January 2015).

Huh, J. M., and C. I. Smith. 1972. Coccoliths and related calcareous nannofossils from the Upper Cretaceous Fencepost Limestone of northwestern Kansas. Contributions from the Museum of Paleontology, University of Michigan 24(3):17–22. Available at http://hdl.handle.net/2027.42/48470 (accessed January 2015).

Data Sets

Fort Larned National Historic Site Paleontological Archives
5/1985–present. (hard copy data; reports; electronic data; photographs; maps; publications).
Originated by Santucci, Vincent; status: Active.

Fort Larned National Historic Site Collections
1964–present. (museum specimens; associated specimen notes; collection records; maps; etc.).
Originated by FOLS staff; status: Active.

Fort Union National Monument

Fort Union National Monument (FOUN) commemorates Fort Union, the largest frontier fort of the Southwest (FOUN Figure 1). It was established to preserve and protect the various extant structures and ruins representing the different versions of the fort, which operated between 1851 and 1891 near the junction of the Cimarron and Mountain branches of the Santa Fe Trail. Over this time, Fort Union was part of Indian wars and the Civil War. FOUN was established as a national monument June 28, 1954, and encompasses 291.62 ha (720.60 acres), all of which are federal. Its land is divided into two parcels, separated by Wolf Creek. The smaller western parcel includes the site of the first Fort Union and the remains of the third fort's arsenal, and the larger parcel includes the site of the second "star-shaped" fort and the remains of the third fort. The Santa Fe Trail, which passes through FOUN, is commemorated by another National Park Service unit (Santa Fe National Historic Trail; SAFE). SAFE is discussed in greater detail in a following chapter, "Non-I&M network units within the SOPN."



FOUN Figure 1. The landscape surrounding FOUN, with the former hospital in the foreground (FOUN/NPS).

Geologic Background

FOUN is located in south-central Mora County, northeastern New Mexico. The nearest large city is Las Vegas, New Mexico, about 40 km (25 mi) to the south-southeast. The Mora River, a tributary of the Canadian River, is south of FOUN, and the Sangre de Cristo Mountains rise to the west. A fault known as the Fort Union Fault is present just west of FOUN, forming a northwest-southeast fault scarp just outside of the monument. FOUN is on the down-dropped side of the fault (Johnson 1974). Documents discussing the geology and paleontology of FOUN include Johnson (1974), Koch and Santucci (2003), NPS (2006a, 2006b), Price (2010), Lindline et al. (2011), and KellerLynn (2012). The NPS Geologic Resources Division coordinated a Geologic Resource Evaluation scoping meeting for FOUN in March 2006 (NPS 2006a), and produced a digital map of the monument in 2006 (NPS 2006b). A geologic resources inventory report was prepared for the monument in 2012 (KellerLynn

2012). Koch and Santucci (2003) prepared the original paleontologic resource inventory and summary for FOUN.

The rocks and sediments exposed at FOUN and the immediate vicinity record several episodes of geologic history, from the middle Cretaceous (around 100 Ma, or million years ago), to volcanic activity of the past 8 million years, to recent river erosion (see Appendix A for a geologic time scale). The mesa immediately west of FOUN has extensive exposures of the Dakota Sandstone, a middle Cretaceous formation representing a transition from coastal plain and river deposition to shallow-marine deposition (Kauffman et al. 1969; Bejnar and Lessard 1976; Mateer 1985; Kues and Lucas 1987). When deposition began, streams flowed from highlands on the west to a shallow epicontinental sea on the east. Rising sea levels moved the coast inland, eventually submerging the area (Bejnar and Lessard 1976). The shallow continental sea is known as the Western Interior Seaway or Cretaceous Interior Seaway. It eventually extended from the Arctic to the Gulf of Mexico, bisecting North America (Elder and Kirkland 1993, 1994). Its advances (transgressions) and retreats (regressions) influenced the geology of numerous NPS units both within and outside of the Southern Plains Network (SOPN).

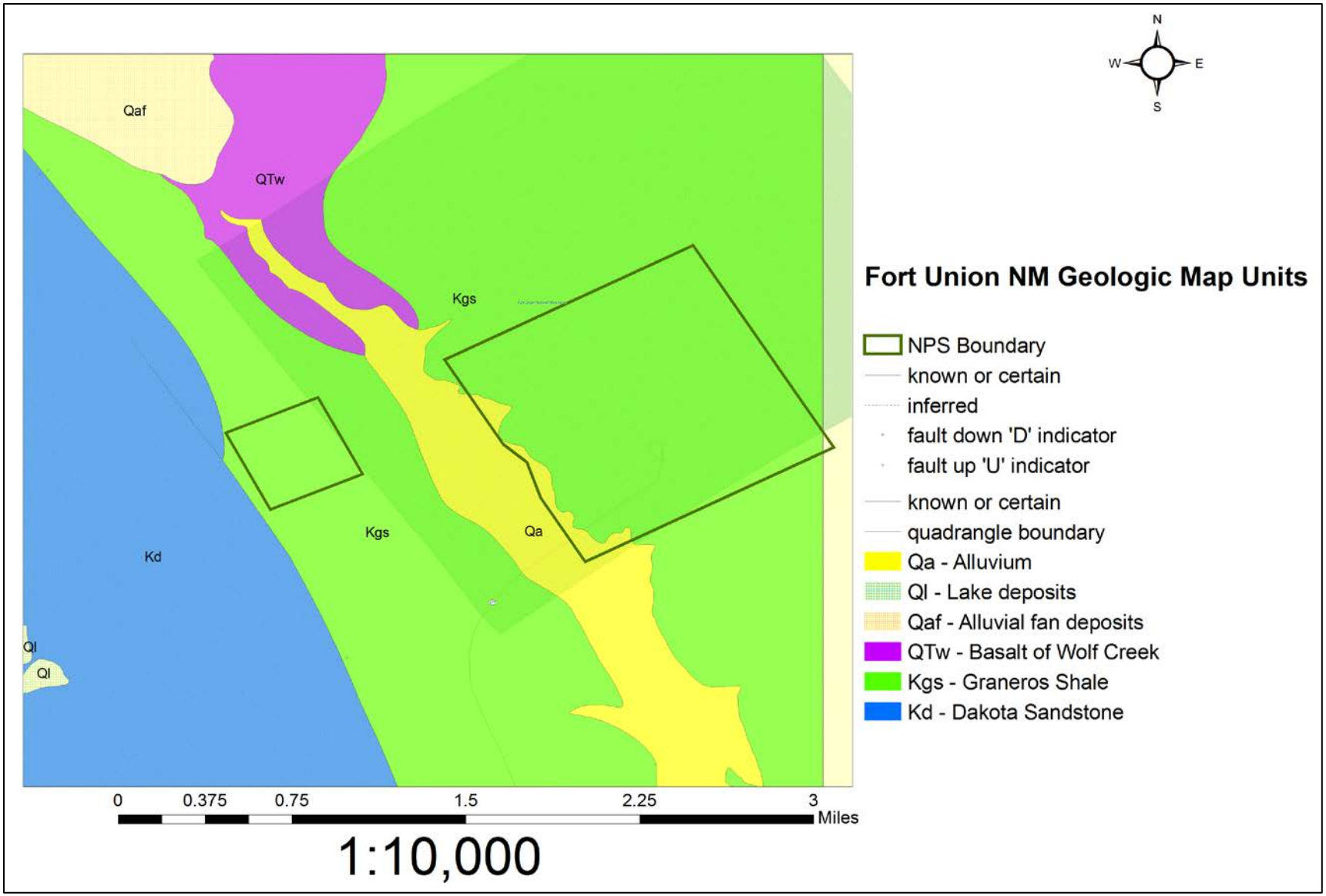
The Western Interior Seaway in northeastern New Mexico was usually less than 90 m (300 ft) deep and rarely greater than 150 m (500 ft) deep, deeper to the west than the east. Regular successions of coastal-plain to coastal-marine to shallow-marine rocks trace the advances and retreats of the seaway over tens of millions of years (Kauffman et al. 1969). Several such cycles of marine transgressions and regressions can be recognized (Kauffman et al. 1969); rocks of the oldest two cycles are present beneath and just outside of FOUN. The Dakota Sandstone includes rocks deposited during part of the first great marine transgression, the Kiowa-Skull Creek cycle, and rocks from the following Greenhorn cycle (Kues and Lucas 1987). The Graneros Shale, underlying FOUN, is also part of the Greenhorn cycle, and represents fully marine deposition (Kauffman et al. 1969). Younger rocks from the seaway, including the Greenhorn Limestone and Carlile Shale, are found a few km or mi north of FOUN (Johnson 1974). The cycles of marine transgressions and regressions continued for a few tens of millions of years until a mountain-building event beginning toward the end of the Cretaceous, roughly 75 Ma, uplifted the region far above sea level. This event, called the Laramide Orogeny, was the first step in the formation of the modern Rocky Mountains. Erosion wore down these peaks until tectonic activity resulted in renewed uplift during the past few million years (Sayre and Ort 2011).

Tectonic activity did not cease in New Mexico with the end of the Laramide Orogeny. A tectonic feature called the Rio Grande Rift became active in central New Mexico around 26 Ma, and remains active in the present (Sayre and Ort 2011). This north–south feature crosses a much older northeast–southwest crustal weakness known as the Jemez Lineament in north-central New Mexico (Kiver and Harris 1999). The Jemez Lineament is a crustal suture or weakness that formed roughly 1.68 to 1.65 billion years ago between two crustal blocks, the Yavapai province on the north and the Mazatzal province on the south (Magnani et al. 2004). The formation of the Rio Grande Rift across this weakness is related to igneous activity in northern New Mexico (Stormer 1987). Volcanic fields associated with the lineament include the Jemez Volcanic Field, the Ocate Volcanic Field, the Raton–Clayton Volcanic Field, and the Taos Plateau Volcanic Field. These fields were all active over

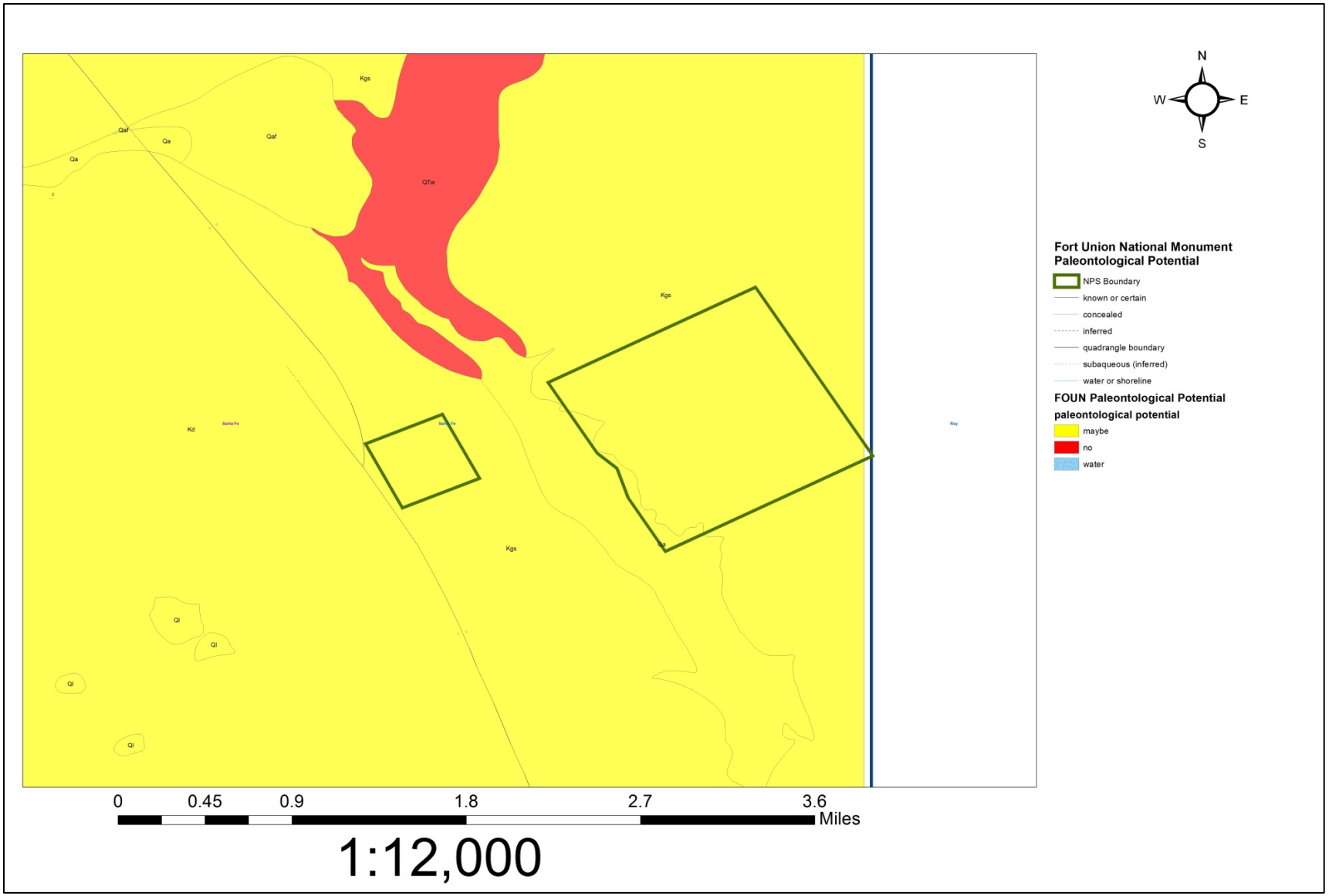
the same general time frame, roughly the past 9 million years (Sayre and Ort 2011). The Raton–Clayton and Ocate volcanic fields represent the most significant late Cenozoic volcanic activity east of the Rockies (Aubele and Crumpler 2001). FOUN is within the Ocate Volcanic Field, and the basalt of Wolf Creek, present just north of FOUN, is a flow from this volcanic field (KellerLynn 2012). This flow erupted approximately 2.4 Ma (Olmsted and McIntosh 2004). The Ocate Volcanic Field was active between about 8.2 Ma and 800,000 years ago, with perhaps 14 pulses of activity (Olmsted and McIntosh 2004).

Humans have been documented in northeastern New Mexico since the latest Pleistocene, and some of the most important Paleoindian sites are from this area. Clovis, in Curry County in east-central New Mexico, gave its name to the Clovis tradition, and the slightly younger Folsom tradition is named for the Folsom archeological site in northeastern Colfax County, over 130 km (80 mi) northeast of FOUN. The Clovis tradition existed between approximately 11,200 and 10,900 radiocarbon years before present, and the Folsom tradition existed between approximately 10,900 and 10,200 radiocarbon years before present (Holliday 2000). (Note that radiocarbon dates are not the same as calendar dates, and must be calibrated to approximate calendar years. Dates can be calibrated using a calibration program such as Calib 7.1 [http://calib.qub.ac.uk/calib/] if error ranges are provided. “Present” in “before present” is 1950.) Regional climate during Clovis time appears to have been wetter than present, with drier conditions in Folsom time, followed by a general continuation of drying until the warm and dry Altithermal began around 8,000 years ago (Holliday 2000). This latest Pleistocene–Holocene period of time also shows rapid and extensive incision on the Canadian River drainage system (Frye et al. 1978), which includes Wolf Creek. Fluvial terraces from the Pleistocene are present in the FOUN area (KellerLynn 2012).

Geologic units present at or near the surface within FOUN include the Upper Cretaceous Graneros Shale and Quaternary alluvium, attributed to the Holocene (Johnson 1974; NPS 2006b) (FOUN Figure 2). A third unit, the Lower Cretaceous Dakota Sandstone, is present on the fault scarp just beyond the smaller parcel (Johnson 1974; NPS 2006b), and probably erodes into it. None of the geologic units within or immediately adjacent to FOUN are known to have yielded fossils within the monument, but all three have some potential to do so (FOUN Figure 3).



FOUN Figure 2. Schematic geologic map of FOUN. Map graphic adapted from digital geologic map data available at the following URL: https://irma.nps.gov/App/Reference/Profile/1040284.



FOUN Figure 3. Paleontological potential map of FOUN, showing the distribution of geologic units where fossils have been found and may be found. Map graphic adapted from digital geologic map data available at the following URL: https://irma.nps.gov/App/Reference/Profile/1040284.

FOUN Table 1. Summary of FOUN stratigraphy, fossils, and depositional settings in descending order of age, from youngest to oldest. Details and references can be found in the text.

Formation	Age	Fossils Within FOUN	Depositional Environment
Quaternary sediments	Holocene	None to date; mollusk fossils are most likely	Fluvial (Wolf Creek)
Graneros Shale	Late Cretaceous	None to date; mollusk fossils are most likely	Shallow marine
Dakota Sandstone (not exposed in FOUN, but exposed in the mesa immediately west of the detached unit)	Early–Late Cretaceous	None to date; wood fragments and dinosaur footprints are most likely	Coastal plain and fluvial transitioning to coastal marine over time

Potential Sources of Paleontological Resources

Fossils have not yet been documented from the following rock units within FOUN. However, they are known to preserve fossils elsewhere, and future field investigations within the monument may result in the discovery of fossils from one or more of these units.

Dakota Sandstone (Lower–Upper Cretaceous)

The Dakota Sandstone is not present at the surface within FOUN, but is present just beyond the boundary of the western parcel on the west (upthrown) side of the Fort Union Fault (Johnson 1974). Stone from this formation was used to build structures at FOUN (KellerLynn 2012), and its presence at a higher elevation just outside of FOUN makes it a likely candidate to erode into the monument, so it is discussed here. The Dakota Sandstone of the FOUN area is as much as 60 m (200 ft) thick and is divisible into three parts: a lower interval of tan to brown locally conglomeratic sandstone; a middle interval of carbon-rich shale with thin beds of siltstone and some coal; and an upper interval of tan to brown sandstone with thin beds of gray shale (Johnson 1974). Under more recent usage, this would be described as the Dakota Group, or would be broken up into three formations, in ascending order the Mesa Rica Sandstone, the Pajarito Shale, and the Romeroville Sandstone. To maintain continuity between Geologic Resource Division products, the usage of NPS (2006b) and KellerLynn (2012), adapted from Johnson (1974), will be maintained. In a further complication, the Dakota Sandstone was named for rocks on the east side of the Western Interior Seaway. Usage of the name on the western side of the seaway, in places like eastern New Mexico, has a long history, but this usage has been challenged in recent years (Mateer 1987; Witzke and Ludvigson 1994; Carpenter 2014). It may be worthwhile to attempt to distinguish the three intervals in future geologic work in the area of FOUN, which would allow more detailed comparison to the rest of northeastern New Mexico and would sidestep comparison with rocks in other parts of the country that may or may not be equivalent. In particular, it would be useful to know which division(s) of the formation is(are?) present just outside of the monument, because this would inform what types of fossils would be most likely to be found.

The Dakota Sandstone of northeastern New Mexico has long been interpreted as a sequence of coastal-plain to shallow-marine deposition (Kauffman et al. 1969; Bejnar and Lessard 1976; Mateer 1985; Kues and Lucas 1987). The lower (Mesa Rica Sandstone) interval is interpreted as fluvial in origin, perhaps from braided streams or meandering streams with low sinuosity. The middle (Pajarito Shale) interval is interpreted as having been deposited in a low-energy but fluctuating environment,

like the floodplain of a low-gradient river. The upper (Romeroville Sandstone) interval was deposited in shallow-marine and beach/bar settings. The overall sequence is that of a piedmont plain becoming a coastal plain and finally a litoral/beach/lagoon/marine complex. Streams flowing east from the Sevier highlands to the Western Interior Seaway began as braided, then became meandering over time. Eventually, the seaway submerged the coastal plain and continued moving west, signaling the onset of the shaly shallow-marine deposition that became the Graneros Shale. The climate was probably warm and humid during this period of deposition (Bejnar and Lessard 1976).

The age of rocks assigned to the Dakota Sandstone varies from place to place. In northeastern New Mexico, the rocks were deposited near the Early Cretaceous–Late Cretaceous boundary of 100.5 Ma, from the late Albian to the early Cenomanian (roughly 105 to 97 Ma). The Mesa Rica Sandstone is late Albian in age (Lucas et al. 1998), the Pajarito Shale is latest Albian in age, and the Romeroville Sandstone is early Cenomanian in age (Scott et al. 2004). The Mesa Rica Sandstone grades into the Pajarito Shale (Lucas et al. 2001), but the contact between the Pajarito and Romeroville formations is sometimes interpreted as conformable (Kues and Lucas 1987), and sometimes as disconformable (Lucas et al. 1998, 2001). The upper contact with the Graneros Shale is transitional (Kauffman et al. 1969), and the upper interval of the Dakota Sandstone represents the early transgression of the Graneros sea (Kues and Lucas 1987).

Given the questions associated with the usage of the “Dakota” name, it seems most prudent to restrict a discussion of “Dakota Sandstone” fossils to northeastern New Mexico and the Mesa Rica, Pajarito, and Romeroville units. Dakota Sandstone fossils are not currently known from FOUN, and relatively few fossils have been reported from the Dakota Sandstone in the vicinity of FOUN. However, Bejnar and Lessard (1976) have reported a dinosaur track in Dakota Sandstone float discovered near FOUN, so the potential is clear. In Mora and San Miguel counties, each of the three portions of the formation has yielded a few fossils. The lower interval (Mesa Rica Sandstone) has yielded silicified logs and reworked Paleozoic rocks with fossils including fusulinid foraminifera (“amoebas with shells”) and bryozoans (moss animals). The middle interval (Pajarito Shale) has yielded carbonized wood fragments and molds, a mold of a cone, fern and lycopod (clubmoss) spores, conifer and angiosperm pollen, root casts, and fungal spores. The upper interval (Romeroville Sandstone) has yielded carbonized wood fragments and wood molds, and invertebrate burrows (Bejnar and Lessard 1976). A few additional fossil types are present farther afield in northeastern New Mexico. Other fossils reported from the lower interval include dinoflagellates (single-celled organisms that move using one or more whip-like flagella), spores, pollen (Scott et al. 2004), ammonites (Lucas et al. 2001), possible fish fragments (Kues and Lucas 1987), and invertebrate burrows (Mateer 1985). Other fossils reported from the middle interval include foraminifera, dinoflagellates (Scott et al. 2004), bivalves (Dobrovolney et al. 1946), gastropods (Kues and Lucas 1987), bioturbation (Lucas et al. 2001), and shark teeth (Scott et al. 2004). Both the middle and upper intervals have yielded dinosaur tracks and other tracks (see below) (Hunt and Lucas 1998). Finally, the upper interval sometimes includes general bioturbation (Kues and Lucas 1987). A flora of conifer and angiosperm foliage has also been reported from the northeastern part of the state (Newberry 1898). Wood fragments are probably most likely for FOUN, because of their durability.

The upper Mesa Rica/lower Pajarito rocks of the northeastern corner of New Mexico are noted for vertebrate tracks (Lucas et al. 1989, 2000; Hunt and Lucas 1998; Lockley et al. 2000). The best-known site is at Clayton Lake State Park, over 160 km (100 mi) northeast of FOUN. Over 400 tracks have been found there, mostly from ornithopods (beaked, herbivorous, bipedal dinosaurs) (Gillette and Thomas 1985; Hunt and Lucas 1998). Several types of tracks are found at these sites, including two types of ornithopod tracks (*Caririchnium* and *Amblydactylus*), at least three types of theropod tracks (bipedal carnivorous dinosaurs), and crocodilian tracks (formerly mistaken for tracks of pterosaurs, also known as flying reptiles), as well as invertebrate traces. Tracks at these sites show evidence of gregarious dinosaurs, limping dinosaurs, and tail marks (Hunt and Lucas 1998). The New Mexico track localities have been included in a "dinosaur freeway" of track sites between eastern Colorado and the Oklahoma Panhandle in the Dakota Group (Hunt and Lucas 1998; Lockley et al. 2006a), although not all authorities agree with the interpretation of a megatracksite (Lucas et al. 2000). The "Dinosaur Freeway" includes more than 60 sites, with more than 1,000 trackways; collectively (Kukihara and Lockley 2012). The tracks include footprints of crocodilians, pterosaurs, theropod, ornithopod, and armored dinosaurs, and birds (Lockley et al. 2000b, 2006; Kukihara and Lockley 2012).

Graneros Shale (Upper Cretaceous)

The Graneros Shale makes up the nearsurface bedrock of FOUN. This unit is a dark gray shale with interbeds of more silty or sandy shale, and a few thin beds of bentonite, a clay formed from the breakdown of volcanic ash. The thickness here is not known for certain, but is estimated at around 45 m (150 ft) (Johnson 1974). A limestone unit known as the Thatcher Limestone is sometimes present in the middle of the formation in northeastern New Mexico (Kauffman et al. 1969), but is not reported from the FOUN area. It represents the maximum extent of marine flooding during deposition of the Graneros Shale (Scott et al. 2004). Farther west in New Mexico, the Graneros interval is divided into shaly beds (the Mancos Shale) and sandy beds (members of the Dakota Sandstone) (Lucas et al. 1998). It is a widely distributed formation, with the name "Graneros Shale" in use as far away as Minnesota and Montana.

The Graneros Shale is a shallow-marine unit. In northeastern New Mexico, the sea generally deepened over time, from sublittoral to midshelf, and was deeper in the west than in the east (Kauffman et al. 1969). The age of the Graneros Shale varies from place to place because it records part of a marine transgression that arrived in different areas at different times (Witzke et al. 1983; Witzke and Ludvigson 1987). In New Mexico, it is dated to the early to late Cenomanian (Lucas et al. 1998, 2001), a subdivision of the Late Cretaceous currently dated from 100.5 to 93.9 Ma. The Thatcher Bed is dated to 95.78 Ma (Scott et al. 2004).

No fossils have been reported from the Graneros Shale in FOUN to date. Most fossils reported from the Graneros Shale are from north of New Mexico. The fossil assemblage of the Graneros Shale as a whole is dominated by marine invertebrates. The invertebrate assemblage includes tintinnids (a type of protozoan) (Eicher 1965a), foraminifera (Eicher 1965b), coccoliths (mineralized plates of plankton) (Witzke and Ludvigson 1987), corals (Dane et al. 1937), rare bivalves and ammonites (DeGraw and Pabian 1980; Witzke and Ludvigson 1987), nautiloids, gastropods, scaphopods (Dane

et al. 1937), invertebrate trace fossils (Archer and Hattin 1984), and fecal pellets (Witzke and Ludvigson 1987). Vertebrates are represented by chondrichthyans (cartilaginous fish) including sharks (DeGraw and Pabian 1980) and guitarfish (Everhart 2007), bony fish, the turtle *Desmatochelys*, plesiosaurs, unidentified marine reptiles, and vertebrate coprolites (fossil feces) (Witzke 1981). Plesiosaurs include the elasmosaurids *Hydralmosaurus* (Matson et al. 2002) and *Thalassomedon* (Carpenter 1999). In New Mexico, fossils reported from the Graneros Shale include foraminifera, dinoflagellates, spores, pollen (Scott et al. 2004), plant fragments, bivalves, ammonites, gastropods, and invertebrate burrows (Kauffman et al. 1969). The Graneros Shale is generally fossil-poor in New Mexico, although the Thatcher Bed is more fossiliferous, and shows a mix of Gulf Coast and more northern forms (Kauffman et al. 1969).

Quaternary rocks and sediments (Holocene)

The recent sedimentary deposits of FOUN consist of gravel, sand, silt, and clay, deposited during the Holocene by Wolf Creek (Johnson 1974; KellerLynn 2012). Aside from faunal remains from archeological sites, most of the fossils reported from the Holocene of northeastern New Mexico are mollusks. The presence of Wolf Creek increases the likelihood of mollusk fossils. Holocene mollusk fossils include freshwater bivalves and freshwater and terrestrial snails (Frye et al. 1978).

It is entirely possible that more Holocene vertebrate fossils exist in northeastern New Mexico than have been reported, but they may not attract attention, because they would more closely resemble modern fauna than more exotic older Pleistocene fossils of extinct animals like mammoths. Although Pleistocene fossils are not known from FOUN and are unlikely to be found there, there may be some interest in them for educational purposes. Pleistocene vertebrate finds of New Mexico are well documented, and there are several inventories that illustrate the locations and diversity of these finds (Lucas and Effinger 1991; Morgan et al. 2001; Morgan and Lucas 2005a, 2005b). Mammoth and bison are common Pleistocene finds in the region (Morgan and Lucas 2005a, 2005b).

Park Collections

No fossils are currently reported to be in FOUN collections, and no FOUN fossils are currently reported to be in the collections of other institutions.

Cultural Resources Connections

No fossils have been reported from cultural resource contexts at FOUN, although such associations would not be unprecedented. Potentially fossiliferous Dakota Sandstone rocks were used as building stone at the fort (KellerLynn 2012). Microscopic fossils and fossil fragments may be present in the mortar used in the fort: nearby outcrops of the Graneros and Greenhorn formations are likely sources for the limy fraction of the mortar, and the Dakota Sandstone is probably the source of quartz grains (Lindline et al. 2011). Another common type of cultural association for this area is fossiliferous stone used for artifacts. For example, in the Southwest, petrified wood from the Upper Triassic Chinle Formation was often used for artifacts. The majority of parks in the neighboring Southern Colorado Plateau Network have examples (Tweet et al. 2009). Fossils may have also been collected by the fort personnel. Kenworthy and Santucci (2006) presented an overview and cited selected examples of National Park Service fossils found in cultural resource contexts.

Paleontological Resource Management, Preliminary Recommendations

- Staff from the monument should be encouraged to observe exposed rocks and sedimentary deposits for fossil material while conducting their usual duties. To promote this, staff should also receive guidance regarding how to recognize common local fossils. When opportunities arise to observe paleontological resources in the field and take part in paleontological field studies with trained paleontologists, staff should take advantage of them, if funding and time permit.

- Staff should photodocument and monitor any occurrences of paleontological resources that may be observed in situ. Fossils and their associated geologic context (surrounding rock) should be documented but left in place unless they are subject to imminent degradation by artificially accelerated natural processes or direct human impacts. A Geologic Resource Monitoring Manual by the Geological Society of America and NPS Geologic Resources Division includes a section on paleontological resource monitoring (Santucci et al. 2009). Santucci and Koch (2003) present information on paleontologic resource monitoring.

- Fossils found in a cultural context should be documented like other fossils, but will also require the input of an archeologist or a cultural resource specialist. Any fossil which has a cultural context may be culturally sensitive as well (e.g., subject to NAGPRA) and should be regarded as such until otherwise established. The Geologic Resources Division can coordinate additional documentation/research of such material.

- Contact the NPS Geologic Resources Division for technical assistance with paleontological resource management issues.

References Cited

Archer, A. W., and D. E. Hattin. 1984. Trace fossils in Upper Cretaceous argillaceous marine facies of the U. S. Western Interior. Palaeogeography, Palaeoclimatology, Palaeoecology 45(2):165–187.

Aubele, J. C., and L. S. Crumpler. 2001. Raton-Clayton and Ocate volcanic fields. Pages 69–76 *in* S. G. Lucas and D. S. Ulmer-Scholle, editors. Geology of the Llano Estacado. New Mexico Geological Society, Socorro, New Mexico. Guidebook 52. Available at http://nmgs.nmt.edu/publications/guidebooks/downloads/52/52_p0069_p0076.pdf (accessed January 2015).

Bejnar, D. C., and R. H. Lessard. 1976. Paleocurrents and depositional environments of the Dakota Group, San Miguel and Mora counties, New Mexico. Pages 157–163 *in* R. C. Ewing and B. S. Kues, editors. Vermejo Park. New Mexico Geological Society, Socorro, New Mexico. Guidebook 27. Available at https://nmgs.nmt.edu/publications/guidebooks/downloads/27/27_p0157_p0163.pdf (accessed January 2015).

Carpenter, K. 1999. Revision of North American elasmosaurs from the Cretaceous of the Western Interior. Paludicila 2(2):148–173.

Carpenter, K. 2014. Where the sea meets the land—the unresolved Dakota problem in Utah. Pages 357-372 *in* J. S. MacLean, R. F. Biek, and J. E. Huntoon, editors. Geology of Utah's far south. Utah Geological Association Publication 43.

Dane, C. H., W. G. Pierce, and J. B. Reeside, Jr. 1937. The stratigraphy of the Upper Cretaceous rocks north of the Arkansas River in eastern Colorado. U.S. Geological Survey, Washington, D.C. Professional Paper 186-K. Available at http://pubs.er.usgs.gov/publication/pp186K (accessed January 2015).

DeGraw, H. M., and R. Pabian. 1980. Collecting in Nebraska's Cretaceous strata. Rocks and Minerals 55(3):97–102.

Dobrovolny, E., C. H. Summerson, and R. G. Bates. 1946. Geology of northwestern Quay County, New Mexico. U.S. Geological Survey, Washington, DC. Oil and Gas Investigation Map 62. Scale 1:62,500. Available at http://pubs.er.usgs.gov/publication/om62 (accessed January 2015).

Eicher, D. L. 1965a. Cretaceous tintinnids from the western interior of the United States. Micropaleontology 11(4):449–456.

Eicher, D. L. 1965b. Foraminifera and biostratigraphy of the Graneros Shale. Journal of Paleontology 39(5):875–909.

Elder, W. P., and J. I. Kirkland. 1993. Cretaceous paleogeography of the Colorado Plateau and adjacent areas. Museum of Northern Arizona Bulletin 59:129–151.

Elder, W. P., and J. I. Kirkland. 1994. Cretaceous paleogeography of the southern Western Interior region. Pages 415–440 in M. V. Caputo, J. A. Peterson, and K. J. Franczyk, editors. Mesozoic System of the Rocky Mountain region, USA. Rocky Mountain Section, Society for Sedimentary Geology, Denver, Colorado.

Everhart, M. J. 2007. New stratigraphic records (Albian-Campanian) of *Rhinobatos* sp. (Chondrichthyes, Rajiformes) from the Cretaceous of Kansas. Transactions of the Kansas Academy of Science 110(3–4):225–235.

Frye, J. C., A. B. Leonard, and H. D. Glass. 1978. Late Cenozoic sediments, molluscan faunas, and clay minerals in northeastern New Mexico. New Mexico Bureau of Geology & Mineral Resources, Socorro, New Mexico. Circular 160.

Gillette, D. D., and D. A. Thomas. 1985. Dinosaur tracks in the Dakota Formation (Aptian-Albian) at Clayton Lake State Park, Union County, New Mexico. Pages 283–288 in S. G. Lucas and J. Zidek, editors. Santa Rosa, Tucumcari Region. New Mexico Geological Society Guidebook 36. Available at http://nmgs.nmt.edu/publications/guidebooks/downloads/36/36_p0283_p0288.pdf (accessed January 2015).

Holliday, V. T. 2000. Folsom drought and episodic drying on the Southern High Plains from 10,900-10,200 ^{14}C yr B.P. Quaternary Research 53(1):1–12. Available at http://www.argonaut.arizona.edu/articles/holliday2000_2.pdf (accessed January 2015).

Hunt, A. P., and S. G. Lucas. 1998. Tetrapod ichnofaunas from the Lower Cretaceous of northeastern New Mexico, USA. New Mexico Museum of Natural History and Science Bulletin 14:163–167.

Johnson, R. B. 1974. Geologic map of the Fort Union Quadrangle, Mora County, New Mexico. U.S. Geological Survey, Washington, DC. Geologic Quadrangle Map 1164. Scale 1:24,000. Available at http://pubs.er.usgs.gov/publication/gq1164 (accessed January 2015).

Kauffman, E. G., J. D. Powell, and D. E. Hattin. 1969. Cenomanian-Turonian facies across the Raton Basin. The Mountain Geologist 6(3):93–118.

KellerLynn, K. 2012. Fort Union National Monument: geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2012/580. National Park Service, Fort Collins, Colorado. Available at www.nature.nps.gov/geology/inventory/publications/reports/foun_gri_rpt_view.pdf (accessed January 2015).

Kenworthy, J. P., and V. L. Santucci. 2006. A preliminary investigation of National Park Service paleontological resources in cultural resource contexts, Part 1: general overview. New Mexico Museum of Natural History and Science Bulletin 34:70–76. Available at http://nature.nps.gov/geology/paleontology/pub/fossil_conference_7/9%20Kenworthy.pdf (accessed December 2014).

Kiver, E. P., and D. V. Harris. 1999. Geology of U.S. parklands. 5th edition. John Wiley & Sons, Inc., New York, New York.

Koch, A. L., and V. L. Santucci. 2003. Fort Union National Monument. Pages 14–15 *in* A. L. Koch and V. L. Santucci. Paleontological resource inventory and monitoring: Southern Plains Network. TIC# D-107. National Park Service, Denver, Colorado.

Kues, B. S., and S. G. Lucas. 1987. Cretaceous stratigraphy and paleontology in the Dry Cimarron Valley, New Mexico, Colorado and Oklahoma. Pages 167–198 *in* S. G. Lucas and A. P. Hunt, editors. Northeastern New Mexico. New Mexico Geological Society, Socorro, New Mexico. Guidebook 38. Available at http://nmgs.nmt.edu/publications/guidebooks/downloads/38/38_p0167_p0198.pdf (accessed January 2015).

Kukihara, R., and M. G. Lockley. 2012. Fossil footprints from the Dakota Group (Cretaceous) John Martin Reservoir, Bent County, Colorado: new insights into the paleoecology of the Dinosaur Freeway. Cretaceous Research 33(1):165–182.

Lindline, J., S. Geil, H. Lara, and M. S. Petronis. 2011. Mineralogic study of mortar from Fort Union ruins, Mora County, New Mexico. New Mexico Geology 33(2):59–60.

Lockley, M. G., S. G. Lucas, and A. P. Hunt. 2000. Dinosaur tracksites in New Mexico: a review. New Mexico Museum of Natural History and Science Bulletin 17:9–16.

Lockley, M. G., M. Matsukawa, and D. Witt. 2006a. Giant theropod tracks from the Cretaceous Dakota Group of northeastern New Mexico. New Mexico Museum of Natural History and Science Bulletin 35:83–87.

Lockley, M. G., J. Holbrook, R. Kukihara, and M. Matsukawa. 2006b. An ankylosaur-dominated dinosaur tracksite in the Cretaceous Dakota Group of Colorado: paleoenvironmental and sequence stratigraphic context. New Mexico Museum of Natural History and Science Bulletin 35:95–106.

Lucas, S. G., and J. A. Effinger. 1991. *Mammuthus* from Lincoln County and a review of the mammoths from the Pleistocene of New Mexico. Pages 277–282 *in* J. M. Barker, B. S. Kues, G. S. Austin, and S. G. Lucas, editors. Geology of the Sierra Blanca, Sacramento and Capitan Ranges, New Mexico. New Mexico Geological Society, Socorro, New Mexico. Guidebook 42. Available at http://nmgs.nmt.edu/publications/guidebooks/downloads/42/42_p0277_p0282.pdf (accessed December 2014).

Lucas, S. G., A. P. Hunt, and K. K. Kietzke. 1989. Stratigraphy and age of Cretaceous dinosaur footprints in northeastern New Mexico and northwestern Oklahoma. Pages 217–221 *in* D. D. Gillette and M. G. Lockley, editors. Dinosaur tracks and traces. Cambridge University Press, Cambridge, United Kingdom.

Lucas, S. G., O. J. Anderson, and J. W. Estep. 1998. Stratigraphy and correlation of Middle Cretaceous rocks (Albian-Cenomanian) from the Colorado Plateau to the Southern High Plains, north-central New Mexico. New Mexico Museum of Natural History and Science Bulletin 14:57–66.

Lucas, S. G., A. B. Heckert, and R. M. Sullivan. 2000. Cretaceous dinosaurs in New Mexico. New Mexico Museum of Natural History and Science Bulletin 17:83–90.

Lucas, S. G., B. S. Kues, and A. P. Hunt. 2001. Cretaceous stratigraphy and biostratigraphy, east-central New Mexico. Pages 215–220 *in* S. G. Lucas and D. S. Ulmer-Scholle, editors. Geology of the Llano Estacado. New Mexico Geological Society, Socorro, New Mexico. Guidebook 52. Available at http://nmgs.nmt.edu/publications/guidebooks/downloads/52/52_p0215_p0220.pdf (accessed January 2015).

Magnani, M. B., K. C. Killer, A. Levander, and K. Karlstrom. 2004. The Yavapai-Mazatzal boundary: a long-lived tectonic element in the lithosphere of southwestern North America. Geological Society of America Bulletin 116(9–10):1137–1142.

Mateer, N. J. 1985. Pre-Graneros Cretaceous stratigraphy of northeastern New Mexico. Pages 243–246 in S. G. Lucas and J. Zidek, editors. Santa Rosa, Tucumcari Region. New Mexico Geological Society Guidebook 36. Available at

https://nmgs.nmt.edu/publications/guidebooks/downloads/36/36_p0243_p0246.pdf (accessed January 2015).

Mateer, N. J. 1987. The Dakota Group of northeastern New Mexico and southern Colorado. Pages 223–236 *in* S. G. Lucas and A. P. Hunt, editors. Northeastern New Mexico. New Mexico Geological Society, Socorro, New Mexico. Guidebook 38. Available at http://nmgs.nmt.edu/publications/guidebooks/downloads/38/38_p0223_p0236.pdf (accessed January 2015).

Matson, S. D., M. R. Voorhies, R. G. Corner, R. M. Joeckel, and B. Vrana. 2002. A new long-necked plesiosaur specimen from the Graneros Shale (Cretaceous, Cenomanian), Ponca State Park, Nebraska. Program and Proceedings - Nebraska Academy of Sciences 112:54–55.

Morgan, G. S., and S. G. Lucas. 2005a. Pleistocene vertebrates from Rio Arriba and Taos counties, northernmost New Mexico. Pages 416–424 *in* S. G. Lucas, K. E. Zeigler, V. W. Lueth, and D. E. Owen, editors. Geology of the Chama Basin. New Mexico Geological Society, Socorro, New Mexico. Guidebook 56. Available at http://nmgs.nmt.edu/publications/guidebooks/downloads/56/56_p0416_p0424.pdf (accessed January 2015).

Morgan, G. S., and S. G. Lucas. 2005b. Pleistocene vertebrate faunas in New Mexico from alluvial, fluvial, and lacustrine deposits. New Mexico Museum of Natural History and Science Bulletin 28:185–248.

Morgan, G. S., S. G. Lucas, P. L. Sealey, and A. P. Hunt. 2001. A review of Pleistocene vertebrate faunas from northeastern New Mexico. Pages 265–284 *in* S. G. Lucas and D. S. Ulmer-Scholle, editors. Geology of the Llano Estacado. New Mexico Geological Society, Socorro, New Mexico. Guidebook 52. Available at http://nmgs.nmt.edu/publications/guidebooks/downloads/52/52_p0265_p0284.pdf (accessed January 2015).

National Park Service, Geologic Resources Inventory Program. 2006b. Digital Geologic Map of Fort Union National Monument and Vicinity, New Mexico (NPS, GRD, GRE, FOUN). NPS Geologic Resources Inventory Program. Lakewood, Colorado. Geospatial Dataset-1040284. Available at https://irma.nps.gov/App/Reference/Profile/1040284 (accessed January 2015).

National Park Service. 2006a. Geologic resource evaluation scoping summary: Fort Union National Monument, New Mexico. National Park Service, Geologic Resources Division, Denver, Colorado. Available at www.nature.nps.gov/geology/inventory/publications/s_summaries/FOUN_scoping_summary_2006-0504.pdf (accessed January 2015).

Newberry, J. S. 1898. The later extinct floras of North America. U.S. Geological Survey, Washington, DC. Monograph 35. Available at https://archive.org/details/laterextinctflor00newb (accessed January 2015).

Olmsted, B. W., and W. C. McIntosh. 2004. $^{40}Ar/^{39}Ar$ geochronology of the Ocate volcanic field, northcentral New Mexico. Pages 297–308 *in* S. M. Cather, W. C. McIntosh, and S. A. Kelley, editors. Tectonics, geochronology, and volcanism in the Southern Rock Mountains and Rio Grande rift. New Mexico Bureau of Geology and Mineral Resources, Socorro, New Mexico. Bulletin 160.

Price, L. G. 2010. Fort Union National Monument. Pages 325–329 *in* Price, L. G., editor. The geology of northern New Mexico's parks, monuments, and public lands. New Mexico Bureau of Geology and Mineral Resources, Socorro, New Mexico.

Santucci, V. L., and A. L. Koch. 2003. Paleontological resource monitoring strategies for the National Park Service. Park Science 22(1):22–25. Available at http://www.nature.nps.gov/ParkScience/archive/PDF/ParkScience22%281%29Fall2003.pdf (accessed January 2015).

Santucci, V. L., J. P. Kenworthy, and A. L. Mims. 2009. Monitoring in situ paleontological resources. Pages 189–204 *in* R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado.

Sayre, W. O., and M. H. Ort. 2011. A geologic study of the Capulin Volcano National Monument and surrounding areas, Union and Colfax counties, New Mexico. New Mexico Bureau of Geology and Mineral Resources, Socorro, New Mexico. Open File Report 541. Available at http://geoinfo.nmt.edu/publications/openfile/details.cfml?Volume=541 (accessed January 2015).

Scott, R. W., J. M. Holbrook, F. E. Oboh-Ikuenobe, M. J. Evetts, D. G. Benson, and B. S. Kues. 2004. Middle Cretaceous stratigraphy, southern Western Interior Seaway, New Mexico and Oklahoma. Mountain Geologist 41(2):33–61.

Stormer, J. C., Jr. 1987. Capulin Mountain Volcano and the Raton-Clayton volcanic field, northeastern New Mexico Pages 421–424 *in* Beus, S., editor. Rocky Mountain section of the Geological Society of America. Geological Society of America, Boulder, Colorado. Centennial field guide.

Tweet, J., V. L. Santucci, J. P. Kenworthy, and A. L. Mims. 2009. Paleontological resource inventory and monitoring: Southern Colorado Plateau Network. Natural Resource Technical Report NPS/NRPC/NRTR—2009/245. TIC# D-59. National Park Service, Fort Collins, Colorado.

Witzke, B. J. 1981. Cretaceous vertebrate fossils of Iowa and nearby areas of Nebraska, South Dakota, and Minnesota. Pages 105–122 *in* R. L. Brenner, R. F. Bretz, B. J. Bunker, D. L. Iles, G. A. Ludvigson, R. M. McKay, D. L. Whitley, and B. J. Witzke, editors. 1981. Cretaceous stratigraphy and sedimentation in northwest Iowa, northeast Nebraska and southeast South Dakota. Iowa Geological Survey, Iowa City, Iowa. Guidebook Series 4. Available at http://s-iihr34.iihr.uiowa.edu/publications/uploads/gb-04.pdf (accessed January 2015).

Witzke, B. J., and G. A. Ludvigson. 1987. Cretaceous exposures, Big Sioux river valley north of Sioux City, Iowa. Pages 97–102 *in* D. L. Biggs, editor. North-central section of the Geological Society of America. Geological Society of America, Boulder, CO. Centennial Field Guide 3.

Witzke, B. J., and G. A. Ludvigson. 1994. The Dakota Formation in Iowa and the type area. Pages 43–78 in G. W. Shurr, G. A. Ludvigson, and R. H. Hammond, editors. Perspectives on the eastern margin of the Cretaceous Western Interior Basin. Geological Society of America, Boulder, CO. Special Paper 287.

Witzke, B. J., G. A. Ludvigson, J. R. Poppe, and R. L. Ravn. 1983. Cretaceous paleogeography along the eastern margin of the Western Interior Seaway, Iowa, southern Minnesota, and eastern Nebraska and South Dakota. Pages 225–252 *in* W. W. Reynolds, and E. D. Dolly, editors. Mesozoic paleogeography of west central United States. Rocky Mountain section of Society of Economic Paleontology, Denver, Colorado. Rocky Mountain Paleogeography Symposium 2.

Additional References

Baldridge, W. S. 2004. Geology of the American Southwest: a journey through two billion years of plate-tectonic history. Cambridge University Press, Cambridge, United Kingdom.

Bennett, S. C. 1992. Reinterpretation of problematical tracks at Clayton Lake State Park, New Mexico: not one pterosaur, but several crocodiles. Ichnos 1:37–42.

Dean, J. S., W. J. Robinson, and M. R. Rose. 1982. Dendroclimatic reconstructions for Arroyo Hondo, New Mexico: A.D. 900-1970. Program and Abstracts - American Quaternary Association. Conference 7:89.

Elias, S. A. 1997. The Ice Age history of southwestern National Parks. Smithsonian Institution Press, Washington, D.C.

Ellwood, B. B. 1996. Geology and America's National Park areas. Prentice Hall, Upper Saddle River, New Jersey.

Everhart, M. J. 2005. Oceans of Kansas: a natural history of the Western Interior Sea. Indiana University Press, Bloomington and Indianapolis, Indiana.

Gillette, D. D., and D. A. Thomas. 1989. Problematic tracks of late Albian (Early Cretaceous) age, Clayton Lake State Park, New Mexico, USA. Pages 337–342 *in* D. D. Gillette and M. G. Lockley, editors. Dinosaur tracks and traces. Cambridge University Press, Cambridge, United Kingdom.

Graham, R. W. 1987. Late Quaternary mammalian faunas and paleoenvironments of the southwestern Plains of the United States. Pages 24–86 *in* R. W. Graham, H. A. Semken, Jr., and M. A. Graham, editors. Late Quaternary mammalian biogeography and environments of the Great Plains and prairies. Illinois State Museum, Springfield, Illinois. Scientific Papers 22.

Harris, A. H. 1985. Late Pleistocene vertebrate paleoecology of the west. University of Texas Press, Austin, Texas.

Hay, O. P. 1924. The Pleistocene of the middle region of North America and its vertebrated animals. Carnegie Institute of Washington Publication 322A. Available at https://archive.org/details/pleistoceneofmid00hayo (accessed January 2015).

Hay, O. P. 1927. The Pleistocene of the western region of North America and its vertebrated animals. Carnegie Institute of Washington Publication 322B.

Holliday, V. T. 1997. Paleoindian geoarchaeology of the southern High Plains. University of Texas Press, Austin, Texas.

Hoppe, K. A. 2004. Late Pleistocene mammoth herd structure, migration patterns, and Clovis hunting strategies inferred from isotopic analyses of multiple death assemblages. Paleobiology 30(1):129–145.

Jelinek, A. J. 1969. Identification of mammalian fauna. Pages 127–133 *in* C. H. McNutt, editor. Early Puebloan occupations at Tesuque By-Pass and in the upper Rio Grande Valley. University of Michigan, Museum of Anthropology, Ann Arbor, Michigan. Anthropological Papers 40.

Lang, R. W., and A. H. Harris. 1984. The faunal remains from Arroyo Hondo Pueblo, New Mexico: a study in short-term subsistence change. School of American Research Press, Santa Fe, New Mexico. Arroyo Hondo Archaeological Series 5.

Lessard, R. H. 1976. First day road log from Las Vegas to Raton via Montezuma, Sapello, La Cueva (and vicinity) Ocate, Wagon Mound and Springer. Pages 1–23 *in* R. C. Ewing and B. S. Kues, editors. Vermejo Park. New Mexico Geological Society, Socorro, New Mexico. Guidebook 27.

Mayor, A. 2005. Fossil legends of the first Americans. Princeton University Press, Princeton, New Jersey.

McNutt, C. H. 1969. Early Puebloan occupations at Tesuque By-Pass and in the upper Rio Grande Valley. University of Michigan, Museum of Anthropology, Ann Arbor, Michigan. Anthropological Papers 40.

Olsen, S. J. 1971. Zooarchaeology: animal bones in archaeology and their interpretation. Addison-Wesley Publishing Company, New York City, New York.

Wisniewski, P. A., and F. J. Pazzaglia. 2002. Epeirogenic controls on Canadian River incision and landscape evolution, Great Plains of northeastern New Mexico. Journal of Geology 110(4):437–456.

Data Sets

Fort Union National Monument Paleontological Archives

5/1985–present. (hard copy data; reports; electronic data; photographs; maps; publications). Originated by Santucci, Vincent; status: Active.

Fort Union National Monument Digital Geologic Map
2006–present. (geologic map data; electronic files; GIS metadata; associated report). Originated by NPS-Geologic Resources Inventory staff; status: Active. Online. https://irma.nps.gov/App/Reference/Profile/1040284.

Lyndon B. Johnson National Historical Park

Lyndon B. Johnson National Historical Park (LYJO) preserves a number of structures related to Lyndon B. Johnson, the 36th President of the United States. Among them are his reconstructed birthplace, boyhood home, and ranch, his grandparents' log cabin, and the Johnson family cemetery. LYJO is composed of two units, the Johnson City District in Johnson City and the LBJ Ranch District near Stonewall, Texas, approximately halfway between Fredericksburg and Johnson City on U.S. Route 290. The Johnson City District includes the Visitor Center, Johnson's boyhood home, and several historic structures related to the Johnson family. The LBJ Ranch District includes the Johnson ranch, also known as the Texas White House for the President's frequent use of the site during his administration. LYJO was authorized as a national historic site December 2, 1969, and redesignated a national historical park December 28, 1980. The historical park encompasses 635.42 ha (1,570.15 acres), 272.84 ha (674.20 acres) of which are federal.

Geologic Background

LYJO is located in central Texas; the Johnson City District is in central Blanco County, and the LBJ Ranch District is about 18 km (11 mi) to the west in eastern Gillespie County. The Johnson City District is on the southwest side of Johnson City, founded by the president's uncle James Polk Johnson. The LBJ Ranch District is on the east side of the community of Stonewall, and north of the adjacent Lyndon B. Johnson State Park. For the most part, the Pedernales River (LYJO Figure 1) separates the national historical park from the state park, although a small portion of the LBJ Ranch District is south of the river. Fredericksburg is about 21 km (13 mi) west of the LBJ Ranch District. The city of Austin is about 64 km (40 mi) east of Johnson City, and San Antonio is about 95 km (60 mi) south of Johnson City. In terms of physiography, LYJO is on the south side of the Llano Uplift, in the eastern part of the Edwards Plateau (Thornberry-Ehrlich 2008). Publications describing the geology and paleontology of LYJO and its immediate surroundings include Jones (1929), Barnes et al. (1963), Barnes (1964, 1965a, 1965b, 1967), Koch and Santucci (2003), NPS (2003, 2008), Nordt (2003), and Thornberry-Ehrlich (2008). The NPS Geologic Resources Division coordinated a Geologic Resource Evaluation scoping meeting for LYJO in May 2003 (NPS 2003), and produced a digital map of the historical park in 2008 (NPS 2008). A geologic resources inventory report was prepared for the historical site in 2008 (Thornberry-Ehrlich 2008). Koch and Santucci (2003) prepared the original paleontologic resource inventory and summary for LYJO.

Geologic units near the surface or exposed at LYJO were deposited during the Late Cambrian–Early Ordovician (about 490 Ma, or million years ago), Early Cretaceous (about 115 Ma), and the Quaternary (2.6 Ma to the present) (see the Appendix for a geologic time scale). Because of the presence of the ancient Llano Uplift nearby, relatively few formations have been deposited in this area. The Llano Uplift is composed of a complex assortment of metamorphosed sedimentary and volcanic rocks, and younger igneous intrusions (Jensen 1980; Barnes 1988). The metamorphosed volcanic and sedimentary rocks appear to have been part of a volcanic island arc that existed over a billion years ago (Barnes 1988). A major continental collision around this time caused a mountain-building event along the eastern and southern margin of North America, known as the Grenville

Orogeny. The Llano Uplift appears to be related to this event, with deformation peaking around 1167 Ma and persisting for tens of millions of years (Carter 1989; Nelis et al. 1989).



LYJO Figure 1. The Pedernales River at the LBJ Ranch District. Cambrian and Cretaceous rocks crop out in the vicinity of the river in this area (LYJO/NPS).

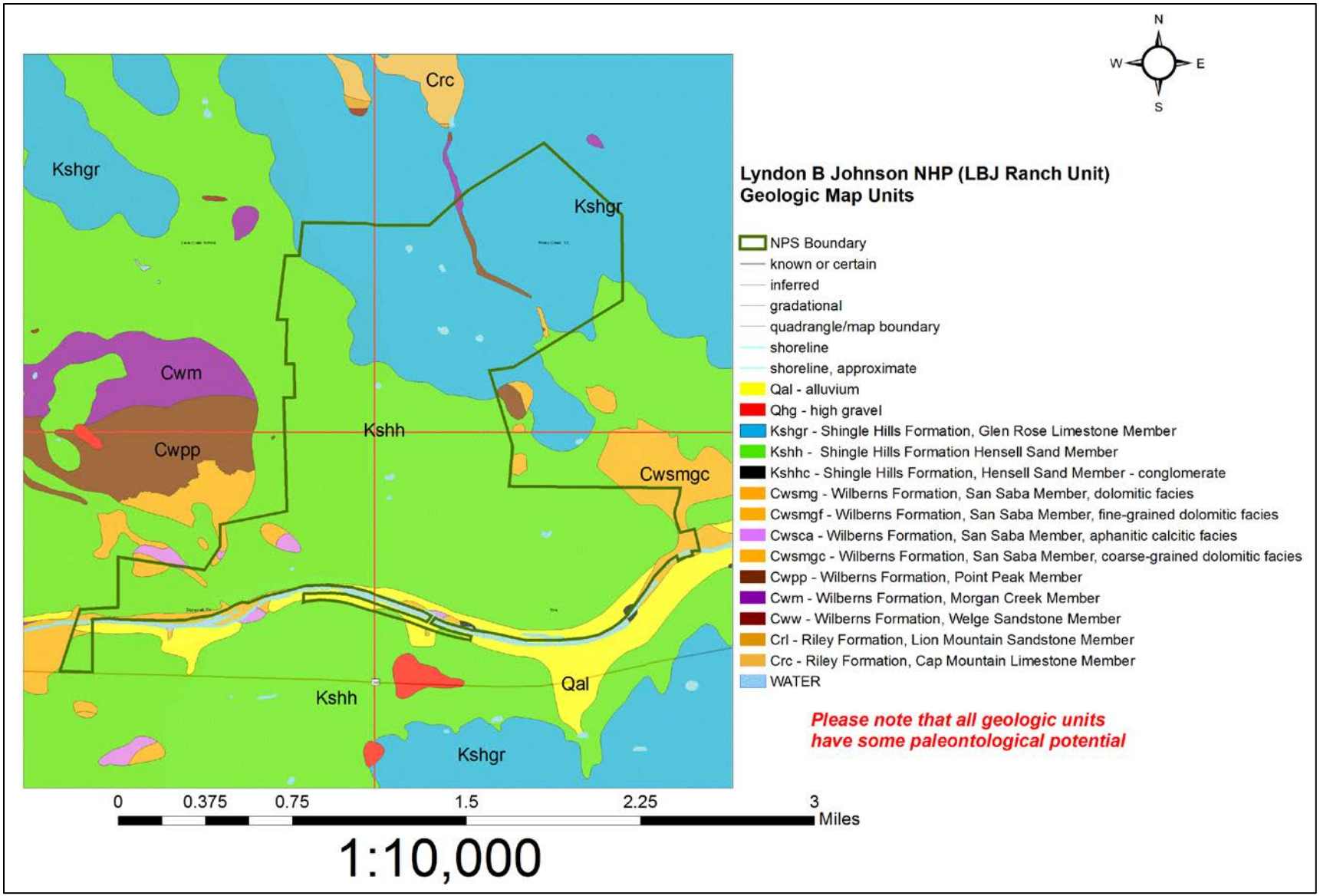
The oldest formation mapped at LYJO, the Wilberns Formation, was deposited near the end of the Cambrian. It represents the third and final sub-cycle of one of the great marine transgression-regression (advance-retreat) cycles of the Paleozoic of North America, known as the Sauk Cycle (Rowland and Shapiro 2002). At this time, central Texas was south of the equator, with winds from the southeast (Ruppel and Kerans 1987; Rowland and Shapiro 2002). Deeper basins existed on the north, south, and east (Ruppel and Kerans 1987). The climate was semi-arid to arid (Chafetz 1980), and the marine waters were slightly more saline than typical modern marine water (Johnson and Goldstein 1993). Microbial reefs formed to the west of LYJO (Watson 1980). Late in the Cambrian or early in the Ordovician, the sea retreated, ending deposition of the Wilberns Formation. Eventually the sea returned and additional Lower Paleozoic marine rocks were deposited (Freed 1986), but they are not seen at LYJO.

There is little direct evidence of geologic events in or near LYJO for several hundred million years after the deposition of the Wilberns Formation, until another time of significant marine encroachment and deposition began during the Cretaceous, about 120 Ma. This episode of deposition produced the Hensel and Glen Rose formations of LYJO. The sea approached from the south (Pittman 1989). As it advanced, depositional environments in central Texas shifted from valleys, to rivers, to low-gradient coastal plains, to tidal flats and lagoons, and finally to shallow marine (Payne and Scott 1982). The climate was semi-arid and seasonal (Payne and Scott 1982), and transitioned from relatively cool to warmer, arid conditions as central Texas moved through arid latitudes (25° N) (White et al. 2009). After the sea reached central Texas, its position oscillated, leading to cycles of transgression and regression during the overall marine advance (Smith and Rader 2009). The Llano Uplift is reconstructed as projecting out from the coast into the advancing sea (Pittman 1990). The uplift formed the landward boundary of the marine shelf during the Cretaceous deposition, and was occasionally a source of sediment as well. To the southeast was an early version of the Gulf of Mexico (Bay and Bebout 1983). Marine deposition continued for tens of millions of years in the area

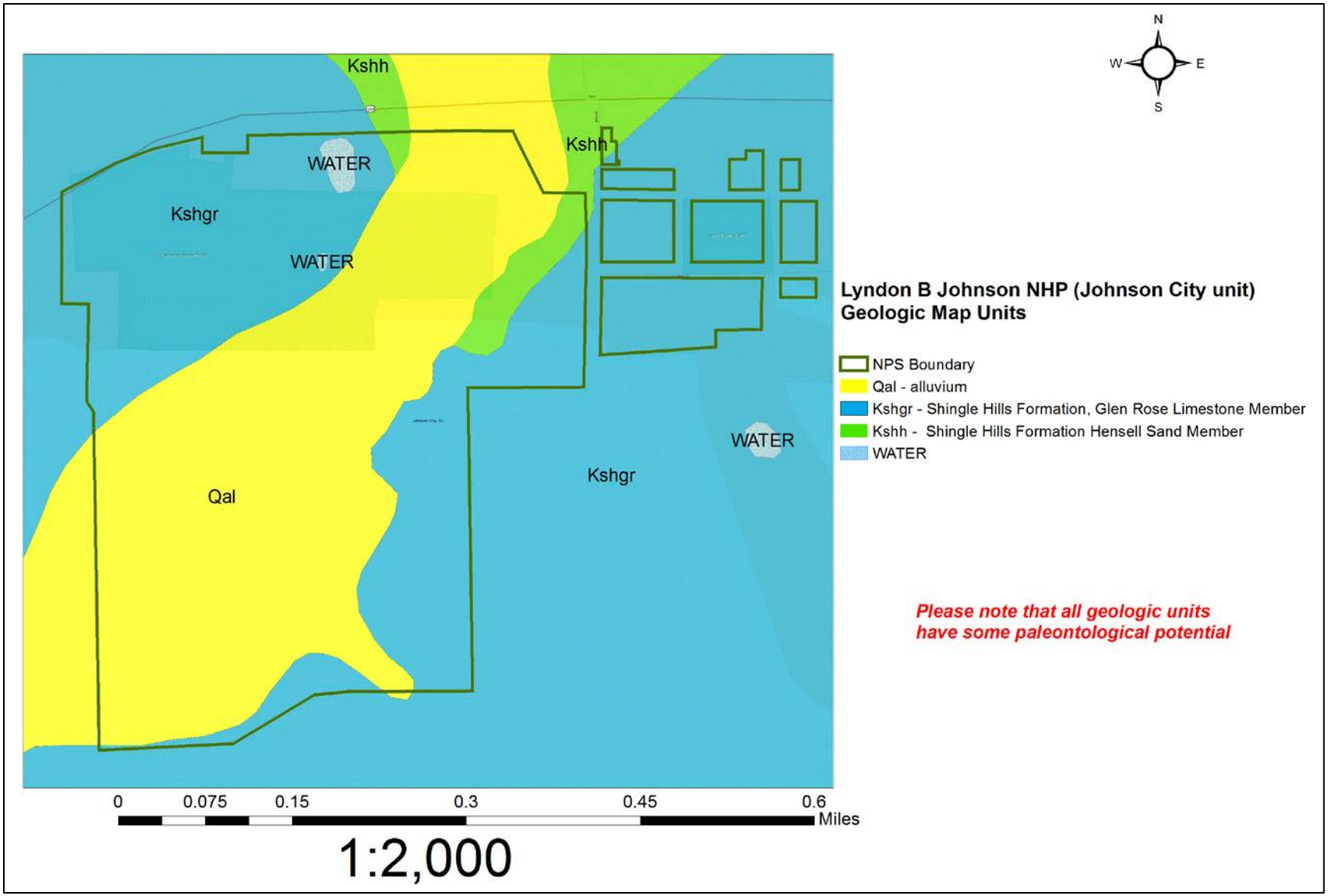
after the deposition of the Glen Rose Formation, although it is not recorded at LYJO. Around 80 Ma, a group of at least 60 volcanic centers, known as the Balcones Igneous Province, was active in central Texas from southwest of Uvalde to northeast of Austin. At least some of these were primarily submarine volcanoes (Barker and Younger 1979).

Following the Cretaceous, another depositional hiatus occurred in central Texas, persisting until the Quaternary. The past 25,000 years are documented in the Edwards Plateau by a series of caves and the fossils found within them. The climate at the end of the Pleistocene was wetter, and possibly cooler overall or with less extreme summers (Patton 1963). It is thought that the jet stream was detouring far to the south because of the continental ice sheets, increasing precipitation in central Texas (Musgrove et al. 2001). The Edwards Plateau is interpreted as a grassland with pines and deciduous trees in canyons and near rivers (Hall and Valastro 1995). During the latest part of the Pleistocene, a great deal of soil was lost from central Texas, possibly as a result of increased aridity, seasonality, and/or intensity of precipitation (Cooke et al. 2003). Temperatures have increased and precipitation has decreased during the Holocene, with a particularly dry period between about 8,500 and 6,000 years ago (Ellwood and Gose 2006). Humans have been present in the Edwards Plateau since at least the end of the Pleistocene (Holliday 1992).

Geologic units present at or near the surface within LYJO include several members of the Wilberns Formation (Upper Cambrian–Lower Ordovician?), the Hensel Sand and Glen Rose Formation (Lower Cretaceous), and Quaternary sediments (Pleistocene–Holocene) (Barnes et al. 1963; Barnes 1964, 1965a, 1965b; Nordt 2003; NPS 2008) (LYJO Figure 2, 3). The original maps and GRI digital maps identify the Cretaceous units as the Hensell Sand and Glen Rose Limestone members of the Shingle Hills Formation, but that is not followed here because they are almost universally known as the Hensel Sand (or Formation) and the Glen Rose Formation (or Limestone). Fossils have not yet been reported from any of the geologic units at LYJO, although they all have the potential to yield fossils (LYJO Table 1), and some have produced fossils within a few miles of the historical park. Several fossil localities are depicted as blue dots on the digital map, taken from the original Barnes maps. Although geologic maps have been produced for all of the topographic quadrangles containing LYJO, the first author (Tweet) has some concern that historical circumstances may have prevented thorough exploration of the land now in the LBJ Ranch District of LYJO. The quadrangle maps were all produced during the 1960s, when Johnson was Vice President and later President, and not only did Johnson frequently visit his ranch, but he came to the presidency after the assassination of John F. Kennedy.



LYJO Figure 2. Schematic geologic map of the LBJ Ranch District of LYJO. Map graphic adapted from digital geologic map data available at the following URL: https://irma.nps.gov/App/Reference/Profile/1045532.



LYJO Figure 3. Schematic geologic map of the Johnson City District of LYJO. Map graphic adapted from digital geologic map data available at the following URL: https://irma.nps.gov/App/Reference/Profile/1045532.

LYJO Table 1. Summary of LYJO stratigraphy, fossils, and depositional settings in descending order of age, from youngest to oldest. Details and references can be found in the text.

Formation	Age	Fossils Within LYJO	Depositional Environment
Quaternary sediments	Pleistocene–Holocene	None to date; isolated bones of mammoths, mastodons, horses, or bison are most likely	Associated with the Pedernales River
Glen Rose Formation	Early Cretaceous	None to date; marine invertebrates are most likely	Shallow marine
Hensel Sand	Early Cretaceous	None to date; root traces, bivalves, and gastropods are most likely	Transition from fluvial and coastal plain to very shallow marine
Wilberns Formation	Late Cambrian–Early Ordovician?	None to date; stromatolites and other microbial structures, brachiopods, and trilobites are most likely	Shallow coastal marine

Potential Sources of Paleontological Resources

Fossils have not yet been documented from the following geologic units within LYJO. However, they are known to preserve fossils elsewhere, and future field investigations within the historical park may result in the discovery of fossils in one or more of them.

Wilberns Formation (Upper Cambrian–Lower Ordovician?)

The Wilberns Formation is a mixed geologic unit primarily composed of dolomite and limestone, with lesser amounts of sandstone, siltstone, and shale. The formation is divisible into four members, in ascending order the Welge Sandstone, Morgan Creek Limestone, Point Peak, and San Saba members. A fifth member, the Pedernales Dolomite Member, is now considered to be part of the San Saba Member (Watson 1980). The Welge Sandstone Member is not exposed in LYJO, but the other three members are mapped in the LBJ Ranch District of the historical park. Most of the mapped Wilberns Formation is a coarse dolomitic facies of the San Saba Member, present in several areas of the southern part of the district, but small areas of the Morgan Creek Limestone and Point Peak members are mapped in the northern part of the district (NPS 2008). In the Llano Uplift area, the Morgan Creek Limestone grades out of the underlying Welge Sandstone Member, and is composed primarily of green-gray to olive-gray limestone, 34.7 to 43.6 m (114 to 143 ft) thick. The Point Peak Member is composed of siltstone and limestone with minor shale, averaging 46 m (150 ft) thick. It sometimes grades into the overlying San Saba Member, which is composed of limestone and dolomite with chert (the former Pedernales Dolomite) and can be as thick as 140 m (450 ft) in the Johnson City area (Watson 1980). The San Saba Member is sandier in the west, and the carbonate in the west has not been as strongly affected by dolomitization as in the east, so there is more limestone in the west (Winston and Nicholls 1967).

As noted in the Geologic Background, the Wilberns Formation represents a sub-cycle of a major marine transgression-regression cycle (Rowland and Shapiro 2002). Another sub-cycle ended shortly before the beginning of Wilberns Formation deposition, and most areas had a depositional hiatus between the underlying rocks and the Wilberns Formation. Overall, the Wilberns Formation represents one transgression and regression cycle, with the initial marine incursion represented by the

Welge Sandstone, followed by deepening water and eventually a retreat, with shoaling conditions in the upper San Saba Member (Ruppel and Kerans 1987). Depositional settings range from intertidal to deeper subtidal and shelf, with no terrestrial deposition (Chafetz 1980). During the deposition of the upper Point Peak and San Saba members, stromatolitic reefs were present west of LYJO, going north-south and separating sandy deposition on the west from purer carbonate (limestone/dolomite) deposition on the east (Watson 1980). Reefs covered an area of as much as 25 km^2 (10 mi^2) of nearby Mason County (Droxler et al. 2014). Deposition of the Wilberns Formation occurred during the Late Cambrian and perhaps the Early Ordovician; the faunal stages cited by Miller et al. (2012) extend into the Early Ordovician, but the biostratigraphy of the Cambrian–Ordovician boundary has been problematic. The biostratigraphic zones of the lower Wilberns Formation cited by Miller et al. (2012) are approximately 494.5 to 491 million years old.

The Wilberns Formation is not known to be fossiliferous within LYJO, but there is great potential for the discovery of fossils within the LBJ Ranch District of the historical park, judging by finds in the area (Jones 1929; Barnes 1964, 1965a, 1965b, 1967). Generally speaking, the most common fossils visible to the naked eye in the Wilberns Formation are brachiopods, trilobites, and microbial structures such as stromatolites (layered microbial mats formed by the trapping of sediment). Brachiopods and trilobites are probably much more obvious to the eye, but the microbial structures can cover large areas, as noted above. Reefs and other biological structures are among the more notable features of the formation, present in all of the members except the Welge Sandstone Member (Ahr 1988; Johns et al. 2007). The nomenclature and definition of the structures are complicated, given that they include multiple types of organisms and take on different forms (Ruppel and Kerans 1987). Among the constituents of the various structures are cyanobacteria (“blue-green algae”), calcareous algae, sponges, eocrinoids (an extinct group of stalked echinoderm superficially similar to crinoids [sea lilies]), and fragments of cyanobacterial sheaths (Ruppel and Kerans 1987; Ahr 1971, 1988; Johns et al. 2007). A common combination consists of sponges, microbial remains, and eocrinoids in the lower part of a reef, and stromatolites in the upper part (Johns et al. 2007). Reef structures range from patch reefs 0.5 to 10 m (2 to 33 ft) across and 1 m (3 ft) tall, to barrier reefs 25 m (82 ft) thick (Johns et al. 2007).

The Wilberns Formation has a broadly typical Upper Cambrian shallow-marine faunal assemblage outside of the biological structures. The Welge Sandstone Member has few fossils (Watson 1980), although trilobites have been reported (Wilson 1933). All of the other members include brachiopods (lamp shells) and trilobites. In the Morgan Creek Member, trilobites are found throughout, brachiopods are found in the upper half, and stromatolites are found in the upper third (Watson 1980). The Point Peak Member has few body fossils except for brachiopods (Barnes 1965b). Unusual sponge spicules (Rigby 1975), trilobites, and crinoids and other stalked echinoderms have also been reported (Ruppel and Kerans 1987). The San Saba Member has few fossils except for reef and other biogenic structures, trilobites, and burrows (Ruppel and Kerans 1987); some brachiopods, gastropods, and gastropod-like mollusks are also present (Barnes et al. 1963). Stromatolites are most common in the western part of the formation, where dolomite is more common (Watson 1980). Body fossils are found in chert nodules in the dolomite (Winston and Nicholls 1967). Most body fossils are found in the chert of the dolomitic rocks (Barnes 1964). Other fossils from the Wilberns Formation,

not assigned to a member, include limpet-like monoplacophoran mollusks (Bell and Ellinwood 1962), aglaspidids (extinct arthropods that resembled a cross between a trilobite and a horseshoe crab), possible worms, graptolites (passively floating or attached colonial animals) (Decker 1944), and conodonts (eel-like extinct animals within or closely related to Vertebrata) (Miller 1987).

Hensel Sand (Lower Cretaceous)

The Hensel Sand is a heterogeneous unit. In the Llano Uplift area, this unit is composed of conglomerate, sand, silt, clay, and dolomitic limestone, and is 12 to 30 m (40 to 100 ft) thick (Brown 1980), as much as 40 m (130 ft) thick in the Stonewall 7.5 minute quadrangle (Barnes 1965b). The basal part is conglomeratic, and the unit becomes finer-grained progressing upward in the sedimentary sequence (Barnes 1965b). It is mostly red and gray in color, and forms gentle slopes (Barnes 1964). The upper contact with the Glen Rose Formation is gradational, with interbedding of the two formations reported. As the sea encroached upon the area from the southeast, marine life also spread, and terrestrial input decreased, which can be seen in the beds near the contact (Amsbury 1996a, 1996b). The Hensel Sand is mapped as the bedrock unit nearest the surface for the southern two-thirds of the LBJ Ranch District of LYJO and smaller areas of the central Johnson City District (NPS 2008).

The Hensel Sand is the lower part of a marine transgression which continued into the overlying Glen Rose Formation (Scott et al. 2007a). This cycle is itself part of a larger cycle (Smith and Rader 2009). Early deposition filled valleys; fluvial deposition followed. As the sea approached and the gradient decreased, fine-grained coastal plain deposits were laid down, succeeded by deposits from tidal flats and lagoons, and eventually marine carbonates of the Glen Rose Formation (Payne and Scott 1982). The Hensel Sand was deposited during the late Early Cretaceous, although because it is not as fossiliferous as the Glen Rose Formation, its age is not as constrained. Deposition may have begun around 118 Ma (Scott et al. 2007b). The Glen Rose Formation was deposited between about 113.3 to 108.0 Ma (Scott et al. 2007a), so the end of Hensel Sand deposition must predate this.

The Hensel Sand is not known to be fossiliferous in LYJO. For the most part, fossils are uncommon in the lower Hensel Sand, although root traces are present (Payne and Scott 1982), and there are some lenses of limestone with fragments of mollusks and ostracodes (Amsbury 1996a). Most fossils are found near the top of the unit, showing the influence of the approaching sea. They include foraminifera (“amoebas with shells”) (Jones and Kullman 1997), bivalves, gastropods, crabs (Scott et al. 2007b), ostracodes (seed shrimp) (Jones and Kullman 1997), echinoids (sea urchins), ophiuroids (brittle stars), and burrows and bioturbation (Scott et al. 2007b). Burrows in the upper part of the formation can include a variety of microscopic remains, including fecal pellets and fragments of foraminifera, bryozoans (moss animals), bivalves, echinoids, and ophiuroids (Amsbury 1996a, 1996b). Bivalves and gastropods have been reported from the LYJO area (Barnes 1965b). Fossils of terrestrial organisms are rare except for root traces, although there is one site with tracks of ornithopod dinosaurs (beaked, bipedal herbivores) (Pittman 1989).

Glen Rose Formation (Lower Cretaceous)

The Glen Rose Formation is mapped as the bedrock unit nearest the surface in the northern and northeastern parts of the LBJ Ranch District of LYJO, and the majority of the Johnson City District

(NPS 2008). The Glen Rose Formation of the LYJO area is composed of alternating beds with various combinations of dolomite, limestone, clay, silt, and sand. Some of these beds are much more resistant to erosion than others, so the Glen Rose Formation weathers into a characteristic "stair-step" topography (Barnes 1965b). The geologic unit is on the order of 82 m (270 ft) (Barnes 1965b) to 110 m (350 ft) thick (Barnes 1964) in the LYJO area. Lithologies vary greatly over short distances, both vertically and horizontally (Rodgers 1964), indicating diverse depositional environments and processes. Typically, the Glen Rose Formation is found to consist of upper and lower members, separated by a widespread marker bed known as the *Corbula* bed because of the abundant fossils of tiny bivalves (Scott et al. 2007a). The namesake bivalve was formerly known as *Corbula martinae*, but the taxonomy has changed over time, with the most recent designation being *Eoursivivas harveyi* (Scott 2007). The *Corbula* bed is mapped, at least in part, in the LYJO area, but is not depicted in either of the historical park's districts. It is mapped south of the Johnson City District and is not mapped on the north side of the Pedernales River in the vicinity of the LBJ Ranch District (NPS 2008). This strongly implies that only the lower part of the Glen Rose Formation is present in the Johnson City District, but a similar assumption cannot be made for the LBJ Ranch District; in fact, the *Corbula* bed is depicted near the contact with the Hensel Sand on the south side of the Pedernales River (NPS 2008), so a simple mirror-image extrapolation would suggest that the *Corbula* bed should be present in LYJO. If the bed is present, then the Glen Rose Formation would be fossiliferous within LYJO.

The Glen Rose Formation is primarily a shallow-marine formation. The basic setting was a broad, flat, marginal shelf (Rodgers 1964). Multiple smaller transgression-regression cycles occurred during a larger cycle that began in the underlying Hensel Sand and continued into overlying rocks. Two sub-cycles are attributed to the lower part of the Glen Rose Formation and as many as four are seen in the upper part (Smith and Rader 2009). During the cycles, sea level would fall, and deposition would shift from open marine to lagoonal and other very shallow settings (Bay and Bebout 1983). Prominent accumulations of rudist bivalve and coral fossils, sometimes described as reefs, formed east and south of LYJO. Stromatolites and dinosaur tracks are sometimes found at the tops of these biostromes (Perkins 1985; Scott et al. 2007a). The overall environment has been compared to the White Bank sand shoal of south Florida, albeit larger (Bay and Bebout 1983). The climate has been interpreted as subtropical (Stead 1951) and semi-arid (Winkler et al. 1990), and the sea was generally of normal marine salinity, becoming brackish or hypersaline at times and in certain areas (Rodgers 1964). Deposition of the Glen Rose Formation occurred from about 113.3 to 108.0 Ma (Scott et al. 2007a).

The Glen Rose Formation is not known to be fossiliferous at LYJO, although it has good potential because of the abundance of fossils elsewhere. A survey of the literature indicates that the most commonly mentioned fossils are probably foraminifera, corals, bivalves, gastropods, worm tubes, ostracodes, echinoids, and dinosaur tracks. Fossils reported from the immediate vicinity of LYJO include the possible alga *Porocystis* (globular dimpled fossils), bivalves, gastropods, tubes of serpulid worms, echinoids, and borings (Barnes 1964, 1965b). Common fossils from the lower part of the Glen Rose Formation, the part of the formation expected in the Johnson City District of LYJO, include foraminifera, *Porocystis*, bivalves, ammonites, gastropods, echinoids, pellets, burrows, and

stromatolites (Amsbury 1988). Rudist bivalve and coral “reefs” are well-developed (Scott et al. 2007a).

Marine invertebrates and microfossils are the most common and diverse Glen Rose fossils. Some groups that have been described in publications more or less devoted to them include foraminifera (Applin et al. 1950; Stead 1951; Conkin and Conkin 1956), cysts of dinoflagellates (a type of plankton that moves with whip-like flagella) (Kessler 1968), corals (Scott et al. 2007a), brachiopods (Ager 1964), bivalves (Stanton 1947; Whitney 1952; Scott 2007), ammonites (Young 1974; Kennedy et al. 1998), gastropods (Stanton 1947), horseshoe crabs (Feldmann et al. 2011), decapod crustaceans including hermit crabs, crabs, and mud shrimp (Bishop 1983), crinoids (Peck and Watkins 1972), and echinoids (Whitney and Kellum 1966; Smith and Rader 2009). Other marine fossils, either rare or more commonly mentioned in passing, include *Porocystis* (Barnes 1964), various other forms of algae, stromatoporoid sponges (Bay and Bebout 1983), bryozoans (Rodgers 1964), serpulid worms, ostracodes (Ward and Ward 2007), and holothurians (sea cucumbers) (Stead 1951; Ward and Ward 2007). Marine trace fossils include stromatolites (Ward and Ward 2007), invertebrate burrows (Blair et al. 2012), fecal pellets (Behrens 1965), and gastropod drill holes on ostracodes (Maddocks 1998). Specific depositional settings have characteristics assemblages of marine fossils, which can show areas of open marine, shoal water, reef, and lagoon deposition (Bay and Bebout 1983).

Although marine fossils are more abundant, the most famous Glen Rose Formation fossils are dinosaur tracks. Tracks have been reported since the early 20th century (Shuler 1917). Several types are recognized, including tracks of carnivorous theropod dinosaurs (narrow and three-toed), ponderous sauropod dinosaurs, and rare ornithopod dinosaurs (wide and three-toed). Tracks are most abundant near the top of the Glen Rose Formation and below the *Corbula* bed. Most tracks are from supratidal or intertidal coastal settings (Pittman 1989). The historic interpretation of the tracks is that the animals were swimming or at least wading (Bird 1944), but more recent interpretation indicates that many tracks are not the actual footprints but are underprints, indirect impressions of the feet in layers beneath the original surface (Lockley and Rice 1990). Among the tracks are elongate specimens that resemble human tracks, but were actually made by theropods moving in crouched stances and leaving metatarsal impressions (Kuban 1989; Farlow et al. 2013), and a famous set of tracks described as a chase (Falkingham et al. 2014). Other vertebrate trace fossils include possible turtle traces (Wright and Farlow 2004), disputed pterosaur tracks (Murry et al. 1991), and an egg of a crocodile or close relative (Rogers 2001). One notable area of tracks, near Glen Rose in Somervell County about 230 km (140 mi) northeast of Johnson City, is now protected as Dinosaur Valley State Park, a U.S. National Natural Landmark since 1968.

Vertebrate body fossils include fragmentary remains (teeth, scales, isolated bones, etc.) of rays, sharks, and several types of bony fish (Winkler et al. 1990; Rogers 2003), turtles (Vineyard 2009), at least two crocodilians or crocodile relatives, including *Pachycheilosuchus* (Rogers 2003), the pterosaur *Radiodactylus* (Andres and Myers 2013), a theropod tooth (Rogers 2001), and partial remains of sauropods (Tidwell and Carpenter 2003). Finally, plants are represented by fern spores, pollen of conifers, gnetaleans, and angiosperms (Kessler 1968), wood fragments, pieces of stems (Rogers 2001), the horsetail *Equisetites*, which is common in a “plant bed” southeast of the LYJO

area (Perkins 1985), cycadeoids, conifers, fossil cones of uncertain origin (Watson and Fisher 1984), and root casts (Kessler 1968).

Quaternary rocks and sediments (Pleistocene–Holocene)

Alluvium and colluvium from the recent geologic past are present in various areas of LYJO, especially near the Pedernales River and in the central Johnson City District (NPS 2008). Fossils have not yet been reported from LYJO's Quaternary deposits, but similar deposits have yielded fossils within about 100 km (60 mi) of the historical park. Useful online paleontological resources for this area include the Neotoma paleoecology database (http://www.neotomadb.org/), and Faunmap, which is the vertebrate element of Neotoma (http://www.ucmp.berkeley.edu/faunmap/).

The best-known Quaternary fossils from central Texas are Late Pleistocene and Holocene vertebrates from caves that formed in the underlying Cretaceous limestones. Including one older Pleistocene site, there are at least 37 such cave sites in the Edwards Plateau (Lundelius 2013), and the abundance of cave sites drove the creation of the database that became Faunmap (Lundelius 2003). About half of these sites are within the 100 km radius of LYJO (Lundelius 2003). Most of the caves formed in limestone of the Edwards and Georgetown formations (Lundelius 2013), which are not present beneath LYJO, reducing the probability of finding a cave site within the historical park. There are three major types of vertebrates in these caves: extinct Late Pleistocene forms, such as sloths, saber-toothed cats, mammoths, mastodons, horses, tapirs, peccaries, camels, llamas, and extinct species of bison; extant species which are only found to the north today, including various shrews, rodents, and mustelids; and forms that still live in central Texas today, including various rodents, rabbits, bats, coyotes, skunks, and deer (Lundelius 1967). The nearest sites are Levi Shelter, about 35 km (22 mi) east-northeast of Johnson City, and Cave Without a Name, about 44 km (27 mi) due south of the LBJ Ranch District. Levi Shelter, a rock shelter instead of a fully enclosed cave, is a Paleoindian campsite on a tributary to the Pedernales River. Bone and stone artifacts and remains of bivalves, gastropods, fish, snakes, lizards, insectivores, rodents, rabbits, canids (including dire wolf fossils), felids, skunks, raccoons, horses, tapirs, peccaries, pronghorns, deer, and bison were found here (Alexander 1963). Accumulation of bones at the site began before 10,000 ± 175 radiocarbon years before present (12,170 to 11,090 calibrated years before present) and continued beyond 6,750 ± 150 radiocarbon years before present (7,880 to 7,420 calibrated years before present) (Lundelius 1967). (Note that radiocarbon dates are not the same as calendar dates, and must be calibrated to approximate calendar years. Dates can be calibrated using a calibration program such as Calib 7.1 [http://calib.qub.ac.uk/calib/] if error ranges are provided. "Present" in "before present" is 1950.)

Cave Without A Name yielded an assemblage of frogs, salamanders, turtles, lizards, snakes (Holman 1969), moles, shrews, armadillos, rodents, rabbits, bats, canids, felids, bears, raccoons, mustelids, skunks, mastodons, horses, deer, bison, and indeterminate artiodactyls (odd-toed ungulates) (Lundelius 1967). The fossils here go back to at least 10,980 ± 190 radiocarbon years before present (13,230 to 12,560 calibrated years before present) (Holman 1969). The most famous of these cave sites is perhaps Friesenhahn Cave, about 80 km (50 mi) south-southeast of the LBJ Ranch District. Friesenhahn Cave includes diverse Late Pleistocene fossils, but is best-known for abundant remains of the "scimitar cat" *Homotherium* and juvenile mammoths, leading to the hypothesis that the cats

used the cave as a den and brought in prey (the mammoths) (Graham et al. 2013). Aside from late Quaternary vertebrates, a number of climatological and ecological proxies have been studied from the caves, including sediments (Cooke et al. 2003; Ellwood and Gose 2006), speleothems (various cave structures such as stalagmites and stalactites) (Musgrove et al. 2001), and pollen (Hall and Valastro 1995). Other Quaternary fossils and types of fossil-bearing deposits, such as snails and isolated vertebrate remains in fluvial settings, have not received the same extensive coverage as cave fossils in central Texas, although that is probably a reflection of the strength of the cave record. Per Hay (1924), there are numerous examples of isolated bones of mastodons, mammoths, horses, and bison within 100 km (60 mi) of LYJO, with 10 such occurrences just of mastodons. Very few of Hay's sites are within Blanco or Gillespie counties, though. Given what is known about the distribution of caves, isolated mammal bones are more likely for LYJO.

Park Collections

No fossils are currently reported to be in LYJO collections, and no LYJO fossils are currently reported to be in the collections of other institutions.

Cultural Resource Connections

No fossils have been reported from cultural resource contexts at LYJO, although such associations would not be unprecedented. The most likely type of cultural association for this area would be fossiliferous stone used for artifacts. For example, in the Southwest, petrified wood from the Upper Triassic Chinle Formation was often used for artifacts. The majority of parks in the neighboring Southern Colorado Plateau Network have examples (Tweet et al. 2009). Another common type of cultural association is fossils in building stone. Kenworthy and Santucci (2006) presented an overview and cited selected examples of National Park Service fossils found in cultural resource contexts.

Paleontological Resource Management, Preliminary Recommendations

- Staff from the historical park should be encouraged to observe exposed rocks and sedimentary deposits for fossil material while conducting their usual duties. To promote this, they should also receive guidance regarding how to recognize common local fossils. When opportunities arise to observe paleontological resources in the field and take part in paleontological field studies with trained paleontologists, staff should take advantage of them, if funding and time permit. It is likely that fossils exist within the historical park, in the same formations found to be fossiliferous just outside of the park.

- Staff should photodocument and monitor any occurrences of paleontological resources that may be observed in situ. Fossils and their associated geologic context (surrounding rock) should be documented but left in place unless they are subject to imminent degradation by artificially accelerated natural processes or direct human impacts. A Geologic Resource Monitoring Manual by the Geological Society of America and NPS Geologic Resources Division includes a section on paleontological resource monitoring (Santucci et al. 2009). Santucci and Koch (2003) present information on paleontologic resource monitoring.

- Fossils found in a cultural context should be documented like other fossils, but will also require the input of an archeologist or a cultural resource specialist. Any fossil which has a cultural context may be culturally sensitive as well (e.g., subject to NAGPRA) and should be regarded as such until otherwise established. The Geologic Resources Division can coordinate additional documentation/research of such material.

- Contact the NPS Geologic Resources Division for technical assistance with paleontological resource management issues.

References Cited

Ager, D. V. 1964. Further new rhynchonelloid brachiopods from the Texas Cretaceous. Journal of Paleontology 38(1):109–112.

Ahr, W. M. 1971. Paleoenvironment, algal structures, and fossil algae in the upper Cambrian of central Texas. Journal of Sedimentary Petrology 41(1):205–216.

Ahr, W. M. 1988. Cambrian algal reefs of the upper Wilberns Formation, central Texas, the Camp San Saba locality. Pages 339–342 *in* O. T. Hayward, editor. South-central section of the Geological Society of America. Geological Society of America, Boulder, Colorado. Centennial field guide 4.

Alexander, H. L., Jr. 1963. The Levi site: a Paleoindian campsite in central Texas. American Antiquity 28(4):510–528.

Amsbury, D. L. 1988. The middle Comanchean section of central Texas. Pages 373–376 *in* O. T. Hayward, editor. South-central section of the Geological Society of America. Geological Society of America, Boulder, Colorado. Centennial field guide 4.

Amsbury, D. L. 1996a. Observation of Hensel outcrops and cores, central Texas. Pages 69–99 *in* D. L. Amsbury and J. O. Jones, editors. A field book for the Early Cretaceous rocks of south-central Texas. South Texas Geological Society, San Antonio, Texas.

Amsbury, D. L. 1996b. Pearsall (Aptian Cretaceous) subsurface to outcrop sequence stratigraphy, central Texas. Transactions - Gulf Coast Association of Geological Societies 46:1–7.

Andres, B., and T. S. Myers. 2013. Lone Star pterosaurs. Earth and Environmental Science Transactions of the Royal Society of Edinburgh 103(3–4):383–398.

Applin, E. E. R., A. R. Loeblich, Jr., and H. N. Tappan. 1950. Two new Lower Cretaceous lituolid Foraminifera. Journal of the Washington Academy of Sciences 40(3):75–79. Available at http://biodiversitylibrary.org/page/39703829 (accessed February 2015).

Barker, D. S., and K. P. Young. 1979. A marine Cretaceous nepheline basanite volcano at Austin, Texas. Texas Journal of Science 31(1):5–24.

Barnes, V. E. 1964. Geologic map of the Hye Quadrangle, Blanco, Gillespie, and Kendall counties, Texas. Geologic Quadrangle Map 27. Bureau of Economic Geology, University of Texas at Austin, Austin, Texas. Scale 1:24,000. Available at http://www.lib.utexas.edu/books/landscapes/detail.php?work_id=288322, http://ngmdb.usgs.gov/Prodesc/proddesc_41611.htm (accessed February 2015).

Barnes, V. E. 1965a. Geologic map of the Rocky Creek Quadrangle, Blanco and Gillespie counties, Texas. Geologic Quadrangle Map 29. Bureau of Economic Geology, University of Texas at Austin, Austin, Texas. Scale 1:24,000. Available at http://ngmdb.usgs.gov/Prodesc/proddesc_41613.htm (accessed February 2015).

Barnes, V. E. 1965b. Geologic map of the Stonewall Quadrangle, Gillespie and Kendall counties, Texas. Geologic Quadrangle Map 31. Bureau of Economic Geology, University of Texas at Austin, Austin, Texas. Scale 1:24,000. Available at http://www.lib.utexas.edu/books/landscapes/detail.php?work_id=288323, http://ngmdb.usgs.gov/Prodesc/proddesc_41615.htm (accessed February 2015).

Barnes, V. E. 1967. Geologic map of the Cave Creek School Quadrangle, Gillespie County, Texas. Geologic Quadrangle Map 32. Bureau of Economic Geology, University of Texas at Austin, Austin, Texas. Scale 1:24,000. Available at http://ngmdb.usgs.gov/Prodesc/proddesc_41616.htm (accessed February 2015).

Barnes, V. E. 1988. The Precambrian of central Texas. Pages 361–368 *in* O. T. Hayward, editor. South-central section of the Geological Society of America. Geological Society of America, Boulder, Colorado. Centennial field guide 4.

Barnes, V. E., L. E. Warren, and A. R. Palmer. 1963. Geologic map of the Johnson City Quadrangle, Blanco County, Texas. Geologic Quadrangle Map 25. Bureau of Economic Geology, University of Texas at Austin, Austin, Texas. Scale 1:24,000. Available at http://ngmdb.usgs.gov/Prodesc/proddesc_96334.htm (accessed February 2015).

Bay, A. R., and D. G. Bebout. 1983. Cyclic, shoaling-carbonate banks in the lower Glen Rose Formation (Cretaceous), South Texas. Pages 429–462 *in* P. M. Harris, editor. Carbonate buildups: a core workshop. Society for Sedimentary Geology, Tulsa, Oklahoma. Core Workshop 4.

Behrens, E. W. 1965. Environment reconstruction for a part of the Glen Rose Limestone, central Texas. Sedimentology 4(1):65–111.

Bell, W. C., and H. L. Ellinwood. 1962. Upper Franconian and Trempealeauan Cambrian trilobites and brachiopods, Wilberns Formation, central Texas. Journal of Paleontology 36(3):385–423.

Bird, R. T. 1944. Did *Brontosaurus* ever walk on land? Natural History 53(2):60–67.

Bishop, G. A. 1983. Fossil decapod crustaceans from the Lower Cretaceous, Glen Rose Limestone of central Texas. Transactions of the San Diego Society of Natural History 20(2):27–55. Available at http://biodiversitylibrary.org/page/4304395 (accessed February 2015).

Blair, M., B. Dattilo, A. J. Martin, and J. O. Farlow. 2012. Microstratigraphic analysis of burrow-reworked dinosaur track bed at Joanna's track site, Cretaceous Glen Rose Formation, Glen Rose, Texas. Abstracts with Programs - Geological Society of America 44(7):399.

Brown, J. B. 1980. Mesozoic history of the Llano region, Texas. Pages 52–58 *in* D. Windle, editor. Geology of the Llano region, central Texas. West Texas Geological Society, Midland, Texas. Publication 80-73.

Carter, K. E. 1989. Grenville orogenic affinities in the Red Mountain area, Llano Uplift, Texas. Canadian Journal of Earth Sciences 26(6):1124–1135.

Chafetz, H. S. 1980. Evidence for an arid to semi-arid climate during deposition of the Cambrian System in central Texas, U.S.A. Palaeogeography, Palaeoclimatology, Palaeoecology 30(1–2):83–95.

Conkin, J. E., and B. M. Conkin. 1956. *Nummoloculina* in Lower Cretaceous of Texas and Louisiana. Bulletin of the American Association of Petroleum Geologists 40(5):890–896.

Cooke, M. J., L. A. Stern, J. L. Banner, L. E. Mack, T. W. Stafford, and R. S. Toomey. 2003. Precise timing and rate of massive late Quaternary soil denudation. Geology 31(10):853–856.

Decker, C. E. 1944. The Wilberns Upper Cambrian graptolites from Mason, Texas. Bureau of Economic Geology, University of Texas at Austin, Austin, Texas. Publication 4401:13–61. Available at http://www.lib.utexas.edu/books/landscapes/detail_viewer.php?work_id=288335&state=pagescan&page_tab=details&page_num=15/ (accessed February 2015).

Droxler, A. W., P. Khanna, and D. J. Lehrmann. 2014. Growth phases in the Upper Cambrian Wilberns microbial reef evolution (Mason County, Texas). Abstracts: Annual Meeting - American Association of Petroleum Geologists 2014:unpaginated.

Ellwood, B. B., and W. A. Gose. 2006. Heinrich H1 and 8200 yr B.P. climate events recorded in Hall’s Cave, Texas. Geology 34(9):753–756.

Falkingham, P. L., K. T. Bates, and J. O. Farlow. 2014. Historical photogrammetry: Bird’s Paluxy River dinosaur chase sequence digitally reconstructed as it was prior to excavation 70 years ago. Plos One 2014:E93247. Available at http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0093247 (accessed February 2015).

Farlow, J. O., G. J. Kuban, and P. J. Currie. 2013. On the makers of “metatarsal” tridactyl dinosaur footprints of the Paluxy River (Glen Rose Formation, Dinosaur Valley State Park, Somervell County, Texas). Abstracts with Programs - Geological Society of America 45(4):22.

Feldmann, R. M., C. E. Schweitzer, B. Dattilo, and J. O. Farlow. 2011. Remarkable preservation of a new genus and species of limuline horseshoe crab from the Cretaceous of Texas, USA. Palaeontology 54(6):1337–1346.

Freed, R. L. 1986. Summary of the Precambrian and Paleozoic geology of south-central Texas. Compass of Sigma Gamma Epsilon 63(4):130–144.

Graham, R. W., E. L. Lundelius, Jr., L. Meissner, and K. Muhlestein. 2013. Friesenhahn Cave: late Pleistocene paleoecology and predator-prey relationships of mammoths with an extinct scimitar cat. Pages 15–31 *in* B. B. Hunt and E. J. Catlos, editors. Late Cretaceous to Quaternary strata and fossils of Texas: field excursions celebrating 125 years of GSA and Texas geology, GSA South-Central Section Meeting, Austin, Texas, April 2013 Geological Society of America, Boulder, Colorado. Field Guide 30.

Hall, S. A., and S. Valastro, Jr. 1995. Grassland vegetation in the Southern Great Plains during the last glacial maximum. Quaternary Research 44(2):237–245.

Hay, O. P. 1924. The Pleistocene of the middle region of North America and its vertebrated animals. Carnegie Institute of Washington Publication 322A. Available at https://archive.org/details/pleistoceneofmid00hayo (accessed January 2015).

Holliday, V. T. 1992. Soil formation, time, and archaeology. Pages 101–117 *in* V. T. Holland, editor. Soils in archaeology: landscape evolution and human occupation. Smithsonian Institution, Washington, DC.

Holman, J. A. 1969. A Pleistocene herpetofauna from Kendall County, Texas. Florida Scientist 31(3):165–172. Available at http://biodiversitylibrary.org/page/41503452 (accessed February 2015).

Jensen, J. G. 1980. Precambrian geology of the Llano region, central Texas. Pages 9–27 *in* D. Windle, editor. Geology of the Llano region, central Texas. West Texas Geological Society, Midland, Texas. Publication 80-73.

Johns, R. A., B. F. Dattilo, and B. Spincer. 2007. Neotype and redescription of the Upper Cambrian anthaspidellid sponge, *Wilbernicyathus donegani* Wilson, 1950. Journal of Paleontology 81(3):435–444.

Johnson, W. J., and R. H. Goldstein. 1993. Cambrian sea water preserved as inclusions in marine low-magnesium calcite cement. Nature 362(6418):335–337.

Jones, J. O., and A. J. Kullman. 1997. Redesignation of the upper lithofacies in the Hensel Formation (Lower Cretaceous) on the southwestern flank of the Llano Uplift, Kimble County, Texas: a new

interpretation of the depositional environments. Transactions - Gulf Coast Association of Geological Societies 47:251–262.

Jones, R. A. 1929. The Paleozoic of the Pedernales Valley in Gillespie and Blanco counties, Texas. University of Texas Bulletin 2901:95–130. Available at http://www.lib.utexas.edu/books/landscapes/detail.php?work_id=288405 (accessed February 2015).

Kennedy, W. J., N. H. Landman, and W. A. Cobban. 1998. Engonoceratid ammonites from the Glen Rose Limestone, Walnut Clay, Goodland Limestone, and Comanche Peak Limestone (Albian) in Texas. American Museum Novitates 3221. Available at http://digitallibrary.amnh.org/dspace/handle/2246/3505 (accessed February 2015).

Kenworthy, J. P., and V. L. Santucci. 2006. A preliminary investigation of National Park Service paleontological resources in cultural resource contexts, Part 1: general overview. New Mexico Museum of Natural History and Science Bulletin 34:70–76. Available at http://nature.nps.gov/geology/paleontology/pub/fossil_conference_7/9%20Kenworthy.pdf (accessed December 2014).

Kessler, L. G., II. 1968. Palynomorph distribution and depositional environments in the Glen Rose Formation (lower Cretaceous), Somervell County, Texas. Transactions - Gulf Coast Association of Geological Societies 18:208–221.

Koch, A. L., and V. L. Santucci. 2003. Lyndon B. Johnson National Historical Park. Pages 19–22 *in* A. L. Koch and V. L. Santucci. Paleontological resource inventory and monitoring: Southern Plains Network. TIC# D-107. National Park Service, Denver, Colorado.

Kuban, G. J. 1989. Elongate dinosaur tracks. Pages 57–72 *in* D. D. Gillette and M. G. Lockley, editors. Dinosaur tracks and traces. Cambridge University Press, Cambridge, United Kingdom.

Lockley, M. G., and A. Rice. 1990. Did "*Brontosaurus*" ever swim out to sea? Evidence from brontosaur and other dinosaur footprints. Ichnos 1(2):81–90.

Lundelius, E. L., Jr. 1967. Late Pleistocene and Holocene faunal history of central Texas. Pages 287–319 *in* P. S. Martin and H. E. Wright, Jr., editors. Pleistocene extinctions: a search for a cause. Yale University Press, New Haven, Connecticut.

Lundelius, E. L., Jr. 2003. A history of paleontological investigations of Quaternary cave deposits on the Edwards Plateau, central Texas. Pages 201–214 *in* B. W. Schubert, J. I. Mead, and R. W. Graham, editors. Ice age cave faunas of North America. Indiana University Press, Bloomington and Indianapolis, Indiana.

Lundelius, E. 2013. Cave deposits of central Texas. Abstracts with Programs - Geological Society of America 45(3):83–84.

Maddocks, R. F. 1988. One hundred million years of predation on ostracods: the fossil record in Texas. Developments in Palaeontology and Stratigraphy 11:637–657.

Miller, J. F. 1987. Upper Cambrian and basal Ordovician conodont faunas of the southwest flank of the Llano Uplift, Texas. Pages 1–22 *in* R. C. Grayson, Jr., G. K. Merrill, and J. F. Miller. Early and late Paleozoic conodont faunas of the Llano Uplift region, central Texas: biostratigraphy, systemic boundary relationships, and stratigraphic importance. Geological Society of America, Boulder, Colorado.

Miller, J. F., J. D. Loch, and J. F. Taylor. 2012. Biostratigraphy of Cambrian and Lower Ordovician strata in the Llano Uplift, central Texas. Pages 187–202 *in* J. Derby, R. Fritz, S. Longacre, W. Morgan, and C. Sternbach, editors. The great American carbonate bank; the geology and economic resources of the Cambrian-Ordovician Sauk megasequence of Laurentia. American Association of Petroleum Geologists, Tulsa, Oklahoma. Memoir 98.

Murry, P. A., D. A. Winkler, and L. L. Jacobs. 1991. An azhdarchid pterosaur humerus from the Lower Cretaccous Glen Rose Formation of Texas. Journal of Paleontology 65(1):167–170.

Musgrove, M., J. L. Banner, L. E. Mack, D. M. Combs, E. W. James, H. Cheng, and R. L. Edwards. 2001. Geochronology of late Pleistocene to Holocene speleothems from central Texas: implications for regional paleoclimate. Geological Society of America Bulletin 113(12):1532–1543.

National Park Service. 2003. LBJ National Historic Park geologic scoping notes. National Park Service, Geologic Resources Division, Denver, Colorado. Available at http://www.nature.nps.gov/geology/inventory/publications/s_summaries/LYJO_Scoping_Notes.pdf (accessed February 2015).

National Park Service Geologic Resources Inventory. 2008. Digital Geologic Map of Lyndon B. Johnson National Historical Park and Vicinity, Texas (NPS, GRD, GRE, LYJO). NPS Geologic Resources Inventory Program. Lakewood, CO. Geospatial Dataset-1045532. Available at https://irma.nps.gov/App/Reference/Profile/1045532 (accessed February 2015).

Nelis, M. K., S. Mosher, and W. D. Carlson. 1989. Grenville-age orogeny in the Llano Uplift of central Texas: deformation and metamorphism of the Rough Ridge Formation. Geological Society of America Bulletin 101(6):876–883.

Nordt, L. 2003. Late Quaternary geology and geoarchaeology of the LBJ Ranch District and Johnson City District in Gillespie and Blanco counties, Texas. Report prepared for the National Park Service, Order #Q750030001 NORDT,2003.

Patton, T. H. 1963. Fossil vertebrates from Miller's Cave, Llano County, Texas. Bulletin of the Texas Memorial Museum 7:1–41.

Payne, J. H., and A. J. Scott. 1982. Facies analysis of the Cretaceous Hensel Formation: response of a fluvial to a marine transgression. Transactions - Gulf Coast Association of Geological Societies 32:91–100.

Peck, R. E., and W. T. Watkins. 1972. Comatulid crinoids from the lower Cretaceous of Texas. Journal of Paleontology 46(3):410–414.

Perkins, B. F. 1985. Caprinid reefs and related facies in the Comanche Cretaceous Glen Rose Limestone of central Texas. Pages 129–140 *in* D. G. Bebout and D. Ratcliff, editors. Lower Cretaceous depositional environments from shoreline to slope: a core workshop. Society for Sedimentary Geology, Gulf Coast Section, Austin, Texas.

Pittman, J. G. 1989. Stratigraphy, lithology, depositional environment, and track type of dinosaur track-bearing beds of the Gulf Coastal Plain. Pages 135–153 *in* D. D. Gillette and M. G. Lockley, editors. Dinosaur tracks and traces. Cambridge University Press, Cambridge, United Kingdom.

Pittman, J. G. 1990. Dinosaur tracks and trackbeds in the middle part of the Glen Rose Formation, western Gulf Basin, Texas. Pages 47–83 *in* G. R. Bergan and J. G. Pittman, leaders. Nearshore clastic-carbonate facies and dinosaur trackways in the Glen Rose Formation (Lower Cretaceous) of central Texas. Dallas Geological Society, Dallas, Texas.

Rigby, J. K. 1975. Some unusual hexactinellid sponge spicules from the Cambrian Wilberns Formation of Texas. Journal of Paleontology 49(2):412–415.

Rodgers, R. W. 1964. Field conference, Glen Rose Limestone of the type area. Baylor University, Waco, Texas.

Rogers, J. V. 2001. A complete crocodiloid egg from the Lower Cretaceous (Albian) Glen Rose Formation, central Texas. Journal of Vertebrate Paleontology 20(4):780–783.

Rogers, J. V., II. 2003. *Pachycheilosuchus trinquei*, a new procoelous crocodyliform from the Lower Cretaceous (Albian) Glen Rose Formation of Texas. Journal of Vertebrate Paleontology 23(1):128–145.

Rowland, S. M., and R. S. Shapiro. 2002. Reef patterns and environmental influences in the Cambrian and earliest Ordovician. Pages 95–128 *in* W. Kiessling, E. Fluegel, and J. Golonka, editors. Phanerozoic reef patterns. Society for Sedimentary Geology, Tulsa, Oklahoma. Special Publication 72.

Ruppel, S. C., and C. Kerans. 1987. Paleozoic buildups and associated facies, Llano Uplift, central Texas. Austin Geological Society, Austin, Texas. Guidebook 10.

Santucci, V. L., and A. L. Koch. 2003. Paleontological resource monitoring strategies for the National Park Service. Park Science 22(1):22–25. Available at http://www.nature.nps.gov/ParkScience/archive/PDF/ParkScience22%281%29Fall2003.pdf (accessed January 2015).

Santucci, V. L., J. P. Kenworthy, and A. L. Mims. 2009. Monitoring in situ paleontological resources. Pages 189–204 *in* R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado.

Scott, R. W. 2007. Key bivalves of the lower Albian Glen Rose Formation, Texas, U.S.A. Pages 247–252 *in* Scott, R. W., editor. Cretaceous rudists and carbonate platforms: environmental feedback. Society for Sedimentary Geology, Tulsa, Oklahoma. Special Publication 87.

Scott, R. W., A. M. Molineux, H. Loeser, and E. A. Mancini. 2007a. Lower Albian sequence stratigraphy and coral buildups: Glen Rose Formation, Texas, U.S.A. Pages 181–191 *in* Scott, R. W., editor. Cretaceous rudists and carbonate platforms; environmental feedback. Society for Sedimentary Geology, Tulsa, Oklahoma. Special Publication 87.

Scott, R. W., D. L. Amsbury, A. Molineux, and W. C. Ward. 2007b. Late Aptian bivalve assemblage of the transgressive Hensel Sandstone, central Texas. New Mexico Museum of Natural History and Science Bulletin 39:1–6.

Shuler, E. W. 1917. Dinosaur tracks in the Glen Rose limestone near Glen Rose, Texas. American Journal of Science 44(262):294–298.

Smith, A. B., and W. L. Rader. 2009. Echinoid diversity, preservation potential and sequence stratigraphical cycles in the Glen Rose Formation (early Albian, Early Cretaceous), Texas, USA. Palaeobiodiversity and Palaeoenvironments 89(1–2):7–52.

Stanton, T. W. 1947. Studies of some Comanche pelecypods and gastropods. U.S. Geological Survey, Washington, D.C. Professional Paper 211. Available at http://pubs.er.usgs.gov/publication/pp211 (accessed February 2015).

Stead, F. L. 1951. Foraminifera of the Glen Rose Formation (Lower Cretaceous) of central Texas. Texas Journal of Science 3(4):577–605.

Thornberry-Ehrlich, T. 2008. Lyndon B. Johnson National Historical Park: geologic resource evaluation report. Natural Resource Report NPS/NRPC/GRD/NRR—2008/024. National Park Service, Fort Collins, Colorado. Available at http://www.nature.nps.gov/geology/inventory/publications/reports/lyjo_gre_rpt_view.pdf (accessed February 2015).

Tidwell, V., and K. Carpenter. 2003. Braincase of an Early Cretaceous titanosauriform sauropod from Texas. Journal of Vertebrate Paleontology 23(1):176–180.

Tweet, J., V. L. Santucci, J. P. Kenworthy, and A. L. Mims. 2009. Paleontological resource inventory and monitoring: Southern Colorado Plateau Network. Natural Resource Technical Report NPS/NRPC/NRTR—2009/245. TIC# D-59. National Park Service, Fort Collins, Colorado.

Vineyard, D. 2009. A new eucryptodiran turtle from the Lower Cretaceous Glen Rose Formation of Texas. Thesis. Southern Methodist University, Dallas, Texas.

Ward, W. C., and W. B. Ward. 2007. Stratigraphy of middle part of Glen Rose Formation (lower Albian), Canyon Lake Gorge, central Texas, U. S. A. Pages 193–210 *in* Scott, R. W., editor. Cretaceous rudists and carbonate platforms: environmental feedback. Society for Sedimentary Geology, Tulsa, Oklahoma. Special Publication 87.

Watson, J., and H. L. Fisher. 1984. A new conifer genus from the Lower Cretaceous Glen Rose Formation, Texas. Palaeontology 27(4):719–727. Available at http://cdn.palass.org/publications/palaeontology/volume_27/pdf/vol27_part4_pp719-727.pdf (accessed February 2015).

Watson, W. G. 1980. Paleozoic stratigraphy of the Llano area—a review. Pages 28–51 *in* D. Windle, editor. Geology of the Llano region, central Texas. West Texas Geological Society, Midland, Texas. Publication 80-73.

White, L. A., D. Paul, and S. Birnbaum. 2009. Oxygen isotopes and major elements in Cretaceous Hensel Formation paleosol indicate aridity and rising temperatures. Abstracts with Programs - Geological Society of America 41(7):566.

Whitney, M. I. 1952. Some new Pelecypoda from the Glen Rose Formation of Texas. Journal of Paleontology 26(5):697–707.

Whitney, M. I., and L. B. Kellum. 1966. Echinoids of the Glen Rose Limestone of Texas. Annual Report of the Michigan Academy of Science 51:241–263. Available at http://condor.cmich.edu/cdm/ref/collection/p1610-01coll1/id/3241 (accessed February 2015).

Wilson, J. L. 1949. The trilobite fauna of the *Elvinia* zone in the basal Wilberns limestone of Texas. Journal of Paleontology 23(1):25–44

Winkler, D. A., P. A. Murry, and L. L. Jacobs. 1990. Early Cretaceous (Comanchean) vertebrates of central Texas. Journal of Vertebrate Paleontology 10(1):95–116.

Winston, D., and H. Nicholls. 1967. Late Cambrian and Early Ordovician faunas from the Wilberns Formation of central Texas. Journal of Paleontology 41(1):66–96.

Wright, J. L., and J. O. Farlow. 2004. Large enigmatic trace fossils from the Glen Rose Formation (Lower Cretaceous), Texas. Abstracts with Programs - Geological Society of America 36(5):380.

Young, K. 1974. Lower Albian and Aptian (Cretaceous) ammonites of Texas. Geoscience and Man 8:175–228.

Additional References

Bay, A. R. 1985. Carbonate shoaling cycles in the lower Glen Rose Formation (Lower Cretaceous), South Texas. Pages 37–46 *in* D. G. Bebout and D. Ratcliff, editors. Lower Cretaceous depositional environments from shoreline to slope: a core workshop. Society for Sedimentary Geology, Gulf Coast Section, Austin, Texas.

Caran, S. C., T. Housh, and A. J. Cherepon. 2007. Volcanic features of the Austin area, Texas. Austin Geological Society, Austin, Texas. Guidebook 26.

Collins, E. W. 2007. Lower Cretaceous Trinity rocks at and near historically key outcrops along the Pedernales River valley, Central Texas. Pages 12–24 *in* B. B. Hunt, C. M. Woodruff, Jr., and E. W. Collins, editors. Reimers Ranch and Westcave Preserve; landscapes, water, and Lower Cretaceous stratigraphy of the Pedernales watershed, western Travis County, Texas. Austin Geological Society, Austin, Texas. Guidebook 28.

Daghlian, C. P., and C. P. Person. 1977. The cuticular anatomy of *Frenelopsis varians* from the Lower Cretaceous of central Texas. American Journal of Botany 64(5):564–569.

Elias, S. A. 1997. The Ice Age history of southwestern National Parks. Smithsonian Institution Press, Washington, D.C.

Ellwood, B. B. 1996. Geology and America's National Park areas. Prentice Hall, Upper Saddle River, New Jersey.

Evans, G. L. 1961. The Friesenhahn Cave. Bulletin of the Texas Memorial Museum 2:5–22.

Farlow, J. O. 2001. *Acrocanthosaurus* and the maker of Comanchean large-theropod footprints. Pages 408–427 *in* D. H. Tanke, K. Carpenter, and M. W. Skrepnick, editors. Mesozoic vertebrate life: new research inspired by the paleontology of Phillip J. Currie. Indiana University Press, Bloomington, Indiana.

Farlow, J. O., J. G. Pittman, and J. M. Hawthorne. 1989. *Brontopodus birdi*, Lower Cretaceous sauropod footprints from the U.S. Gulf Coastal Plain. Pages 371–394 *in* D. D. Gillette and M. G. Lockley, editors. Dinosaur tracks and traces. Cambridge University Press, Cambridge, United Kingdom.

Fieseler, R. G. 1978. Archeology. Pages 65–67 *in* R. G. Fieseler, J. Jasek, and M. Jasek, editors. An introduction to the caves of Texas. National Speleological Society, Huntsville, Alabama. Annual Convention Guidebook 19.

Fieseler, R. G. 1978. Paleontology. Pages 69–71 *in* R. G. Fieseler, J. Jasek, and M. Jasek, editors. An introduction to the caves of Texas. National Speleological Society, Huntsville, Alabama. Annual Convention Guidebook 19.

Gallup, M. R. 1989. Functional morphology of the hindfoot of the Texas sauropod *Pleurocoelus* sp. indet. Pages 71–74 *in* J. O. Farlow, editor. Paleobiology of the dinosaurs. Geological Society of America, Boulder, Colorado. Special Paper 238.

Graham, R. W. 1987. Late Quaternary mammalian faunas and paleoenvironments of the southwestern Plains of the United States. Pages 24–86 *in* R. W. Graham, H. A. Semken, Jr., and M. A. Graham, editors. Late Quaternary mammalian biogeography and environments of the Great Plains and prairies. Illinois State Museum, Springfield, Illinois. Scientific Papers 22.

Harris, A. H. 1985. Late Pleistocene vertebrate paleoecology of the west. University of Texas Press, Austin, Texas.

Hay, O. P. 1927. The Pleistocene of the western region of North America and its vertebrated animals. Carnegie Institute of Washington Publication 322B.

Helper, M. A. 2000. Geology of the eastern Llano Uplift. Pages 33–47 *in* R. J. Kyle, editor. Geology and historical mining, Llano Uplift region, central Texas. Austin Geological Society, Austin, Texas. Guidebook 20.

Hopkins, J. 2007. Lithofacies, depositional environments and paleopedogenesis of the Hensel Formation, central Texas. Pages 42–53 *in* B. B. Hunt, C. M. Woodruff, Jr., and E. W. Collins, editors. Reimers Ranch and Westcave Preserve: landscapes, water, and Lower Cretaceous stratigraphy of the Pedernales watershed, western Travis County, Texas. Austin Geological Society, Austin, Texas. Guidebook 28.

Langston, W., Jr. 1974. Nonmammalian Comanchean tetrapods. Geoscience and Man 8:77–102.

Longacre, S. A. 1970. Trilobites of the upper Cambrian ptychaspid biomere Wilberns Formation, central Texas. Paleontological Society Memoir 4(44).

Lundelius, E. L., Jr. 1991. The Avenue local fauna, late Pleistocene vertebrates, from terrace deposits at Austin, Texas. Annales Zoologici Fennici 28(3–4):329–340.

Matthews, W. H., III. 1963. The geologic story of Longhorn Cavern. Bureau of Economic Geology, University of Texas at Austin, Austin, Texas. Guidebook 4.

Mayor, A. 2005. Fossil legends of the first Americans. Princeton University Press, Princeton, New Jersey.

McGehee, R. V. 1979. Precambrian rocks of the southeastern Llano region, Texas. Bureau of Economic Geology, University of Texas at Austin, Austin, Texas. Geological Circular 79-3. Available at http://www.lib.utexas.edu/books/landscapes/detail.php?work_id=288645 (accessed February 2015).

McGehee, R. V., compiler. 1963. Geologic map of southeastern Llano Uplift, Llano, Burnet, Blanco, and Gillespie counties, Texas. Bureau of Economic Geology, University of Texas at Austin, Austin, Texas. Miscellaneous Map 12. Scale 1:36,000.

Miller, J. F., and J. H. Stitt. 1995. Stratigraphic position and significance of *Jujuyaspis* and *Iapetognathus* in the Wilberns Formation, Texas. Pages 105–108 *in* J. D. Cooper, M. L. Droser, and S. C. Finney, editors. Ordovician odyssey: short papers for the seventh international symposium on the Ordovician System, 1995. Pacific Section, Society of Economic Paleontologists and Mineralogists, Fullerton, California. Field Trip Guidebook 77.

Olsen, S. J. 1971. Zooarchaeology: animal bones in archaeology and their interpretation. Addison-Wesley Publishing Company, New York City, New York.

Patton, T. H. 1962. Fossil vertebrates from Miller's Cave, Llano County, Texas. Texas Journal of Science 14(4):418–419.

Perkins, B. F. 1974. Paleoecology of a rudist reef complex in the Comanche Cretaceous Glen Rose Limestone of central Texas. Geoscience and Man 8:131–173.

Perkins, B. F., and C. L. Stewart. 1971. Stop 7: Dinosaur Valley State Park. Pages 56–59 *in* B. F. Perkins, editor. Trace fossils: A field guide to selected localities in Pennsylvanian, Permian, Cretaceous, and Tertiary rocks of Texas. Louisiana State University, Baton Rouge, Louisiana. School of Geoscience Miscellaneous Publication 71-1.

Perkins, B. F., and W. Langston, Jr., editors. 1979. Lower Cretaceous shallow marine environments in the Glen Rose Formation: dinosaur tracks and plants. American Association of Stratigraphic Palynologists Field Trip Guide 12.

Pittman, J. G. 1989. Stratigraphy of Glen Rose Formation, western Gulf Coastal Plain. Transactions - Gulf Coast Association of Geological Societies 39:247–264.

Rader, W. L. 2005. The *Corbula* bed: marine fossils as far as the eye can see. Rock & Gem 35(3):70.

Rader, W. L. 2005. The Heritage Museum track site: central Texas' largest collection of dinosaur footprints. Rock & Gem 35(12):60–64.

Sagebiel, J. C. 2010. Late Pleistocene fauna from Zesch Cave, Mason County, Texas. Quaternary International 217(1–2):159–174.

Semken, H. A., Jr. 1961. Fossil vertebrates from Longhorn Cavern, Burnet County, Texas. Texas Journal of Science 13(3):290–310.

Spincer, B. R. 1998. Oolitized fragments of filamentous calcimicrobes and the pseudofossil affinity of *Nuia* Maslov from the Upper Cambrian rocks of central Texas. Journal of Paleontology 72(3):577–584.

Stitt, J. H., and J. F. Miller. 1987. *Jujuyaspis borealis* and associated trilobites and conodonts from the Lower Ordovician of Texas and Utah. Journal of Paleontology 61(1):112–121.

Stricklin, F. L., C. I. Smith, and F. E. Lozo. 1971. Stratigraphy of Lower Cretaceous Trinity deposits of central Texas. Bureau of Economic Geology, University of Texas at Austin, Austin, Texas. Report of Investigations 71.

Whitney, M. I. 1952. Some zone marker fossils of the Glen Rose Formation of central Texas. Journal of Paleontology 26(1):65–73.

Wilson, F., and G. Harmison. 1979. Lower Cretaceous tropical “bone fish”, Glen Rose Formation, Central Texas. Bulletin of the South Texas Geological Society 19(5):22–24.

Winkler, A. J. 1990. Small mammals from a Holocene sequence in central Texas and their paleoenvironmental implications. Southwestern Naturalist 35(2):199–205.

Winkler, A. J., and W. Gose. 2003. Mammalian fauna and paleomagnetics of the middle Irvingtonian (early Pleistocene) Fyllan Cave and Kitchen Door localities, Travis County, Texas. Pages 215–261 *in* B. W. Schubert, J. I. Mead, and R. W. Graham, editors. Ice age cave faunas of North America. Indiana University Press, Bloomington and Indianapolis, Indiana.

Data Sets

Lyndon B. Johnson National Historical Park Paleontological Archives
5/1985–present. (hard copy data; reports; electronic data; photographs; maps; publications). Originated by Santucci, Vincent; status: Active.

Lyndon B. Johnson National Historical Park Digital Geologic Map
2008–present. (geologic map data; electronic files; GIS metadata; associated report). Originated by NPS-Geologic Resources Inventory staff; status: Active. Online.
https://irma.nps.gov/App/Reference/Profile/1045532.

Pecos National Historical Park

Pecos National Historical Park (PECO) preserves cultural resources related to 12,000 years of human history. Among them are the remains of American Indian structures such as Pecos Pueblo (PECO Figure 1), Spanish missions, Mexican-era homesteads, American frontier landmarks such as parts of the Santa Fe Trail (Santa Fe National Historic Trail; SAFE), sites related to the Civil War battle of Glorieta Pass, and a 1900s ranch. PECO was authorized as Pecos National Monument June 28, 1965, and redesignated Pecos National Historical Park June 27, 1990. Its boundaries changed October 21, 1976, June 27, 1990, and November 8, 1990. Today the historical park encompasses 2699.09 ha (6,669.59 acres), 2,571.92 ha (6,355.36 acres) of which are federal. PECO is divided into three units (PECO Figure 2), with most of its area in the original unit south of Pecos. The two smaller units are the Pigeon Ranch and Cañoncito units. The Pigeon Ranch unit is about 4 km (2.5 mi) west-northwest of the main unit, and the Cañoncito unit is about 11 km (7 mi) west of the main unit, on the other side of Glorieta Mesa.



PECO Figure 1. The ancient inhabitants of the archeological sites protected at PECO collected hundreds of fossils from the vicinity (T. Connors/NPS).

Geologic Background

PECO is located in north-central New Mexico. The two smaller parcels are located in eastern Santa Fe County, and the main unit is in adjoining western San Miguel County. The topography is mountainous, and composed of folded and faulted rocks. The Sangre de Cristo Mountains are on the northwest, and Glorieta Mesa forms the highland on the south, between the main unit and Cañoncito units. The Pecos River flows south through the main unit, where it joins Glorieta Creek flowing from the northwest. Glorieta Creek passes through the Pigeon Creek unit. Galisteo Creek passes through

the Cañoncito unit. PECO is located between Santa Fe, about 19 km (12 mi) northeast of the Cañoncito unit, and Las Vegas, New Mexico, about 40 km (25 mi) east of the main unit. Pecos Village is just north of the main unit. The geology and paleontology of PECO have been documented in several publications. These include Kidder (1932), Langston (1953), Romer (1960), Johnson (1969, 1972, 1973), Booth (1977), Robertson et al. (1979), Bezy (1981), Burtchin (1983), Chronic (1987), Ilg et al. (1997), Read and Rawling (2002), Koch and Santucci (2003), NPS (2006, 2009), Rawling (2010), and Croskrey and Hybels (2011). The NPS Geologic Resources Division coordinated a Geologic Resource Evaluation scoping summary for PECO in March 2006 (NPS 2006), and produced a digital map of the historical park in 2009 (NPS 2009). A geologic resources inventory report was prepared for the park in 2015 (Port 2015). Koch and Santucci (2003) prepared the original paleontologic resource inventory and summary for PECO.

The bedrock geology of PECO includes Precambrian igneous and metamorphic rocks, upper Paleozoic rocks representing a time when north-central New Mexico was just above or just below sea level, Triassic river and floodplain rocks, and comparatively recent Quaternary sediments, mostly associated with the modern rivers and streams (see Appendix A for a geologic time scale). Most of the exposed bedrock or surficial deposits date to between approximately 310 and 210 Ma (million years ago), or the past few tens of thousands of years.

The ancient Precambrian rocks of the southern Sangre de Cristo Mountains area include a combination of metamorphosed sedimentary rocks, younger metamorphosed igneous rocks, and some unmetamorphosed granitic bodies. The metasedimentary rocks appear to represent a shallow shelf. The sediments on the shelf were consolidated, uplifted, and eroded back to sea level, where volcanic activity mingled with additional deposition. These rocks were then buried and deformed, and intruded by granite, all long before the deposition of the unmetamorphosed Paleozoic sedimentary rocks (Miller et al. 1963). A large and long-lived fault, called the Picuris–Pecos fault, formed west of PECO in the Sangre de Cristo Mountains perhaps as early as the Grenville Orogeny (mountain-building event) (Bauer and Ralser 1995), which occurred between about 1.25 and 1 billion years ago. This fault can be traced for at least 84 km (52 mi) in northern New Mexico, with movement of some 37 km (23 mi) over multiple episodes of activity. It seems to have had little or no movement since about 26 Ma (Bauer and Ralser 1995).

Rocks that formed between the Precambrian and the Middle Pennsylvanian are not exposed at PECO, although rocks in the vicinity partially bridge the gap. These older rocks show that shallow-marine deposition occurred at times during the ~200 million years before the Alamitos Formation, the oldest unmetamorphosed rocks exposed in PECO (Miller et al. 1963). Some of these older rocks can be seen in the Pecos River valley north of Pecos Village (Johnson 1969). North America was farther south during the late Paleozoic, and was rotated clockwise with respect to its present location. Northeastern New Mexico was within 5° N of the Equator at the beginning of the Permian, moving north into the 5°–10° N range toward the middle of the period. As it moved north, the climate went from warm and semi-arid or subhumid, to more arid conditions (Mack 2003). Glaciation occurred at higher latitudes during deposition of the Pennsylvanian formations, but local sea level was much more affected by tectonics in a nearby mountain range known as the Ancestral Rockies (Krainer et al.

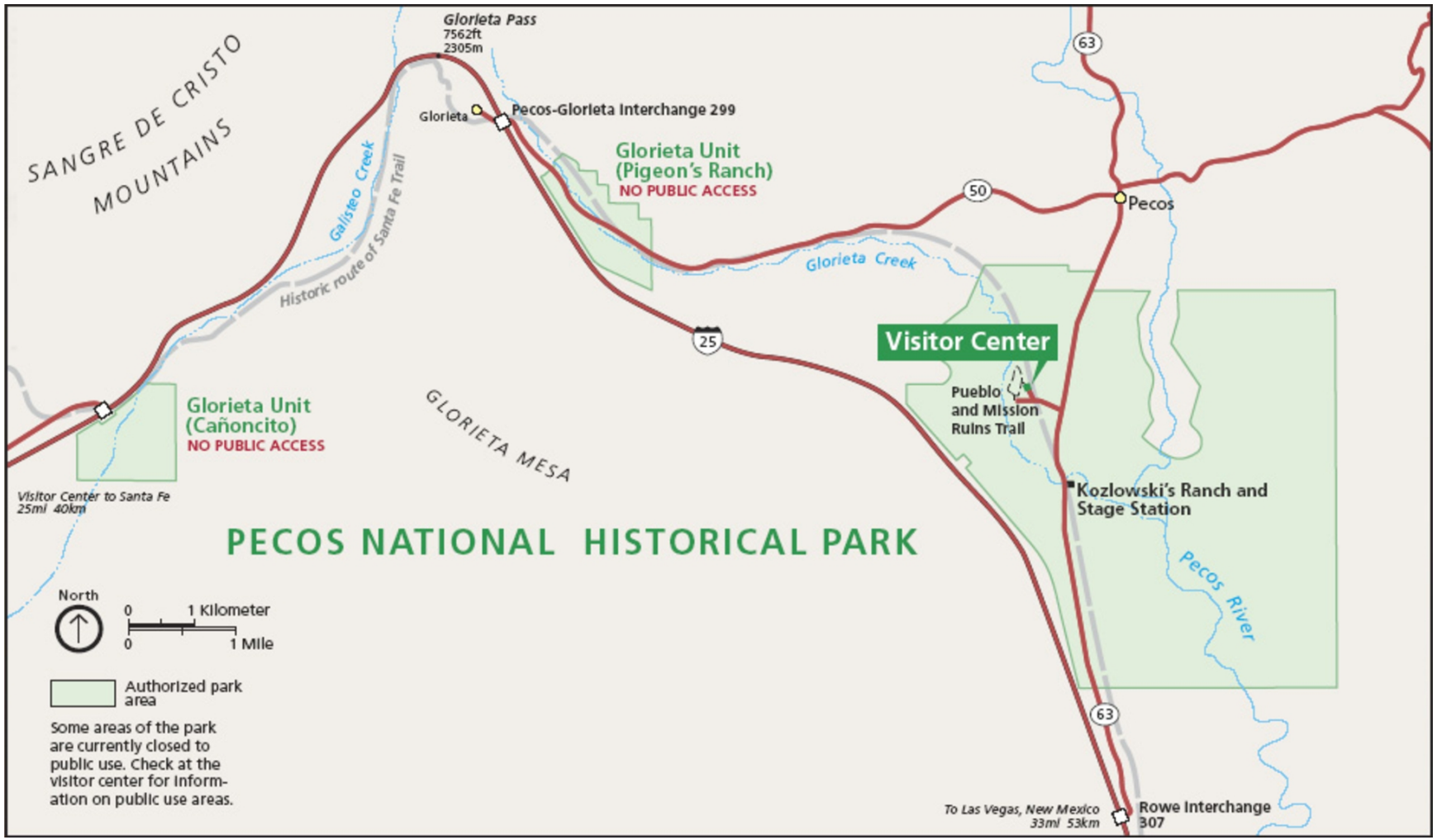
2004). Tectonic activity began in the region during the late Pennsylvanian (Kottlowski 1961) and continued into the early Permian, between about 280 and 270 Ma (Mack and Dinterman 2002). By the Permian, an area of highlands known as the Uncompahgre–San Luis highlands was present to the north and northwest of PECO, in the general area of Taos County, and another uplift was present to the east in the area of Colfax and Harding counties, with a low area called the Sangre de Cristo Trough between them (Milner 1978). A transcontinental river system is thought to have been present farther to the north, draining the Appalachian and Ouachita mountains and the Canadian Shield, with some of the sediment making its way to the sand sheets and dunes of northern New Mexico (Mack and Bauer 2014). Throughout the Pennsylvanian and Permian deposition, a sea was present to the south, and periodically submerged parts of northern New Mexico, including the PECO area (Krainer et al. 2004; Brown 1984). Between marine transgressions (advances), coastal terrestrial deposition occurred in the PECO area, with the climate becoming more arid during the Permian (Stanesco 1991).

Triassic deposition in the PECO area is all non-marine. The oldest Triassic rocks (the Moenkopi Formation) are interpreted as fluvial and lacustrine (Kietzke 1989), with a system of northward-flowing braided streams (Lupe 1988). The top of the Moenkopi Formation is separated from Upper Triassic rocks (including the Santa Rosa and Chinle formations by millions of years, with intervening erosion (Pipiringos and O'Sullivan 1978). The Chinle climate is thought to have been seasonal, with wet and dry periods (Lucas 1993). Fluvial and lacustrine deposition occurred at different times (Lupe 1988; Stewart et al. 1972a), and distant volcanic eruptions contributed substantial amounts of volcanic sediment (Riggs et al. 2003).

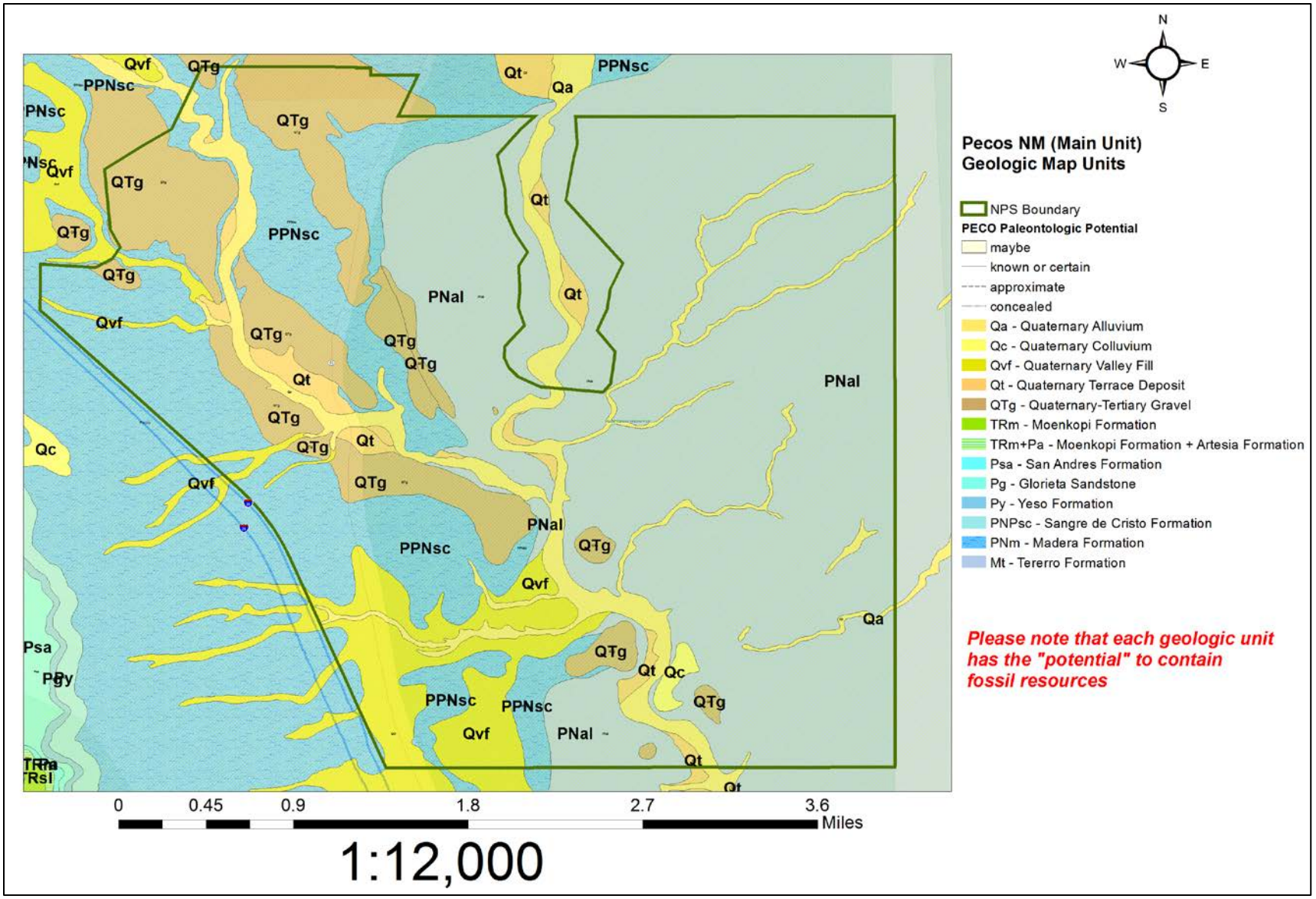
Direct evidence for the events of the approximately 210 million years that followed is not present at PECO. It is known that a structure called the Rio Grande Rift became active just to the west about 26 Ma (Sayre and Ort 2011). The intersection of this feature with an ancient crustal weakness, called the Jemez Lineament, appears to have promoted volcanic activity throughout northern New Mexico. The Jemez Volcanic Field is just to the northwest of Santa Fe and has been active since about 13.4 Ma (Rowe et al. 2007). Major eruptions occurred at 1.61 Ma and 1.22 Ma, from Valles Caldera (Jacobs and Kelley 2007), over 60 km (35 mi) northwest of the Cañoncito unit. Humans have been in northern New Mexico since the latest Pleistocene, and some of the most important Paleoindian sites are from New Mexico. Clovis, in Curry County in east-central New Mexico, gave its name to the Clovis tradition, and the slightly younger Folsom tradition is named for the Folsom archeological site in northeastern Colfax County, over 200 km (120 mi) northeast of PECO. The Clovis tradition existed between approximately 11,200 and 10,900 radiocarbon years before present, and the Folsom tradition existed between approximately 10,900 and 10,200 radiocarbon years before present (Holliday 2000). (Note that radiocarbon dates are not the same as calendar dates, and must be calibrated to approximate calendar years. Dates can be calibrated using a calibration program such as Calib 7.1 [http://calib.qub.ac.uk/calib/] if error ranges are provided. "Present" in "before present" is 1950.)

The bedrock and surficial geology of the three PECO units differ. In ascending order, the geology of the main unit includes the Alamitos Formation (Middle–Upper Pennsylvanian), the Sangre de Cristo

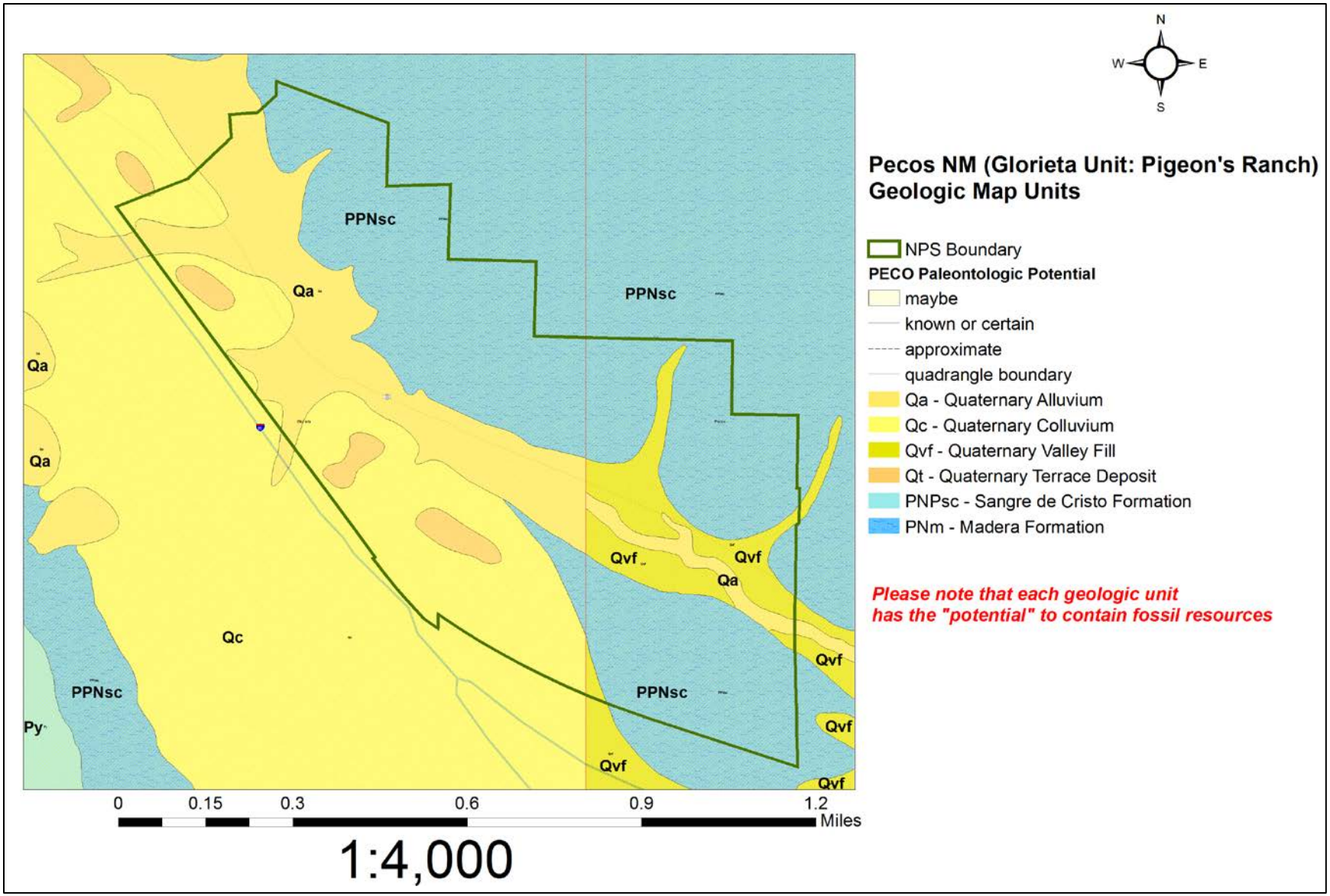
Formation (Upper Pennsylvanian–lower Permian), Tertiary–Quaternary gravel (at least Pleistocene and Holocene), and Quaternary alluvium, colluvium, terrace deposits, and valley fill (Pleistocene–Holocene) (Read and Rawling 2002) (PECO Figure 3). The Pigeon Ranch unit includes the Sangre de Cristo Formation and Quaternary alluvium, colluvium, terrace deposits, and valley fill (Ilg et al. 1997; Read and Rawling 2002) (PECO Figure 4). The Cañoncito unit includes Paleoproterozoic granite and granitic gneiss, the Sangre de Cristo Formation, the Yeso Formation (lower Permian), the Glorieta Sandstone (lower Permian), the San Andres Limestone (lower Permian), the Artesia Formation (middle Permian), the Moenkopi Formation (Middle Triassic), the Santa Rosa Formation (Upper Triassic), undivided Chinle Formation rocks (Upper Triassic), and Quaternary alluvium, colluvium, landslide, and terrace deposits (Ilg et al. 1997) (PECO Figure 5). Of these, only the Alamitos and Sangre de Cristo formations of the main unit are known to be fossiliferous within PECO, but the others all have some potential, particularly the San Andres Limestone, the Triassic formations, and the Quaternary deposits (PECO Table 1). Redeposited petrified wood found in the main unit probably originated from an Upper Triassic unit (Port 2015). In addition, the ancient inhabitants of the area collected hundreds of fossils.



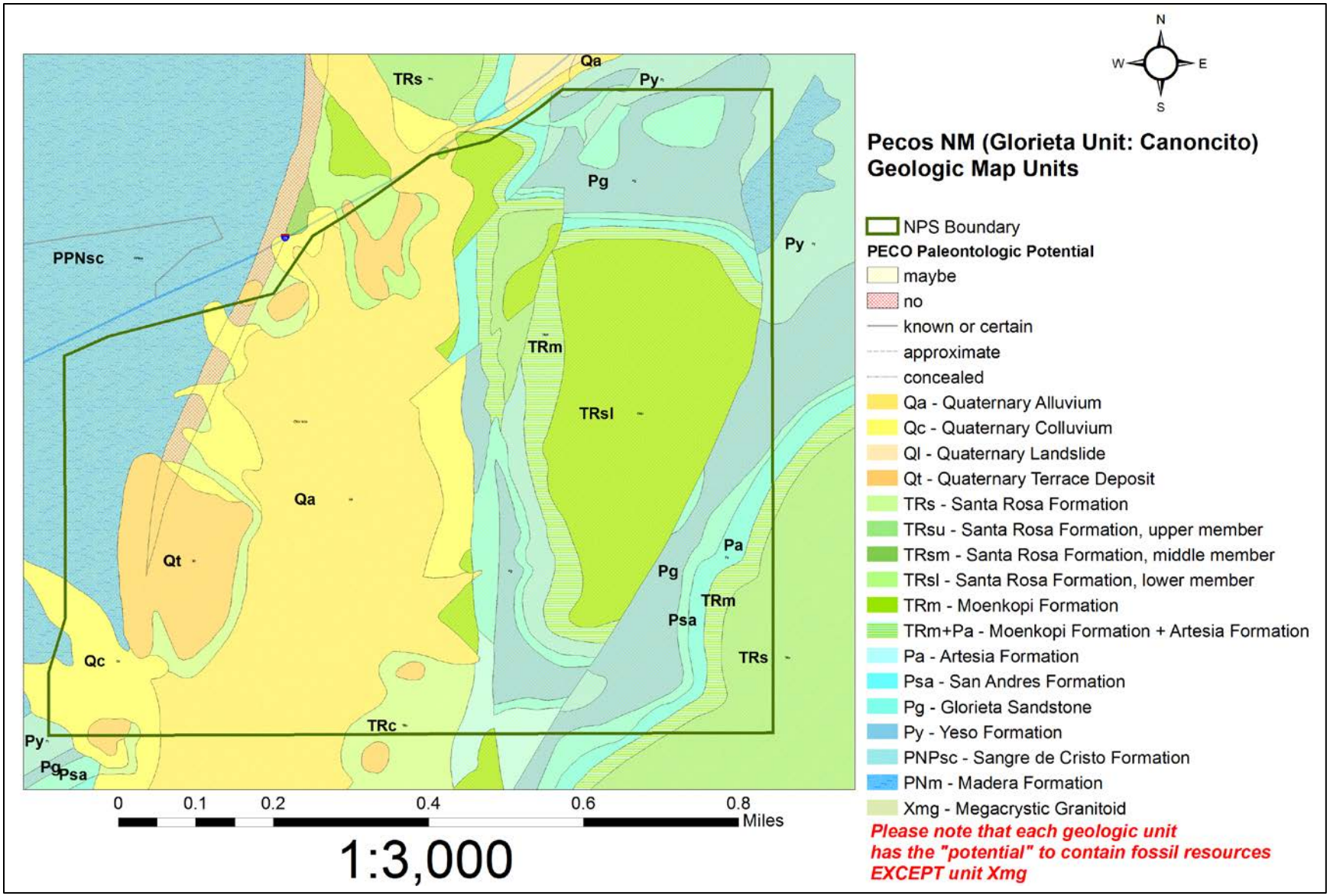
PECO Figure 2. Geography of PECO (NPS).



PECO Figure 3. Schematic geologic map of the main unit of PECO. Map graphic adapted from digital geologic map data available at the following URL: https://irma.nps.gov/App/Reference/Profile/1047622.



PECO Figure 4. Schematic geologic map of the Pigeon's Ranch unit of PECO. Map graphic adapted from digital geologic map data available at the following URL: https://irma.nps.gov/App/Reference/Profile/1047622.



PECO Figure 5. Schematic geologic map of the Cañoncito unit of PECO. Map graphic adapted from digital geologic map data available at the following URL: https://irma.nps.gov/App/Reference/Profile/1047622.

PECO Table 1. Summary of PECO stratigraphy, fossils, and depositional settings in descending order of age, from youngest to oldest. Details and references can be found in the text.

Formation	Age	Fossils Within PECO	Depositional Environment
Quaternary sediments (all)	Pleistocene–Holocene, potentially older in the main unit	None to date; freshwater and terrestrial mollusks and skeletal remains of mammals are most likely	Mixed terrestrial, fluvial important
Chinle Formation undivided (Cañoncito)	Late Triassic	None to date; petrified wood and bone fragments are most likely; potential source of reworked petrified wood in main unit	Fluvial and lacustrine
Santa Rosa Formation (Cañoncito)	Late Triassic	None to date; petrified wood and bone fragments are most likely; potential source of reworked petrified wood in main unit	Fluvial and lacustrine
Moenkopi Formation (Cañoncito)	Middle Triassic	None to date; freshwater invertebrates and bone fragments are most likely	Fluvial and lacustrine
Artesia Formation (Cañoncito)	middle Permian	None to date; fossils are rare	Coastal terrestrial to shallow marine
San Andres Limestone (Cañoncito)	early Permian	None to date; marine invertebrates are most likely	Shallow marine
Glorieta Sandstone (Cañoncito)	early Permian	None to date; fossils are generally rare	Eolian sand sheets
Yeso Formation (Cañoncito)	early Permian	None to date; fossils are generally rare	Eolian and shallow marine
Sangre de Cristo Formation (main, Cañoncito, and Pigeon)	Late Pennsylvanian–early Permian	A shark tooth and bone fragments from the amphibian *Eryops*, a reptile-like diadectid “amphibian”, and the pelycosaur *Sphenacodon*; these are generally early Permian forms	Generally alluvial and fluvial terrestrial
Alamitos Formation, Madera Group (main and Pigeon)	Middle–Late Pennsylvanian	Rugose corals, bivalves, ammonites, unidentified cephalopods, and possibly gastropods present in situ; corals, brachiopods, gastropods, crinoids, and other marine fossils found in PECO ruins may have derived from this formation	Fluctuating between terrestrial (fluvial) and shallow marine
Paleoproterozoic granite and granitic gneiss (Cañoncito)	Paleoproterozoic	Unfossiliferous	Intruded at depth

Sources of Paleontological Resources

The fossils of PECO present opportunities for education, interpretation, and continued or future scientific research in the park.

The geologist Jules Marcou visited the PECO area in 1853 as part of the Whipple expedition and collected fossils from an area north of Pecos Village, north of the main PECO unit. Following a series of conflicts with Secretary of War Jefferson Davis that resulted in Marcou returning to Europe, some of the fossils were described by James Hall (Hall 1856), and others were described by Marcou (Marcou 1858). Those described by Hall are now in the collections of the National Museum of Natural History (Washington, D.C.), while those retained by Marcou are now mostly at the Museum of Natural History (London, United Kingdom) (Sutherland and Harlow 1973). Marcou mistakenly attributed the fossils to the Mississippian, instead of the Pennsylvanian (Kues 1984). John Strong Newberry also visited the PECO area, once in 1857 heading east with the Ives expedition and once in 1859 heading west with the Macomb expedition. He too observed fossils in the area, and reported his geologic observations in two publications (Newberry 1861, 1876). Meek and Hayden (1859), working on fossils from the Kansas and Missouri parts of the Santa Fe Trail, compared their fossils to the Pecos-area material. These fossils are not from PECO, but are of historical interest, and also represent types of fossils that may be found in a formation within PECO; it is now thought that the Pecos-area fossils came from the Alamitos Formation of the Madera Group (Sutherland and Harlow 1973).

Redeposited petrified wood has been reported from the north and east parts of the main unit (Reed et al. 1999; Johnson et al. 2011; Port 2015). Port (2015) suggested that the source was the lower member of the Santa Rosa Formation, exposed at the top of Glorieta Mesa. This is plausible, although Glorieta Mesa itself is unlikely to be the source of all of the wood, because of geography: to reach the east side of the main unit, wood from the mesa would have to cross the Pecos River and potentially Glorieta Creek as well. The Chinle Formation, which is also known from the area and also produces petrified wood, is another plausible source for at least some of the wood. Therefore, the wood is not specifically attributed to a formation here.

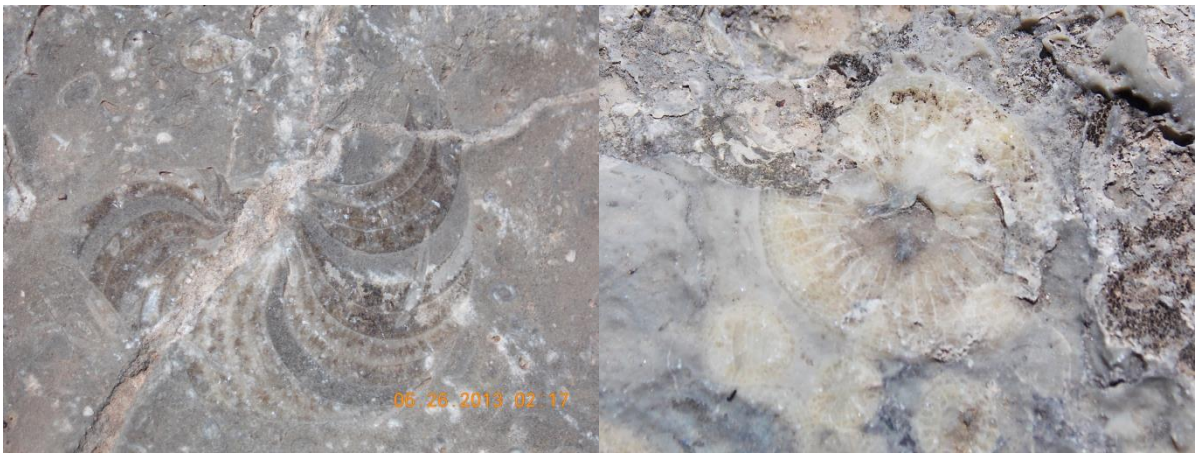
Madera Group: Alamitos Formation (Middle–Upper Pennsylvanian)

The Alamitos Formation is the oldest formation exposed in the main and Pigeon Ranch units of PECO (Ilg et al. 1997; Read and Rawling 2002). In the Pecos area, it consists of gray fossiliferous marine limestone, interbedded with buff to brown coarse arkosic (feldspar-rich) sandstone and dark gray to reddish shale, and is as much as 460 m (1,500 ft) thick (Read and Rawling 2002). Older references identified these rocks as the upper Madera Formation (Johnson 1973; Booth 1977). The Alamitos Formation is approximately equivalent to the informal upper arkosic limestone member of the Madera Formation (Kues 1984).

The Alamitos Formation was deposited by a combination of terrestrial and marine processes. The limestone and some of the shale represent marine incursions, and the sandstone, conglomeratic beds, and other shale represent terrestrial deposition. The terrestrial deposition has been interpreted as fluvial, and was interrupted by marine transgressions (Miller et al. 1963). Multiple transgression-regression cycles, perhaps six, occurred where the Sangre de Cristo Mountains are now, with the sea advancing from the south. Marine deposition took place under shallow water of normal marine salinity (Krainer et al. 2004). The lower part of the formation is more terrestrial in origin, while the upper part is more marine (Miller et al. 1963). The timing of deposition varied, with deposition

beginning earlier in the south than in the north (Miller et al. 1963). Generally, the Alamitos Formation is attributed to the Desmoinesian through Virgilian stages of the Pennsylvanian (Miller et al. 1963; Kues 1984), spanning approximately 308 to 299 Ma. Late Virgilian fusulinid foraminifera have been found near Cañoncito (Booth 1977), indicating an age around 306.5 Ma. The upper contact with the Sangre de Cristo Formation is gradational in the Pecos area (Miller et al. 1963).

The Alamitos Formation is fossiliferous within PECO. The NPS Geologic Resources Division has taken photos of several areas in the main unit where fossils are visible in situ (PECO Figure 6) (R. Port and J. Kenworthy, Geologic Resources Division, pers. comm., March 2015). The lead author (Tweet)'s inspection of the photos indicates that the fossils include solitary rugose corals (horn corals), bivalves, ammonites, unidentified cephalopods, and possibly gastropods. The formation is also notably fossiliferous in the vicinity. Marcou (1858) and Newberry (1861) both noted that beds now thought to belong to this formation were highly fossiliferous in the Pecos Village area, dominated by several species of brachiopods. Fusulinid foraminifera ("amoebas with shells") (Booth 1977), corals, bivalves (Marcou 1858), and echinoids (sea urchins) (Newberry 1876) have also been reported from the vicinity. The Alamitos Formation fossil assemblage includes cyanobacteria (*Girvanella*), encrusting algae (Krainer et al. 2004), wood impressions (Miller et al. 1963), plant fragments (Sutherland and Harlow 1973), fusulinid foraminifera, corals, bryozoans (moss animals), brachiopods (lamp shells), bivalves, gastropods, trilobites, ostracodes (seed shrimp), crinoids (sea lilies), echinoids, conodonts (extinct eel-like vertebrate relatives), and general bioturbation of sediments (Krainer et al. 2004). The limestone is the most fossiliferous part (Booth 1977).



PECO Figure 6. Two examples of fossils in situ in the Alamitos Formation of PECO. Left: An ammonite in the Alamitos Formation in the Cañon de los Trigos of the main unit of PECO (NPS photo by Mario Armijo/PECO). Right: A solitary rugose coral ("horn coral") in cross section in the Alamitos Formation east of the Pecos River in the main unit (NPS photo by Mario Armijo/PECO).

Sangre de Cristo Formation (Upper Pennsylvanian–lower Permian)

The Sangre de Cristo Formation is the primary bedrock formation for the main unit and the Pigeon Ranch unit of PECO (Johnson 1973; Booth 1977). In the PECO area, it is heterogeneous and variegated, consisting of brownish red to purple mudstone, interbedded buff to brown sandstone, and gray to purple limestone (Read and Rawling 2002), along with conglomeratic beds (Johnson 1973).

This unit is as much as at least 790 m (2,600 ft) thick in the Pecos quadrangle (Read and Rawling 2002), but becomes thicker to the west, reaching 900 m (3,000 ft) in the Cañoncito area (Booth 1977). The upper 30 m (100 ft) make up the base of Glorieta Mesa (Johnson 1969). Previously, all of the Pennsylvanian rocks in the Sangre de Cristo Mountains were sometimes lumped into the Sangre de Cristo Formation (Miller et al. 1963).

Deposition of the Sangre de Cristo Formation occurred in a number of settings, mostly terrestrial, including fluvial, alluvial, floodplain, delta, channel fill, lake, and marine settings (Johnson 1969). The basic geometry of the formation is a south-thinning wedge of sediment, formed in response to the growth of the Ancestral Rockies on the north (Soegaard and Caldwell 1990). An overall pattern of floodplain and alluvial fan deposition giving way to coastal plain and fluvial deposition, and then eventually marine deposition, has been reported (Brown 1984). The climate is thought to have been warm and semi-arid to subhumid, with seasonal precipitation (Mack 2003). Deposition spanned the Late Pennsylvanian and early Permian. The basal part of the formation ranges from the Desmoinesian (308–306.5 Ma) to Virgilian (305–299 Ma) stages in age, beginning at different times in different areas. In the Pecos area, the basal beds interfinger with rocks deposited during the late Virgilian (Kues 1984). Deposition continued into the early Permian (Wolfcampian, 299–280 Ma) (Mack 2003). The lower contact with the underlying Alamitos Formation is gradational (Miller et al. 1963), and the upper contact with the Yeso Formation is conformable (Johnson 1969).

The Sangre de Cristo Formation is fossiliferous within PECO. During the 1930s, researchers from several institutions visited the area and collected a small assemblage of vertebrate fossils from between 0.8 and 1.2 km (0.5 and 0.75 mi) north of the mission ruins, within the modern boundaries of the main PECO unit. The fossil locality is a small exposure of the formation, composed of gray shale under a 0.3 m (1 ft)-thick marl (Langston 1953). Alfred Sherwood Romer visited the area in 1931, when he was affiliated with the University of Chicago, and in 1936, when he was affiliated with Harvard's Museum of Comparative Zoology (MCZ) (Romer 1960). Researchers associated with the University of California Museum of Paleontology (UCMP) also visited during the 1930s. Field notes written by Samuel Welles and supplied by Erica Clites (UCMP) document that Welles's party (also including J. B. Johnson and J. Thebaut) visited the area of the ruins from June 7 to June 9, 1937, collecting large fragments of bone (PECO Figure 7).

The PECO locality was given the UCMP locality number V3742, and the fossils brought back to the museum include two bone fragments attributed to the amphibian *Eryops* (E. Clites, pers. comm., January 2015). Romer (1960) also reported that a shark tooth and bones of a diadectid (reptile-like "amphibian) and *Sphenacodon* (a "mammal-like reptile" similar to *Dimetrodon* but with no sail-back) were found within 1.2 km (0.75 mi) of the ruins. As of this writing, these are almost the only lower Permian vertebrate bones known from the National Park System. The finds are sometimes attributed to the Abo Formation (Langston 1953; Romer 1960) or Cutler Formation, but are now known to have come from the Sangre de Cristo Formation. Although the locality information is not precise, it may be possible to relocate the site. In addition to the information from the field notes, there may be physical evidence of the activity, including traces of excavation. Tanke (2005) discussed the relocation of fossil quarries.



PECO Figure 7. Bone fragments attributed to *Eryops* from UCMP V3742, near the ruins in the main unit of PECO (E. Clites/UCMP).

The fossil vertebrates from PECO are part of a small assemblage in the formation, found in the upper Pecos River valley. Animals represented include xenacanth sharks, the lungfish *Gnathorhiza*, several types of temnospondyl amphibians (*Eryops*, the tall-spined *Platyhystrix*, and indeterminate remains), several types of lepospondyl amphibians (boomerang-headed *Diplocaulus*, *Lysophorus*, and *Plegethontia*), the reptile-like "amphibian" *Diadectes*, a captorhinomorph (an early true reptile), and two pelycosaurs ("mammal-like reptiles", *Ophiacodon* and *Sphenacodon*). These fossils are localized to the lower part of the Permian section, and appear to have been deposited in stream channels (Berman 1993; Berman et al. 2013). These vertebrates were collected by researchers from several institutions over a period of decades, including Harvard's Museum of Comparative Zoology and the University of California Museum of Paleontology during the 1930s, the University of California–Los Angeles during the 1960s, and the Carnegie Museum of Natural History during the 1970s (Berman et al. 2013). The rocks are generally sparsely fossiliferous. Most of the fossils in the upper Pecos Valley were found on bluffs (Romer 1960).

Several fossil sites in the literature are just outside of PECO. Darton (1928) reported several discoveries: fossils belonging to the early conifer *Walchia* or something similar were found at the top of the ridge just west of the Cañoncito station, high in the "Abo" Formation; fossil plants and insects were found near the south end of the "great cut" at Glorieta; and *Walchia gracilis* was reportedly abundant in "maroon sandstone at railroad level just west of Glorieta station." Darton et al. (1915) also reported the presence of *Walchia* fragments in the Glorieta Station area. The New Mexico Museum of Natural History and Science has a fossil locality (NMMNH locality 7889) in the Permian part of the formation just north of the Cañoncito Unit in T15N, R11E, section 6. This site has yielded plant debris (fronds of early conifers similar to *Walchia* and material of cordaitaleans, early conifer-like plants), freshwater bivalves, and conchostracans, from a shale interpreted as lacustrine (Rinehart and Lucas 2011). Not only is this site just north of the Cañoncito Unit, but the Santa Fe National Historic Trail passes through the section as well. Finally, fragmentary remains of shark skulls and

pelycosaurs were found near Glorieta Pass (Langston 1953; Romer 1960; Berman 1993; S. Welles's notes as supplied by E. Clites).

The Sangre de Cristo Formation is noted for a substantial Permian terrestrial track fauna, including in the Pecos River Valley (Voigt et al. 2012), but not yet known from PECO. The track assemblage includes tracks of invertebrates and several types of "amphibians", "reptiles", and early mammal relatives (Hunt et al. 1990, 1995a, 2005; Berman 1993; Voigt et al. 2012; quotes used because of the uncertain relationships of many early tetrapods). The tracks are found at a higher level than the vertebrate assemblage, in sand sheets (Berman et al. 2013). Other fossils from the Sangre De Cristo Formation include fragmentary remains of plants, pertaining to clubmoss-like trees (*Lepidodendron*), horsetails (*Calamites*) (Brown 1984), early conifers, and conifer-like cordaitaleans (Rinehart and Lucas 2011), petrified wood, root traces (Soegaard and Caldwell 1990), and lungfish burrows (Vaughn 1964; Berman 1993) (sometimes interpreted as root casts; Bauer et al. 1995).

Potential Sources of Paleontological Resources

Fossils have not yet been documented from the following rock units within PECO. However, they are known to preserve fossils elsewhere, and future field investigations within the park may result in the discovery of fossils from one or more of these units.

Yeso Formation (lower Permian)

The Yeso Formation is one of the bedrock formations exposed in the Cañoncito unit (Ilg et al. 1997). In the Pecos area, it is 50 to 60 m (160 to 200 ft) thick and composed of reddish orange to red mudstone, with interbedded buff, yellow, orange, and red sandstone and buff to yellow nonfossiliferous limestone (Booth 1977; Read and Rawling 2002). The terminology of the Yeso Formation or Group varies from area to area, with different members and formations (Baars 1974; Stanesco 1991; Lucas et al. 2005a, 2013a), but the Yeso Formation has not been divided in the PECO area, so the divisions are omitted for clarity.

Deposition of the Yeso Formation in northern New Mexico appears to have been primarily eolian (wind-blown deposition) and terrestrial during the early and late stages, and shallow marine during the middle stage (Stanesco 1991; Mack and Dinterman 2002), with smaller marine transgression-regression cycles printed on the larger trends (Stanesco 1991). A number of different depositional settings have been identified, including eolian dune fields and sand sheets, coastal plains, sabkhas (salt flats) and mud flats, tidal areas, lagoons, restricted marine areas, and marine shelves, with greater marine influence going south (Stanesco 1991). The climate was arid (Stanesco 1991; Mack and Dinterman 2002), and drier than that of the underlying Sangre de Cristo Formation (Mack 2003). Deposition occurred during the Leonardian stage of the Permian (approximately 280 to 270 Ma), perhaps during the early to middle portion based on stratigraphic relationships with better-dated formations (Lucas et al. 2013a). The upper contact with the Glorieta Sandstone is conformable (Mack and Bauer 2014), and can be gradational (Milner 1978).

Fossils are uncommon in the Yeso Formation, and have not been reported from PECO. The marine beds (limestones and dolomite) and terrestrial red beds have yielded small distinct assemblages. Marine beds occasionally include microbial mat structures, foraminifera, calcareous algae,

brachiopods, bivalves, cephalopods, gastropods, scaphopods (tusk shells), ostracodes, crinoids, and burrows (Stanesco 1991; Lucas et al. 2013a; Vachard et al. 2013). Red beds include plant fossils representing callipterid ferns and conifers, root traces, invertebrate burrows and walking traces, and tetrapod tracks (Lucas et al. 2013a). Named trace fossil taxa, reported from Valencia County, include *Skolithos* (tubes from a worm-like animal), *Diplopodichnus biformis* (probable millipede tracks), and the tetrapod tracks *Amphisauropus*, *Dimetropus*, and *Limnopus* (Lucas et al. 2005b).

Glorieta Sandstone (lower Permian)

The Glorieta Sandstone is present in the Cañoncito unit (Ilg et al. 1997). In the PECO area, this formation is composed of yellow to buff, fine to medium sandstone, and is 25 to 37 m (80 to 120 ft) thick (Read and Rawling 2002). The Glorieta Sandstone was long described as the Glorieta Sandstone Member of the San Andres Formation, and it is often interbedded with the lower San Andres Formation (Lucas et al. 2013b). However, it has a different origin, being an extension of the erg (dune field) that became the Coconino Sandstone of the Grand Canyon region (Mack and Bauer 2014).

Historically, the Glorieta Sandstone has been interpreted as marine (Baars 1974; Milner 1978) or terrestrial, with terrestrial predominating in more recent publications (Brose et al. 2013; Lucas et al. 2013b; Mack and Bauer 2014). Recent descriptions of the formation interpret it as wind-rippled sand sheets southeast of the Coconino dune field (once continental rotation is taken into account). Northeast trade winds blew across the sand sheet. Sediment appears to have come from the north, from a transcontinental river system that was being “deflated” by wind. On the south was the shallow sea that deposited the San Andres Formation, which occasionally encroached on the sand sheet and produced brief coastal and shallow-marine deposition. Shale beds within the sandstone may represent ponds (Mack and Bauer 2014). The sand beds were occasionally reworked during the marine incursions (Lucas et al. 2013b).

Fossils are generally rare in the Glorieta Sandstone. A fairly diverse mixed terrestrial-marine assemblage has been reported from shallow shelf deposits in southwestern Texas (Kamis et al. 2000), but does not seem applicable to the PECO area. In north-central New Mexico, root traces, burrows, and general bioturbation have been found in the sandstone, and stromatolites (layered microbial structures), other microbial structures, corals, bryozoans, brachiopods, ostracodes, and shell molds have occasionally been found in carbonate beds (Mack and Bauer 2014). A few marine foraminifera have also been found (Lucas et al. 2013b).

San Andres Limestone (lower Permian)

The San Andres Limestone is present in the Cañoncito unit (Ilg et al. 1997). In the PECO area, this formation is a thin formation of gray limestone with some interbedded limy sandstone (Booth 1977; Read and Rawling 2002) and shale (Johnson 1973), only about 5 to 14 m (15 to 45 ft) thick (Read and Rawling 2002). In far southeastern New Mexico, it was deposited during the early and middle Permian, from the late Leonardian (before 270 Ma) to the Guadalupian (270 to 260 Ma) (Lucas et al. 2013b), but in northern New Mexico it is restricted to the early Permian (S. Lucas, New Mexico Museum of Natural History and Science, pers. comm., February 2015).

The San Andres Limestone is a shallow-marine formation. The sea that deposited it had occasionally transgressed on the PECO area during the deposition of the underlying Glorieta Sandstone, before making the larger transgression that deposited the San Andres Limestone (Mack and Bauer 2014). As the sea advanced, it reworked some of the sandy terrestrial deposits that became the Glorieta Sandstone. Quiet marine deposition followed, until the sea regressed to the east (Brose et al. 2013). Various rocks have been interpreted to represent a diversity of environmental settings, including tidal flats, lagoons, and shallow shelf marine (Milner 1976). Non-limestone deposition is mostly found in the lower part, corresponding to the initial marine advance (Brose et al. 2013). The formation thickens going south, away from the coast (Brose et al. 2013).

Although fossils have not yet been reported from the San Andres Formation at PECO, fossils are generally common in this formation, albeit often represented only by molds and casts (Lucas and Kues 1994). Most reports of fossils are from areas south of PECO, where the formation is thicker. Fossils reported from this formation include stromatolites and other microbial features (Milner 1976), cyanobacteria (Krainer et al. 2012), calcareous algae, foraminifera, sponges, corals, bryozoans, brachiopods, microconchids ("spirorbids"), chitons (sea cradles), bivalves, ammonites, nautiloids, gastropods, scaphopods, trilobites, ostracodes, crinoids, echinoids (Boyd 1958; Krainer et al. 2012; Brose et al. 2013; Vachard et al. 2013), conodonts, the enigmatic *Tubiphytes* (Wilkinson et al. 1991), shark teeth (Boyd 1958), fish scales (Kues and Lucas 1989), bony fish teeth (Fracasso and Hovorka 1987), burrows, and general bioturbation (Krainer et al. 2012). Distinct normal marine (open waters, normal salinity) and restricted marine forms are known (Milner 1976; Brose et al. 2013). Normal marine rocks may include bryozoans, brachiopods, cephalopods, crinoids, and echinoids, while rocks from restricted marine settings may produce worm tubes, stromatolites and other microbial features, foraminifera, bivalves, gastropods, ostracodes, and burrows (Milner 1976).

Artesia Formation (middle Permian)

The Artesia Formation is exposed in the Cañoncito unit of PECO, in the north and east parts of the unit (Ilg et al. 1997). In the PECO area, it is composed of reddish-brown quartz-rich sandstone and siltstone, and gypsum beds. Some beds display laminations, while others have been bioturbated and lack such features. This formation is between 10 and 20 m (30 and 60 ft) thick (Ilg et al. 1997; Read and Rawling 2002). Previously, the thin Artesia Formation of central and northern New Mexico was frequently lumped with the Moenkopi Formation and described as the Bernal Formation (Lucas 2013). The two can be distinguished by the presence of gypsum in the Artesia Formation and the orange- or brick-red color of the Artesia Formation versus the gray-red color of the Moenkopi Formation (Lucas et al. 1990; Bauer et al. 1995).

The Artesia Formation of central and northern New Mexico represents the thin landward edge of the much thicker Artesia Group present in southern New Mexico. It is equivalent to the lowest two formations of the Artesia Group, the Grayburg and Queen formations. The Artesia Formation was deposited on a broad shelf landward of the great Permian reefs to the south, remnants of which can be seen in Carlsbad Caverns National Park and Guadalupe Mountains National Park. The depositional setting was marginal marine, with environments such as sabkhas, tidal flats, lagoons, and coastal plains (Lucas 2013). The Artesia Formation is difficult to date because of the paucity of

fossils; by correlation, it is thought to have been deposited during the middle part of the middle Permian (Wordian, approximately 269 to 265 Ma) (Lucas 2013).

The Artesia Formation is not known to be fossiliferous in PECO, and overall it is seldom fossiliferous, except for bioturbation (Ilg et al. 1997; Read and Rawling 2002; Lucas 2013).

Moenkopi Formation (Middle Triassic)

The Moenkopi Formation is a widely-distributed Triassic terrestrial formation, found in several western states (McKee 1954; Stewart et al. 1972b). In north-central New Mexico, it is represented by the Anton Chico Member (Lucas and Hunt 1989), which correlates to the Holbrook Member in Arizona (Kietzke 1989; Lucas et al. 1994). The Moenkopi Formation is present within the Cañoncito Unit of PECO (Ilg et al. 1997). In the PECO area, it is composed of grayish red to purplish red sandstone, conglomerate, mudstone, and siltstone, and is 23 to 37 m (75 to 120 ft) thick (Read and Rawling 2002). It was long "hidden" as the upper part of the "Bernal Formation" (see "Artesia Formation" above; Lucas 2013) or the "lower sandstone member" of the Santa Rosa Formation (e.g., Gorman and Robeck 1946; Lucas and Morales 1985; Lucas et al. 1985). It was removed from the Santa Rosa Formation and became the Anton Chico Formation (Lucas and Hunt 1987), and then became the Anton Chico Member of the Moenkopi Formation (Lucas and Hunt 1989).

The Moenkopi Formation of northern New Mexico was deposited in fluvial and lacustrine settings, with sedimentary sources in the Mogollon Highlands (Kietzke 1989). Deposition began with an initial stage of high energy, which later settled into braided fluvial deposition in northward-flowing streams (Lupe 1988). Dissolution of evaporites in underlying Permian formations led to greatly varying thicknesses (Finch 1988). In the Sangre de Cristo Mountains, there is a zone at the top of the formation sometimes described as "mottled strata". It represents one or more paleosols ("fossil" soils) that formed on the surface before the deposition of the Santa Rosa Formation (Lucas et al. 1990). The lower contact is an unconformity (a depositional hiatus) (Gorman and Robeck 1946; Lucas et al. 1990), which represents the late Permian and Early Triassic. The upper contact with Upper Triassic rocks is also an unconformity (Lucas et al. 2001). Deposition occurred during the early Anisian stage of the Middle Triassic (Lucas et al. 1994), approximately 247 Ma.

Fossils have not yet been reported from the Moenkopi Formation of PECO, and generally the formation is only moderately fossiliferous, although a number of finds have been made in recent years. Read and Rawling (2002) mentioned charophyte algae, ostracodes, bones, coprolites (fossil feces), and footprints in their description of the Moenkopi Formation of the Pecos Quadrangle, but this may be a generalized description.

Fossils reported from the Anton Chico Member include plants, invertebrates, vertebrates, and trace fossils. Plants are represented by charophyte algae (Kietzke 1989), the cycadeoid "*Zamites*" (Estep and Lucas 1998; Lucas 2001) and petrified wood (Boy et al. 2001). Freshwater invertebrates are represented by bivalves, conchostracans (Rinehart et al. 2010), ostracodes, worm tube-like fossils ("*Spirorbis*") in lacustrine and fluvial rocks (Kietzke 1989). Vertebrates are represented by fish scales (in coprolites) (Boy et al. 2001), fish teeth (Rinehart et al. 2010), the amphibian *Eocyclotosaurus* (Lucas and Morales 1985), other amphibians (Boy et al. 2001), and several types of

archosaurian reptiles (the group including crocodilians, birds, dinosaurs, and their relatives) (Boy et al. 2001), most notably a *Shanisuchus*-like erythrosuchid (Lucas et al. 2001). Reptiles are unusually common in the Anton Chico Member compared to other members of the Moenkopi Formation (Boy et al. 2001). Finally, trace fossils include burrows, vertebrate coprolites (Boy et al. 2001), and tetrapod tracks, mostly of archosaurs (e.g., *Chirotherium*) and synapsids (mammals and their closest relatives) (*Therapsipus*) (Lucas et al. 2003).

Santa Rosa Formation (Upper Triassic)

The Santa Rosa Formation is present within the Cañoncito Unit of PECO (95 Ilg et al. 1997). In the PECO area, it can be divided into three members. The lower member is composed of gray to buff sandstone with limestone- and chert-pebble conglomerate, and is 30 to 40 m (100 to 130 ft) thick. The middle member is composed of purple and green mudstone, with lesser amounts of limestone, siltstone, and sandstone, and is also about 30 to 40 m (100 to 130 ft) thick. The upper member is composed of buff to dark brown sandstone, with some conglomerate near the base, and is 18 to 24 m (60 to 80 ft) thick (Booth 1977). This sequence appears to correspond to the tripartite division of the Santa Rosa Formation elsewhere, with the lower member as the Tecolotito Member, the middle member as the Los Esteros Member, and the upper member as the Tres Lagunas Member (Lucas et al. 1990). As noted above, the Santa Rosa Formation formerly included an additional sandstone member at the base, which has been transferred to the Moenkopi Formation. This can lead to some confusion, because the “lower member” of older documents usually refers to the Moenkopi Formation, and the “middle sandstone member” becomes the lowest member when the removal of the Moenkopi is taken into account.

The Santa Rosa Formation was deposited in fluvial, alluvial, and lacustrine settings. The lower (Tecolotito) and upper (Tres Lagunas) sandstone-dominated members were deposited primarily by braided streams, with different sediment sources and flow directions: the lower member was deposited by southward-flowing streams, and the upper member was deposited by northward-flowing streams. The middle member (Los Esteros) was probably deposited mostly in lakes, with some associated streams (Lupe 1988). Although it is well-attested as an Upper Triassic formation, recent changes in the Triassic time scale make an exact date uncertain. There is an internal disconformity between the Los Esteros and Tres Lagunas members, but the upper contact with the Chinle Formation can be gradational (Lucas et al. 2001).

The Santa Rosa Formation is not known to be fossiliferous within PECO, but a number of fossils have been reported elsewhere. The majority of fossils have been reported from the Los Esteros Member. Santa Fe County has been particularly productive (Hunt and Lucas 1995). Only petrified wood has been reported from the Tecolotito Member (Gorman and Robeck 1946; Lucas et al. 2001), and the Tres Lagunas Member has a small assemblage including petrified wood (Lucas et al. 2001), metoposaur amphibians (Hunt et al. 1995b), crocodile-like phytosaurs, and armored herbivorous aetosaurs (Hunt and Lucas 2005). The Los Esteros Member includes a variety of fossils. Plants are represented by the fern *Cynepteris*, the cycadeoid *Zamites*, two plants of uncertain relationships (*Dinophyton* and *Samaropsis*), the conifer *Pelourdea*, a pith cast (Ash 1988), and petrified wood (Hunt and Lucas 1988). Invertebrates are represented by bivalves (Hunt and Lucas 1988), tracks

attributed to horseshoe crabs and crustaceans (Hunt et al. 1993), and burrows (Lupe 1988). Vertebrates are represented by bony fish (palaeoniscids and redfieldiids), the lungfish *Arganodus*, metoposaur amphibians, trilophosaurid reptiles, phytosaurs, aetosaurs, early crocodile relatives (including rauisuchians, shuvosaurids [as "*Chatterjeea*"], revueltosaurs [as "ornithischian dinosaurs"], and sphenosuchians), dinosaurs, mammal relatives (dicynodonts and cynodonts), and vertebrate coprolites (Hunt and Lucas 1995); note that many identifications of Triassic vertebrates have changed substantially, making taxonomic lists liable to go out of date quickly. Microbial structures are also reported (Lupe 1988).

Chinle Formation (Upper Triassic)

The Chinle Formation is an important fossiliferous unit of the Colorado Plateau. It is a heterogeneous terrestrial unit largely deposited in various fluvial and lacustrine settings, and is divisible into several subunits depending on location (Stewart et al. 1972a). In the PECO area, the Chinle Formation has been mapped as a distinct unit above the Santa Rosa Formation, with no internal divisions assigned (Booth 1977). It is present in the southern and western parts of the Cañoncito unit (Ilg et al. 1997). Local exposures are composed of red, purple, or green mudstone, buff and light green sandstone, and brown or gray limestone-pebble conglomerate, reaching thicknesses over 187 m (615 ft) (Booth 1977). The Chinle Formation spans much of the Late Triassic. Deposition began about 225 Ma (Ramezani et al. 2011) and ended before the Triassic–Jurassic boundary (201.3 Ma), which is known to have occurred during deposition of an overlying formation (Lucas et al. 1997, 2006).

Fossils have not yet been reported from the Chinle Formation of PECO, but it is one of the more fossiliferous terrestrial formations in the Four Corners states. In the absence of a more specific assignment of the rocks present at PECO, some specificities about potential fossils cannot be known. However, the various units of the Chinle Formation tend to have similar fossils at classifications above genus, differing in the genera and species present and which are most commonly found. Plants are represented by charophyte algae (Lucas and Keitzke 1993), diverse palynomorphs (Gottesfeld 1972; Fisher and Dunay 1984; Parker 2004), and leaves, wood, and other remains of lycopods, horsetails, ferns and fern-like plants, cycads, cycadeoids, ginkgoes, conifers, and taxa of uncertain classifications (Ash 1972, 1989, 2003, 2005a; Stewart et al. 1972a; Parker and Ash 2004). Fossilized fungal remains have also been reported (Ash 1972; Stewart et al. 1972a). Invertebrates are represented by microconchids (enigmatic possible mollusks, misidentified as worm fossils [Ash 2005b]), bivalves, gastropods, ostracodes, conchostracans (Breed 1972; Stewart et al. 1972a), crabs (Rinehart et al. 2003), crayfish (Miller and Ash 1988), insects (Breed 1972; Stewart et al. 1972a), and various trace fossils (Caster 1944; Breed 1972; Gillette et al. 2003; Demko et al. 2005), including borings in wood (Walker 1938; Tapanila and Roberts 2012) and a variety of feeding traces on plants (Ash 1996). Reworked Paleozoic fossils, primarily of invertebrates, are occasionally found in the lowest part of the formation, and include foraminifera, algae, sponges, corals, bryozoans, brachiopods, bivalves, gastropods, ostracodes, and crinoids (McKee 1937; Stewart et al. 1972a).

The Chinle Formation's vertebrate assemblage has been summarized in a number of documents, including Stewart et al. (1972a), Colbert (1972), Parrish (1989), Long and Murry (1995), Heckert et al. (2005a, 2005b), Irmis (2005a), Parker (2005), Lucas et al. (2007), Loughney et al. (2011), and

Parker and Martz (2011). Vertebrates include: freshwater sharks; ray-finned fish; lungfish; coelacanths; several types of enigmatic tetrapods known from isolated bones and teeth; metoposaur amphibians; procolophonids (stocky lizard-like herbivorous and insectivorous reptiles); sphenodontians (relatives of the modern tuatara); trilophosaurids (reptiles that resembled large herbivorous lizards); tanystropheids (long-necked piscivorous reptiles); the unusual aquatic reptile *Vancleavea*; drepanosaurids (beaked, possibly aquatic chameleon-like reptiles); several forms of crocodile-like phytosaurs, known under a variety of names; several forms of herbivorous armored aetosaurs, also known under a variety of names; the small unusual armored *Revueltosaurus*; "rauisuchian" crocodile relatives including poposaurids and rauisuchids, which resembled large carnivorous dinosaurs, and shuvosaurids (toothless forms that resembled ostrich-mimic dinosaurs); "sphenosuchians" (small terrestrial crocodile relatives); lagerpetonids (small bipedal dinosaur relatives); silesaurids (quadrupedal dinosaur relatives); several early dinosaur taxa; and dicynodonts (a type of non-mammalian therapsid, or "mammal-like reptile"). Lungfish, metoposaurs, aetosaurs, and phytosaurs are the most common forms. Vertebrate trace fossils include coprolites (fossil dung) (Hunt et al. 1998), swim traces, and footprints possibly attributable to sphenodontians, tanystropheids, phytosaurs, aetosaurs, carnivorous and herbivorous dinosaurs, and mammal relatives (Hunt and Lucas 2007). Bones accumulated in floodplains, bogs, small ponds, and in or near channels (Parrish 1989).

Quaternary rocks and sediments (Pleistocene–Holocene, potentially older)

Each of the units of PECO has a variety of Quaternary deposits, including alluvium, colluvium, terrace deposits, and valley fill, from the Pleistocene and Holocene (Johnson 1973; Booth 1977; Ilg et al. 1997; Read and Rawling 2002). Any of these deposits may produce fossils, and similar deposits throughout northern and central New Mexico have yielded many paleontological specimens. Useful online paleontological resources for this area include the Neotoma paleoecology database (http://www.neotomadb.org/), Faunmap, which is the vertebrate element of Neotoma (http://www.ucmp.berkeley.edu/faunmap/), and Arthur Harris's "Pleistocene Vertebrates of Southwestern USA and Northwestern Mexico" (http://www.utep.edu/leb/pleistNM/).

The most charismatic Quaternary fossils are the skeletal remains of large extinct Pleistocene mammals such as mammoths, sloths, bison, horses, and camels. Pleistocene vertebrate finds of New Mexico are well documented, and there are several inventories that illustrate the locations and diversity of these finds (Lucas and Effinger 1991; Morgan et al. 2001; Morgan and Lucas 2000, 2005a, 2005b). Within approximately 100 km (60 mi) of PECO at least two dozen such finds have been reported, representing the whole of the Pleistocene (Morgan and Lucas 2000, 2005b). The most frequently reported animals are mammoths, followed by horses and extinct species of bison. Other mammals known from these sites include sloths, glyptodonts, rodents, rabbits, the short-faced bear *Arctodus*, felids, dire wolves, mastodons, camels, llamas, deer, pronghorns, and the shrub-ox *Euceratherium* (Morgan and Lucas 2005b).

Because each unit of PECO has some kind of established drainage, mollusk fossils are a particularly likely type of fossil. Quaternary mollusk fossils in New Mexico include freshwater bivalves and freshwater and terrestrial snails (Springer 1902; Leonard and Frye 1975; Frye et al. 1978).

Another common type of Quaternary fossil in New Mexico is packrat middens. Packrat middens are collections of plant material and food waste constructed by packrats (*Neotoma* spp.) and cemented by their viscous urine. They can be well-preserved in dry caves and rockshelters, and illustrate the environment of the builder's foraging range. Middens are important tools for reconstructing the ecology and climate of the late Pleistocene and Holocene of the southwestern United States (Strickland et al. 2001). The nearest packrat middens to PECO that have been described in the literature are several examples from Frijoles Canyon and Sandia Canyon in the area of Bandelier National Monument, Los Alamos Laboratory, and Valles Caldera National Preserve, approximately 55 km (34 mi) northwest of the Cañoncito unit (Spaulding 1992). All of these middens are fairly young, with the Frijoles Canyon example the oldest at 3,195 ± 85 radiocarbon years before present (3,610–3,210 calibrated years before present) (Spaulding 1992), but middens can be found elsewhere that exceed the range of radiocarbon dating (about 50,000 years). Middens typically include fragments of conifers and angiosperms, pollen, and packrat coprolites, but can hold anything a packrat finds interesting and portable, as well as the remains of other animals that scavenged or took over middens (other rodents, small reptiles, arthropods, and so on). Tweet et al. (2012) presented an overview of packrat middens in NPS units.

Finally, because PECO is also noted for its archeology, there is the possibility of finding floral and faunal remains in archeological sites. An example of this in the vicinity of PECO is the Tesuque By-Pass site, about 27 km (17 mi) north-northwest of the Cañoncito unit, north of Tesuque. At this site, which was probably inhabited between 900 and 1300 AD (McNutt 1969), bones of rodents, rabbits, canids, mule deer, elk, pronghorns, and bison have been found (Jelinek 1969), as well as turkey bones and some shell artifacts (McNutt 1969).

Park Collections

Fossils are present in PECO collections, with 134 catalog numbers assigned to items classified as fossils. All of the items came from archeological contexts. Most of the items which have been identified are brachiopods, crinoids, corals, or bivalves (PECO Figure 8), but also among them are a mammal tooth identified as a rhino tooth in Kidder (1932) (PECO Figure 9), and a piece featuring impressions of *Lepidodendron* or a similar scale tree (PECO Figure 10), previously compared to reptile skin (J. Moss, PECO chief of cultural resources, pers. comm., February 2015).

There are three external collections with fossils from PECO. The Western Archeological and Conservation Center (WACC; Tucson, Arizona) has 18 catalog numbers in its cultural collections for PECO that include fossils in their description: PECO 1601, 1739, 1740, 1743, 1750, 17639, 17647, 17651, 17654, 17661, 17733, 17841, 17980, 18211, 18326, 18327, 18328, and 26785. Most of these are single specimens, with the exception of PECO 17841 and 17980, which are lots of debitage with a single piece of fossil wood each (B. McLain, WACC, pers. comm., March 2015). Aside from the debitage pieces and PECO 1601 (a specimen of the bivalve *Megalonaias gigantea* used as a pendant), none appear to be worked, although several appear to have been worn by handling (PECO Figure 11). A few of the specimens are equivocally fossils: PECO 1601, a very pearly shell, may be essentially modern; PECO 17647, a light-colored fragment questionably described as bone but more similar to silicified wood, which lacks bone or wood texture or structure, and could be a fragment of

fine-grained or carbonate sedimentary rock; PECO 17733, a piece similar to PECO 17647; PECO 18211, a piece identified as petrified shell that again resembles a fragment of sedimentary mineralization; and PECO 18328, identified as a cherty fossil wrapped in carbonate matrix, but more similar to a void space in a rock that has been filled by concentric mineralization. The specimens that can be convincingly described as fossils include the petrified wood debitage, a probable coral, brachiopods, bivalves, and crinoids (one heavily encrusted by bryozoans) (PECO Figures 11 and 12) (J. Tweet, pers. obs., March 2015).

Alfred Vincent Kidder of the Robert S. Peabody Museum of Archaeology (Phillips Academy, Andover, Massachusetts) collected a number of fossils from archeological sites now within PECO during work there between 1915 and 1925, and these specimens are now in the collections of the museum (Kidder 1932; see “Cultural Resource Connections” below for more details). At least some of the material collected from the Sangre de Cristo Formation near the Pecos ruins is in the collections of the UCMP in Berkeley, California: the two unnumbered bone fragments attributed to *Eryops* (PECO Figure 7). Additional documentation produced by the UCMP collectors and museum staff is included below (PECO Figure 13).



PECO Figure 8. A selection of fossil shells from archeological sites at PECO (from left to right PECO 21113, 19000, and 90) (J. Moss/PECO).



PECO Figure 9. A specimen with a *Lepidodendron*-like plant impression (PECO 12273) (J. Moss/PECO).



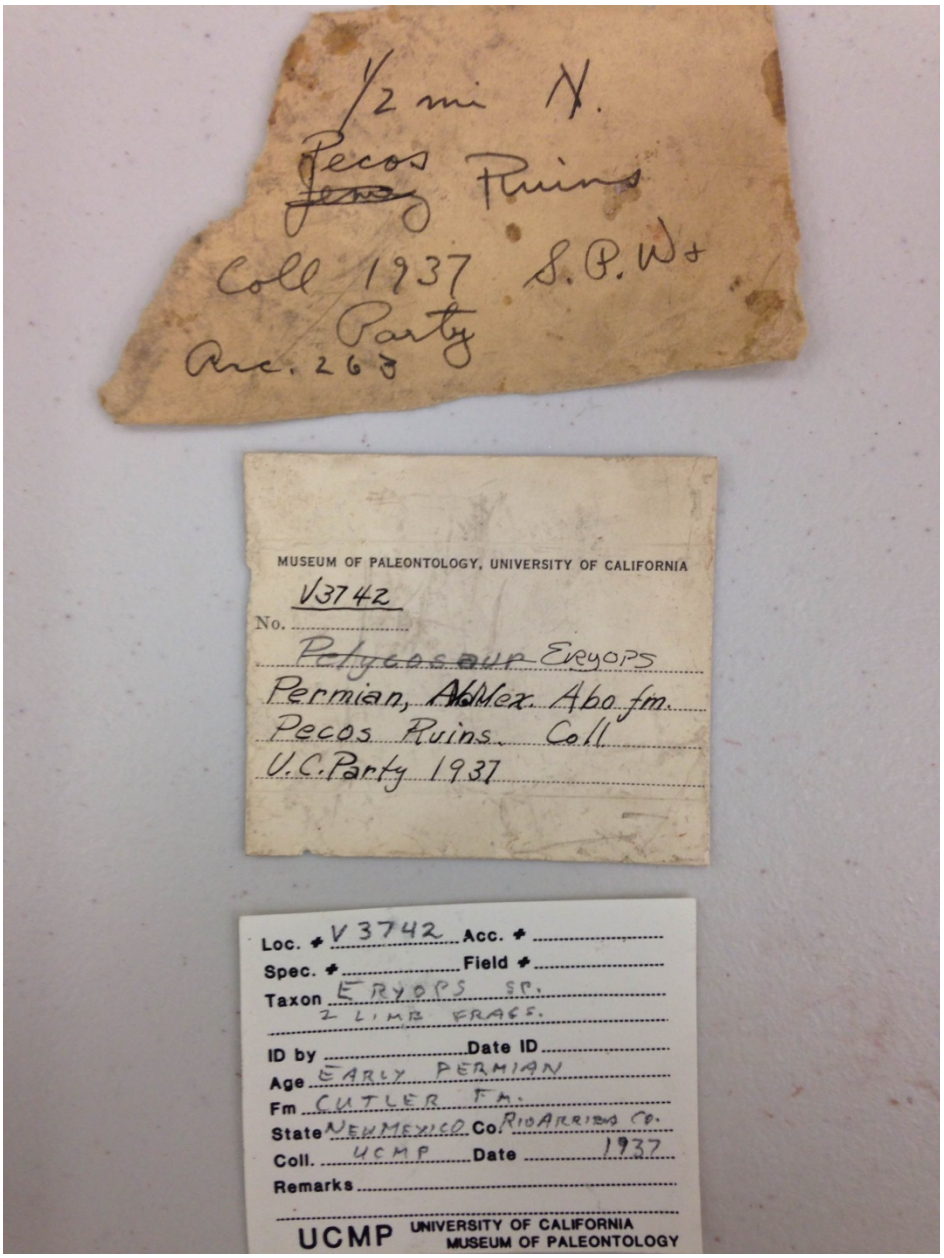
PECO Figure 10. Kidder (1932)'s rhino tooth, now PECO 11854 (J. Moss/PECO).



PECO Figure 11. PECO 1750 in WACC collections: four crinoid columnals, one polished by handling (J. Tweet).



PECO Figure 12. PECO 1743 in WACC collections, identified as a crinoid stem but featuring a coral's structure instead of crinoid columnals (J. Tweet).

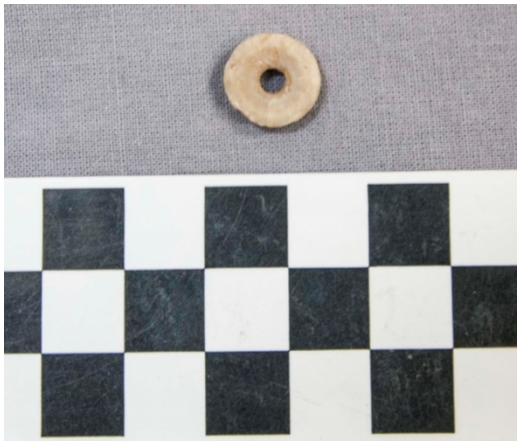


PECO Figure 13. Specimen cards and locality information associated with UCMP Locality V3742 (E. Clites/UCMP).

Cultural Resources Connections

PECO has an excellent record of fossils in cultural resource contexts, examples of which can be found in park collections, at the Robert S. Peabody Museum of Archaeology, and at WACC, as described in the preceding section. Kidder (1932) reported “many hundreds” of fossils were found at Pecos Pueblo during the excavations of 1915–1925. Most of them were marine fossils from “the limestone formations underlying the red sandstones of the valley”, which appears to described the Alamitos Formation. The marine fossils included corals, brachiopods (described in a photo caption as bivalves, which is technically appropriate but can be confusing), gastropods, and crinoids. Not all

were marine, though: one figured specimen is a partial rhinoceros tooth (PECO Figure 10). Kidder noted that the specimens were usually found in rubbish, and suggested that they were collected as curios (Kidder 1932). Kidder observed that none were altered, although the collections catalog of PECO includes several specimens worked into beads or otherwise altered (J. Moss, pers. comm., February 2015) (PECO Figure 14). Some fossils were found in "medicine outfits" included with burials. Petrified wood was found in ceremonial caches, and again was not worked, but sometimes had evidence of extensive handling. Kidder observed that the great majority of the wood was the brown or gray type found southwest of Santa Fe, which does not feature clear grain. He suggested that this wood was collected because of its unusual cleavage and the "clear, resonant tone which it gives when tapped." A few specimens were the more colorful type of wood found in abundance in Petrified Forest National Park (PEFO), and one deep black piece appeared to have come from the Painted Desert. Among the other objects found during the Pecos excavations that may cross cultural and paleontologic resource contexts were numerous artifacts made of sedimentary rocks, which in other places have sometimes been found to contain fossils (note that some PECO artifacts were made from Alibates flint; see the Alibates Flint Quarries National Monument–Lake Meredith National Recreation Area chapter of this report for more information); artifacts made of bone and shell secured from animals living at the time of occupation (some of which is historic, with introduced fauna), and some stones carved in imitation of the contemporary shells; wood and lignite artifacts; waste bone of fauna consumed at the sites, particularly of mule deer, but also a variety of other mammals and birds; and remains of plant foodstuffs, such as seeds. For the record, floral and faunal remains of species not introduced by Europeans include indeterminate wood, pinyon pine nuts, various seeds, fruits, and nuts of angiosperms, shells of bivalves, gastropods, and barnacles, tube worm casings, turtle shells, bones of waterfowl, ground birds, raptors, and perching birds, and bones and teeth of rodents, rabbits, canids, felids, ursids, mustelids, pronghorns, deer, and bovids (Kidder 1932). While some of these must be historic, because of the presence of bones of introduced European animals such as cattle and horses, the chronology of the Pecos sites studied by Kidder go back hundreds of years before contact. In addition to the above, buildings at PECO, including the Pecos mission, were built of local stone (Bezy 1981; Chronic 1987), which is potentially fossiliferous. Kenworthy and Santucci (2006) presented an overview and cited selected examples of National Park Service fossils found in cultural resource contexts.



PECO Figure 14. A drilled crinoid bead (PECO 1192) (J. Moss/PECO).

Paleontological Resource Management, Preliminary Recommendations

- PECO is paleontologically rich but little studied at this point. It should be surveyed for paleontological resources. A secondary goal of a reconnaissance could include relocating the UCMP vertebrate site; it is possible there is still vertebrate material at the site.

- Staff should be encouraged to observe exposed rocks and sedimentary deposits for fossil material while conducting their usual duties. To promote this, staff should also receive guidance regarding how to recognize common local fossils. When opportunities arise to observe paleontological resources in the field and take part in paleontological field studies with trained paleontologists, staff should take advantage of them, if funding and time permit.

- Staff should photodocument and monitor any occurrences of paleontological resources that may be observed in situ. Fossils and their associated geologic context (surrounding rock) should be documented but left in place unless they are subject to imminent degradation by artificially accelerated natural processes or direct human impacts. A Geologic Resource Monitoring Manual by the Geological Society of America and NPS Geologic Resources Division includes a section on paleontological resource monitoring (Santucci et al. 2009). Santucci and Koch (2003) present information on paleontologic resource monitoring.

- Fossils found in a cultural context should be documented like other fossils, but will also require the input of an archeologist or a cultural resource specialist. Any fossil which has a cultural context may be culturally sensitive as well (e.g., subject to NAGPRA) and should be regarded as such until otherwise established. The Geologic Resources Division can coordinate additional documentation/research of such material.

- Because of the extensive occurrences of fossils in cultural contexts at PECO, it may be of interest to create an exhibit or document for the public that ties together the paleontology, geology, and archeology, discussing the fossil collecting of the ancient inhabitants.

- If a fossil packrat midden is located, there are several midden researchers in the Southwest who may be contacted. The GRD maintains a list of active researchers and can facilitate communication between the park and these researchers. Fossil packrat middens are typically found in dry caves and rock shelters, and resemble piles or mounds of plant material with a dark glossy coating of crystallized packrat urine. Fossil middens can provide important paleoecological information.

- Contact the NPS Geologic Resources Division for technical assistance with paleontological resource management issues.

References Cited

Ash, S. R. 1972. Plant megafossils of the Chinle Formation. Museum of Northern Arizona Bulletin 47: 23–44

Ash, S. R. 1988. Fossil plants from the mudstone member of the Santa Rosa Formation at the principal reference section. Pages 21–25 *in* W. I. Finch, editor. Principal reference section for the

Santa Rosa Formation of Middle and Late Triassic age, Guadalupe County, New Mexico. U.S. Geological Survey, Reston, Virginia. Bulletin 1804. Available at http://pubs.er.usgs.gov/publication/b1804 (accessed January 2015).

Ash, S. R. 1989. A catalog of Upper Triassic plant megafossils of the western United States through 1988. Pages 189–222 *in* S. G. Lucas and A. P. Hunt, editors. Dawn of the age of dinosaurs in the American southwest. New Mexico Museum of Natural History, Albuquerque, New Mexico.

Ash, S. R. 1996. Evidence of arthropod-plant interactions in the Upper Triassic of the southwestern United States. Lethaia 29(3):237–248.

Ash, S. 2003. Plant megafossils. Petrified Forest National Park. Available at http://www.nps.gov/pefo/naturescience/plant-megafossils.htm (accessed January 2015).

Ash, S. R. 2005a. Synopsis of the Upper Triassic flora of Petrified Forest National Park and vicinity. Mesa Southwest Museum Bulletin 9:53–62

Ash, S. R. 2005b. A new Upper Triassic flora and associated invertebrate fossils from the basal beds of the Chinle Formation, near Cameron, Arizona. PaleoBios 25(1):17–34.

Baars, D. L. 1974. Permian rocks of north-central New Mexico. Pages 167–169 *in* C. T. Siemers, L. A. Woodward, and J. F. Callender, editors. Ghost Ranch, New Mexico Geological Society, Socorro, New Mexico. Guidebook 25. Available at http://nmgs.nmt.edu/publications/guidebooks/downloads/25/25_p0167_p0169.pdf (accessed January 2015).

Bauer, P. W., and S. Ralser. 1995. The Picuris-Pecos Fault — repeatedly reactivated, from Proterozoic(?) to Neogene. Pages 111–115 in P. W. Bauer, B. S. Kues, N. W. Dunbar, K. E. Karlstrom, and B. Harrison, editors. Geology of the Santa Fe region. New Mexico Geological Society, Socorro, New Mexico. Guidebook 46. https://nmgs.nmt.edu/publications/guidebooks/downloads/46/46_p0111_p0115.pdf (accessed January 2015).

Bauer, P. W., C. G. Daniel, S. G. Lucas, J. M. Barker, and F. E. Kottlowski. 1995. Second-day road log, from Santa Fe to Pecos, Rowe, Bernal, Romeroville, and Mineral Hill. Pages 29–56 in P. W. Bauer, B. S. Kues, N. W. Dunbar, K. E. Karlstrom, and B. Harrison, editors. Geology of the Santa Fe region. New Mexico Geological Society, Socorro, New Mexico. Guidebook 46.

Berman, D. S. 1993. Lower Permian vertebrate localities of New Mexico and their assemblages. New Mexico Museum of Natural History and Science Bulletin 2:11–21.

Berman, D. S., A. C. Henrici, and S. G. Lucas. 2013. *Ophiacodon* (Synapsida, Ophiacodontidae) from the Lower Permian Sangre de Cristo Formation of New Mexico. New Mexico Museum of Natural History and Science Bulletin 60:36–41.

Bezy, J. 1981. The geology of Pecos. In D. G. Noble. Pecos Ruins: geology, archaeology, history, and prehistory. Ancient City Press, Santa Fe, New Mexico.

Booth, F. O., III. 1977. Geologic map of Galisteo Creek area, Lamy to Canoncito, Santa Fe County, New Mexico. U.S. Geological Survey, Washington, DC. Miscellaneous Field Studies Map 823. Scale 1:12,000. Available at http://pubs.er.usgs.gov/publication/mf823 (accessed January 2015).

Boy, J. A., R. R. Schoch, and S. G. Lucas. 2001. The Moenkopi Formation in east central New Mexico: stratigraphy and vertebrate fauna. Pages 103–109 *in* S. G. Lucas and D. S. Ulmer-Scholle, editors. Geology of the Llano Estacado. New Mexico Geological Society, Socorro, New Mexico. Guidebook 52. Available at http://nmgs.nmt.edu/publications/guidebooks/downloads/52/52_p0103_p0109.pdf (accessed January 2015).

Boyd, D. W. 1958. Permian sedimentary facies, central Guadalupe Mountains, New Mexico. New Mexico Bureau of Geology and Mineral Resources, Socorro, New Mexico. Bulletin 49.

Breed, W. J. 1972. Invertebrates in the Chinle Formation. Museum of Northern Arizona Bulletin 47:19–22.

Brose, R. J., S. G. Lucas, and K. Krainer. 2013. The Permian San Andres Formation in central and western New Mexico. New Mexico Museum of Natural History and Science Bulletin 59:213–226.

Brown, C. E. 1984. Depositional environments of the Permo-Pennsylvanian Sangre de Cristo Formation, Coyote Creek District, Mora County, New Mexico. Pages 115–122 *in* W. S. Baldridge, P. W. Dickerson, R. E. Riecker, and J. Zidek, editors. Rio Grande Rift: northern New Mexico. New Mexico Geological Society, Socorro, New Mexico. Guidebook 35. Available at http://nmgs.nmt.edu/publications/guidebooks/downloads/35/35_p0115_p0122.pdf (accessed January 2015).

Burtchin, D. L. 1983. The physical geography of Pecos National Monument, New Mexico. Thesis. University of Arizona, Tucson, Arizona.

Caster, K. E. 1944. Limuloid trails from the Upper Triassic (Chinle) of the Petrified Forest National Monument, Arizona. American Journal of Science 242(2):74–84.

Chronic, H. 1987. Roadside geology of New Mexico. Mountain Press Publishing Company, Missoula, Montana.

Colbert, E. H. 1972. Vertebrates from the Chinle Formation. Museum of Northern Arizona Bulletin 47:1–12.

Croskrey, A. and G. Hybels. 2011. Creation of digital geologic data for Pecos National Historical Park. Pages 251–254 *in* D. R. Soller, editor. Digital mapping techniques '09; workshop

proceedings. U.S. Geological Survey, Reston, Virginia. Open-File Report 2010-1335. Available at http://pubs.er.usgs.gov/publication/ofr20101335 (accessed January 2015).

Darton, N. H. 1928. “Red Beds” and associated formations in New Mexico, with an outline of the geology of the state. U.S. Geological Survey, Washington, D.C. Bulletin 794. Available at http://pubs.er.usgs.gov/publication/b794 (accessed January 2015).

Darton, N. H., and others. 1915. Guidebook of the western United States: Part C, The Santa Fe Route, with a side trip to the Grand Canyon of the Colorado. U.S. Geological Survey Bulletin 613. Available at http://pubs.er.usgs.gov/publication/b613 (accessed February 2015).

Demko, T. M., K. Nicoll, J. J. Beer, S. T. Hasiotis, and L. E. Park. 2005. Mesozoic lakes of the Colorado Plateau. Pages 329–356 *in* J. L. Pederson and C. M. Dehler, editors. Interior western United States. Geological Society of America, Boulder, Colorado. GSA Field Guide 6.

Estep, J. W., and S. G. Lucas. 1998. The cycadeoid *Zamites* from the Middle Triassic Moenkopi Formation, east-central New Mexico. Abstracts with Programs - Geological Society of America 30(6):8.

Finch, W. I. 1988. Description of the principal reference section for the Santa Rosa Formation. Pages 1–10 in W. I. Finch, editor. Principal reference section for the Santa Rosa Formation of Middle and Late Triassic age, Guadalupe County, New Mexico. U.S. Geological Survey, Reston, VA. Bulletin 1804. Available at http://pubs.er.usgs.gov/publication/b1804 (accessed January 2015).

Fisher, M. K., and R. E. Dunay. 1984. Palynology of the Petrified Forest Member of the Chinle Formation (Upper Triassic), Arizona. U.S.A. Pollen et Spores 26(2):241–284.

Fracasso, M. A., and S. D. Hovorka. 1987. First occurrence of a phyllodont tooth plate (Osteichthyes, Platysomidae) from the Permian San Andres Formation, subsurface, Texas Panhandle. Journal of Paleontology 61(2):375–379.

Frye, J. C., A. B. Leonard, and H. D. Glass. 1978. Late Cenozoic sediments, molluscan faunas, and clay minerals in northeastern New Mexico. New Mexico Bureau of Geology & Mineral Resources, Socorro, New Mexico. Circular 160.

Gillette, L., S. G. Pemberton, and W. A. S. Sarjeant. 2003. A Late Triassic invertebrate ichnofauna from Ghost Ranch, New Mexico. Ichnos 10:141–151.

Gorman, J. M., and R. C. Robeck. 1946. Geology and asphalt deposits of north-central Guadalupe County, New Mexico. U.S. Geological Survey, Washington, DC. Oil and Gas Investigation Map 44. Scale 1:63,360. http://pubs.er.usgs.gov/publication/om44 (accessed January 2015).

Gottesfeld, A. S. 1972. Palynology of the Chinle Formation. Museum of Northern Arizona Bulletin 47(supplement):13–18.

Hall, J. 1856. Descriptions and notices of the fossils collected upon the route. Pages 99–105 *in* Chapter IX, No. 1, in Route near the Thirty-Fifth Parallel, explored by Lieut. A. W. Whipple, Topographical Engineer, in 1853 and 1854. Part IV. Report on the geology of the route. Reports of explorations and surveys, to ascertain the most practicable and economical route for a railroad from the Mississippi River to the Pacific Ocean. Volume III. A. O. P. Nicholson, printer, Washington, D.C. Available at https://archive.org/details/reportsofexplora03unit_0 (accessed January 2015).

Heckert, A. B., S. G. Lucas, and A. P. Hunt. 2005a. Triassic vertebrate fossils in Arizona. New Mexico Museum of Natural History and Science Bulletin 29:16–44.

Heckert, A. B., S. G. Lucas, R. M. Sullivan, A. P. Hunt, and J. A. Spielmann. 2005b. The vertebrate fauna of the Upper Triassic (Revueltian: early-mid Norian) Painted Desert Member (Petrified Forest Formation: Chinle Group) in the Chama Basin, northern New Mexico. Pages 302–318 *in* S. G. Lucas, K. E. Zeigler, V. W. Lueth, and D. E. Owen, editors. Geology of the Chama Basin. New Mexico Geological Society, Socorro, NM. Field Conference Guidebook 56.

Holliday, V. T. 2000. Folsom drought and episodic drying on the Southern High Plains from 10,900-10,200 ^{14}C yr B.P. Quaternary Research 53(1):1–12. Available at http://www.argonaut.arizona.edu/articles/holliday2000_2.pdf (accessed January 2015).

Hunt, A. P., and S. G. Lucas. 1988. Late Triassic vertebrates from the Los Esteros Member, Santa Rosa Formation, east-central New Mexico. Journal of Vertebrate Paleontology 8(supplement to 3):18A.

Hunt, A. P., and S. G. Lucas. 1995. Vertebrate paleontology and biochronology of the lower Chinle Group (Upper Triassic), Santa Fe County, north-central New Mexico. Pages 243–246 in P. W. Bauer, B. S. Kues, N. W. Dunbar, K. E. Karlstrom, and B. Harrison, editors. Geology of the Santa Fe region. New Mexico Geological Society, Socorro, New Mexico. Guidebook 46. Available at http://nmgs.nmt.edu/publications/guidebooks/downloads/46/46_p0243_p0246.pdf (accessed January 2015).

Hunt, A. P., and S. G. Lucas. 2005. A skull of the phytosaur Pseudopalatus from the Upper Triassic (late Carnian) Santa Rosa Formation of central New Mexico. New Mexico Geology 27(2):53.

Hunt, A. P., and S. G. Lucas. 2007. Late Triassic tetrapod tracks of western North America. New Mexico Museum of Natural History and Science Bulletin 40:215–230.

Hunt, A. P., S. G. Lucas, and P. Huber. 1990. Early Permian footprint fauna from the Sangre de Cristo Formation of northeastern New Mexico. Pages 291–303 *in* P. W. Bauer, S. G. Lucas, C. K. Mawer, and W. C McIntosh, editors. Tectonic development of the southern Sangre de Cristo Mountains, New Mexico. New Mexico Geological Society, Socorro, New Mexico. Guidebook 41. Available at http://nmgs.nmt.edu/publications/guidebooks/downloads/41/41_p0291_p0303.pdf (accessed January 2015).

Hunt, A. P., M. G. Lockley, and S. G. Lucas. 1993. Vertebrate and invertebrate tracks and trackways from Upper Triassic strata of the Tucumcari Basin, east-central New Mexico, USA. New Mexico Museum of Natural History and Science Bulletin 3:199–201.

Hunt, A. P., S. G. Lucas, M. G. Lockley, H. Haubold, and S. J. Braddy. 1995a. Tetrapod ichnofacies in Early Permian red beds of the American Southwest. New Mexico Museum of Natural History and Science Bulletin 6:295–301.

Hunt, A. P., A. B. Heckert, and S. G. Lucas. 1995b. Vertebrate paleontology and biochronology of the Santa Rosa Formation, Santa Fe County, north-central New Mexico. New Mexico Geology 17(2):32.

Hunt, A. P., S. G. Lucas, and M. G. Lockley. 1998. Taxonomy and stratigraphic and facies significance of vertebrate coprolites of the Upper Triassic Chinle Group, western United States. Ichnos 5:225–234.

Hunt, A. P., S. G. Lucas, and J. A. Spielmann. 2005. Early Permian tetrapod tracksites in New Mexico. New Mexico Museum of Natural History and Science Bulletin 31:46–48.

Ilg, B. R., P. W. Bauer, S. Ralser, J. B. Rogers, and S. Kelley. 1997. Geology of the Glorieta 7.5-minute quadrangle, Santa Fe County, New Mexico. New Mexico Bureau of Geology and Mineral Resources, Socorro, New Mexico. Open-File Geologic Map Series 11. Scale 1:24,000. Available at https://geoinfo.nmt.edu/publications/maps/geologic/ofgm/details.cfml?volume=11 (accessed January 2015).

Irmis, R. B. 2005. The vertebrate fauna of the Upper Triassic Chinle Formation in northern Arizona. Mesa Southwest Museum Bulletin 9:63–88.

Jacobs, E. P., and S. A. Kelley. 2007. The time between the tuffs: deposits of the Cerro Toledo interval in Bandelier National Monument, New Mexico. Pages 308–315 *in* B. S. Kues, S. A. Kelley, and V. W. Lueth, editors. Geology of the Jemez Region II. New Mexico Geological Society, Socorro, New Mexico. Guidebook 58. Available at https://nmgs.nmt.edu/publications/guidebooks/downloads/58/58_p0308_p0315.pdf (accessed January 2015).

Jelinek, A. J. 1969. Identification of mammalian fauna. Pages 127–133 in C. H. McNutt, editor. Early Puebloan occupations at Tesuque By-Pass and in the upper Rio Grande Valley. University of Michigan, Museum of Anthropology, Anthropological Papers 40.

Johnson, R. B. 1969. Pecos National Monument, New Mexico: its geologic setting. U.S. Geological Survey, Washington, DC. Bulletin 1271-E. Available at http://pubs.er.usgs.gov/publication/b1271E (accessed January 2015).

Johnson, R. B. 1972. Geologic map of the Pecos Quadrangle, San Miguel and Santa Fe counties, New Mexico. U.S. Geological Survey, Washington, DC. Open-File Report 72-194. Scale 1:24,000. http://pubs.er.usgs.gov/publication/ofr72194 (accessed January 2015).

Johnson, R. B. 1973. Geologic map of the Pecos Quadrangle, San Miguel and Santa Fe counties, New Mexico. U.S. Geological Survey, Washington, DC. Geologic Quadrangle Map 1110. Scale 1:24,000. Available at http://pubs.er.usgs.gov/publication/gq1110 (accessed January 2015).

Kamis, J., W. Dixon, and R. Vessell. 2000. Environments of deposition for Clear Fork and Glorieta formations, North Robertson Unit, Gaines County, Texas. Pages 307–317 *in* K. S. Johnson, editor. Platform carbonates in the southern Midcontinent, 1996 symposium. Oklahoma Geological Survey, Norman, OK. Circular 101.

Kenworthy, J. P., and V. L. Santucci. 2006. A preliminary investigation of National Park Service paleontological resources in cultural resource contexts, Part 1: general overview. New Mexico Museum of Natural History and Science Bulletin 34:70–76. Available at http://nature.nps.gov/geology/paleontology/pub/fossil_conference_7/9%20Kenworthy.pdf (accessed December 2014).

Kidder, A. V. 1932. The artifacts of Pecos. Yale University Press, New Haven, Connecticut.

Kietzke, K. K. 1989. Calcareous microfossils from the Moenkopi Formation (Triassic, Scythian or Anisian) of central New Mexico. Pages 181–190 *in* O. J. Anderson, S. G. Lucas, D. W. Love, and S. M. Cather, editors. Southeastern Colorado Plateau. New Mexico Geological Society, Socorro, New Mexico. Guidebook 40. Available at http://nmgs.nmt.edu/publications/guidebooks/downloads/40/40_p0181_p0190.pdf (accessed January 2015).

Koch, A. L., and V. L. Santucci. 2003. Pecos National Historical Park. Pages 23–29 *in* A. L. Koch and V. L. Santucci. Paleontological resource inventory and monitoring: Southern Plains Network. TIC# D-107. National Park Service, Denver, Colorado.

Kottlowski, F. E. 1961. Pennsylvanian rocks in north-central New Mexico. Pages 97–104 *in* S. A. Northrop, editor. Albuquerque country. New Mexico Geological Society, Socorro, New Mexico. Guidebook 12. Available at https://nmgs.nmt.edu/publications/guidebooks/downloads/12/12_p0097_p0104.pdf (accessed January 2015).

Krainer, K., S. G. Lucas, and B. S. Kues. 2004. Tectonically induced clastic-carbonate depositional sequences of the Pennsylvanian-Permian transition in the Rowe-Mora Basin, northern New Mexico. Pages 314–325 *in* B. Brister, P. W. Bauer, A. S. Read, and V. W. Lueth, editors. New Mexico Geological Society, Socorro, New Mexico. Guidebook 55. Available at http://nmgs.nmt.edu/publications/guidebooks/downloads/55/55_p0314_p0325.pdf (accessed January 2015).

Krainer, K., S. G. Lucas, and R. J. Brose. 2012. Reference section of the Lower Permian San Andres Formation, Sierra County, New Mexico. Pages 395–406 *in* S. G. Lucas, V. T. McLemore, V. W. Lueth, J. A. Spielmann, and K. Krainer, editors. Geology of the Warm Springs region. New Mexico Geological Society, Socorro, New Mexico. Guidebook 63. Available at

http://nmgs.nmt.edu/publications/guidebooks/downloads/63/63_p0395_p0406.pdf (accessed January 2015).

Kues, B. S. 1984. Pennsylvanian stratigraphy and paleontology of the Taos area, north-central New Mexico. New Mexico Geological Society, Socorro, New Mexico. Guidebook 35:107–114. Available at http://nmgs.nmt.edu/publications/guidebooks/downloads/35/35_p0107_p0114.pdf (accessed January 2015).

Kues, B. S., and S. G. Lucas. 1989. Stratigraphy and paleontology of a San Andres Formation (Permian, Leonardian) outlier, Zuni Indian Reservation, New Mexico. Pages 167–176 *in* O. J. Anderson, S. G. Lucas, D. W. Love, and S. M. Cather, editors. Southeastern Colorado Plateau. New Mexico Geological Society, Socorro, New Mexico. Guidebook 40. Available at http://nmgs.nmt.edu/publications/guidebooks/downloads/40/40_p0167_p0176.pdf (accessed January 2015).

Langston, W., Jr. 1953. Permian amphibians from New Mexico. University of California, Publications in Geological Sciences 29:349–416.

Leonard, A. B., and J. C. Frye. 1975. Pliocene and Pleistocene deposits and molluscan faunas, east-central New Mexico. New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico. Memoir 30.

Long, R. A., and P. A. Murry. 1995. Late Triassic (Carnian and Norian) tetrapods from the southwestern United States. New Mexico Museum of Natural History and Science Bulletin 4.

Loughney, K. M., D. E. Fastovsky, and W. G. Parker. 2011. Vertebrate fossil preservation in blue paleosols from the Petrified Forest National Park, Arizona, with implications for vertebrate biostratigraphy in the Chinle Formation. Palaios 26(11):700–719.

Lucas, S. G. 1993. The Chinle Group: revised stratigraphy and biochronology of Upper Triassic nonmarine strata in the western United States. Museum of Northern Arizona Bulletin 59:27–50.

Lucas, S. G. 2001. The bennettitalean leaf “Zamites” *powellii* from the Middle Triassic Moenkopi Formation, east-central New Mexico. Pages 111–114 *in* S. G. Lucas and D. S. Ulmer-Scholle, editors. Geology of the Llano Estacado. New Mexico Geological Society, Socorro, New Mexico. Guidebook 52. Available at http://nmgs.nmt.edu/publications/guidebooks/downloads/52/52_p0111_p0114.pdf (accessed January 2015).

Lucas, S. G. 2013. The Permian Artesia Formation in central New Mexico. New Mexico Museum of Natural History and Science Bulletin 59:227–232.

Lucas, S. G., and J. A. Effinger. 1991. *Mammuthus* from Lincoln County and a review of the mammoths from the Pleistocene of New Mexico. Pages 277–282 *in* J. M. Barker, B. S. Kues, G. S. Austin, and S. G. Lucas, editors. Geology of the Sierra Blanca, Sacramento and Capitan Ranges, New Mexico. New Mexico Geological Society, Socorro, New Mexico. Guidebook 42.

Available at http://nmgs.nmt.edu/publications/guidebooks/downloads/42/42_p0277_p0282.pdf (accessed December 2014).

Lucas, S. G., and A. P. Hunt. 1987. Stratigraphy of the Anton Chico and Santa Rosa Formations, Triassic of east-central New Mexico. Arizona-Nevada Academy of Science Journal 22(1):21–33.

Lucas, S. G., and A. P. Hunt. 1989. Revised Triassic stratigraphy in the Tucumcari basin, east-central New Mexico. Pages 150–170 *in* S. G. Lucas and A. P. Hunt, editors. Dawn of the age of dinosaurs in the American southwest. New Mexico Museum of Natural History and Science, Albuquerque, New Mexico.

Lucas, S. G., and K. K. Keitzke. 1993. Calcareous microfossils from the Upper Triassic of Petrified Forest National Park, Arizona. Journal of the Arizona–Nevada Academy of Science 27(1):55–68.

Lucas, S. G., and B. S. Kues. 1994. Third-day road log: Permian strata at Horse Mountain. Pages 106–111 *in* R. M. Chamberlin, B. S. Kues, S. M. Cather, J. M. Barker, and W. C. McIntosh, editors. Mogollon Slope, west-central New Mexico and east-central Arizona. New Mexico Geological Society, Socorro, New Mexico. New Mexico Geological Guidebook 45.

Lucas, S. G., and M. Morales. 1985. Middle Triassic amphibian from basal Santa Rosa Formation, east-central New Mexico. Pages 56–61 *in* S. G. Lucas, editor. Santa Rosa-Tucumcari region. New Mexico Geological Society, Socorro, New Mexico. Guidebook 36.

Lucas, S. G., A. P. Hunt, and M. Morales. 1985. Stratigraphic nomenclature and correlation of Triassic rocks of east-central New Mexico: a preliminary report. Pages 171–184 *in* S. G. Lucas and J. Zidek, editors. Santa Rosa, Tucumcari Region. New Mexico Geological Society, Socorro, New Mexico. Guidebook 36. Available at http://nmgs.nmt.edu/publications/guidebooks/downloads/36/36_p0171_p0184.pdf (accessed January 2015).

Lucas, S. G., A. P. Hunt, and P. Huber. 1990. Triassic stratigraphy in the Sangre de Cristo Mountains, New Mexico. Pages 305–318 *in* P. W. Bauer, S. G. Lucas, C. K. Mawer, and W. C McIntosh, editors. Tectonic development of the southern Sangre de Cristo Mountains, New Mexico. New Mexico Geological Society, Socorro, New Mexico. Guidebook 41. Available at http://nmgs.nmt.edu/publications/guidebooks/downloads/41/41_p0305_p0318.pdf (accessed January 2015).

Lucas, S. G., O. J. Anderson, and A. P. Hunt. 1994. Triassic stratigraphy and correlations, Southern High Plains of New Mexico-Texas. New Mexico Bureau of Geology and Mineral Resources Socorro, New Mexico. Bulletin 150:105–126.

Lucas, S. G., A. B. Heckert, J. W. Estep, and O. J. Anderson. 1997. Stratigraphy, biostratigraphy, and sequence stratigraphy of the Upper Triassic Chinle Group, Four Corners region. Pages 81–107 *in* O. J. Anderson, B. Kues, and S. G. Lucas, editors. Mesozoic geology and paleontology of the

Four Corners Region. New Mexico Geological Society, Socorro, NM. Field Conference Guidebook 48.

Lucas, S. G., A. B. Heckert, and A. P. Hunt. 2001. Triassic stratigraphy, biostratigraphy and correlation in east-central New Mexico. Pages 85–102 *in* S. G. Lucas and D. S. Ulmer-Scholle, editors. Geology of the Llano Estacado. New Mexico Geological Society, Socorro, New Mexico. Guidebook 52. Available at http://nmgs.nmt.edu/publications/guidebooks/downloads/52/52_p0085_p0102.pdf (accessed January 2015).

Lucas, S. G., A. B. Heckert, and A. P. Hunt. 2003. Tetrapod footprints from the Middle Triassic (Perovkan-early Anisian) Moenkopi Formation, west-central New Mexico. Pages 231–240 *in* S. G., Lucas, S. C. Semken, W. Berglof, and D. Ulmer-Scholle, editors. Geology of the Zuni Plateau. New Mexico Geological Society, Socorro, New Mexico. Guidebook 54. Available at http://nmgs.nmt.edu/publications/guidebooks/downloads/54/54_p0241_p0244.pdf (accessed January 2015).

Lucas, S. G., K. Krainer, and R. M., Colpitts, Jr. 2005a. Abo-Yeso (Lower Permian) stratigraphy in central New Mexico. New Mexico Museum of Natural History and Science Bulletin 31:101–117.

Lucas, S. G., J. A. Smith, and A. P. Hunt. 2005b. Tetrapod tracks from the Lower Permian Yeso Group, central New Mexico. New Mexico Museum of Natural History and Science Bulletin 31:121–124.

Lucas, S. G., M. G. Lockley, A. P. Hunt, and L. H. Tanner. 2006. Biostratigraphic significance of tetrapod footprints from the Triassic-Jurassic Wingate Sandstone on the Colorado Plateau. New Mexico Museum of Natural History and Science Bulletin 37:109–117.

Lucas, S. G., A. B. Heckert, J. A. Spielmann, L. H. Tanner, and A. P. Hunt. 2007. Third day: Triassic stratigraphy and paleontology in northeastern Arizona. New Mexico Museum of Natural History and Science Bulletin 40:189–197

Lucas, S. G., K. Krainer, and S. Voigt. 2013a. The Lower Permian Yeso Group in central New Mexico. New Mexico Museum of Natural History and Science Bulletin 59:181–199.

Lucas, S. G., K. Krainer, and R. J. Brose. 2013b. The Lower Permian Glorieta Sandstone in central New Mexico. New Mexico Museum of Natural History and Science Bulletin 59:201–211.

Lupe, R. 1988. Interpretive depositional history of the Santa Rosa Formation at the principal reference section. Pages 13–18 *in* W. I. Finch, editor. Principal reference section for the Santa Rosa Formation of Middle and Late Triassic age, Guadalupe County, New Mexico. U.S. Geological Survey, Reston, VA. Bulletin 1804. Available at http://pubs.er.usgs.gov/publication/b1804 (accessed January 2015).

Mack, G. H. 2003. Lower Permian terrestrial paleoclimatic indicators in New Mexico and their comparison to paleoclimate models. Pages 231–240 *in* S. G., Lucas, S. C. Semken, W. Berglof,

and D. Ulmer-Scholle, editors. Geology of the Zuni Plateau. New Mexico Geological Society, Socorro, New Mexico. Guidebook 54. Available at http://nmgs.nmt.edu/publications/guidebooks/downloads/54/54_p0231_p0240.pdf (accessed January 2015).

Mack, G. H., and E. M. Bauer. 2014. Depositional environments, sediment dispersal, and provenance of the Early Permian (Leonardian) Glorieta Sandstone, central New Mexico. Pages 261–271 in G. Rawling, V. T. McLemore, S. Timmons, and N. Dunbar, editors. Geology of the Sacramento Mountains region. New Mexico Geological Society, Socorro, New Mexico. Guidebook 65.

Mack, G. H., and P. A. Dinterman. 2002. Depositional environments and paleogeography of the Lower Permian (Leonardian) Yeso and correlative formations in New Mexico. Mountain Geologist 39(4):75–88.

Marcou, J. 1858. Geology of North America. Zurcher and Furrer, Zurich, Switzerland. Available at https://archive.org/details/geologynorthame00marcgoog (accessed January 2015).

McKee, E. D. 1937. Triassic pebbles in northern Arizona containing invertebrate fossils. American Journal of Science 33(196):260–263.

McKee, E. D. 1954. Stratigraphy and history of the Moenkopi Formation of Triassic age. Geological Society of America, Boulder, Colorado. Memoir 61.

McNutt, C. H. 1969. Early Puebloan occupations at Tesuque By-Pass and in the upper Rio Grande Valley. University of Michigan, Museum of Anthropology, Ann Arbor, Michigan. Anthropological Papers 40.

Meek, F. B., and F. V. Hayden. 1859. Geological explorations in Kansas Territory. Proceedings of the Academy of Natural Sciences of Philadelphia 11:8-30. Available at http://biodiversitylibrary.org/page/26310398 (accessed January 2015).

Miller, G. L., and S. R. Ash. 1988. The oldest freshwater decapod crustacean from the Triassic of Arizona. Palaeontology 31(2):272–279.

Miller, J. P., A. Montgomery, and P. K. Sutherland. 1963. Geology of part of the southern Sangre de Cristo Mountains, New Mexico. New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico. Memoir 11.

Milner, S. 1976. Carbonate petrology and syndepositional facies of the lower San Andres Formation (middle Permian), Lincoln County, New Mexico. Journal of Sedimentary Petrology 46(3):463–482.

Milner, S. 1978. Genesis, provenance, and petrography of the Glorieta Sandstone of eastern New Mexico. New Mexico Bureau of Geology and Mineral Resources, Socorro, New Mexico. Circular 165.

Morgan, G. S., and S. G. Lucas. 2000. Pliocene and Pleistocene vertebrate faunas from the Albuquerque Basin, New Mexico. New Mexico Museum of Natural History and Science Bulletin 16:217–240.

Morgan, G. S., and S. G. Lucas. 2005a. Pleistocene vertebrates from Rio Arriba and Taos counties, northernmost New Mexico. Pages 416–424 *in* S. G. Lucas, K. E. Zeigler, V. W. Lueth, and D. E. Owen, editors. Geology of the Chama Basin. New Mexico Geological Society, Socorro, New Mexico. Guidebook 56. Available at http://nmgs.nmt.edu/publications/guidebooks/downloads/56/56_p0416_p0424.pdf (accessed January 2015).

Morgan, G. S., and S. G. Lucas. 2005b. Pleistocene vertebrate faunas in New Mexico from alluvial, fluvial, and lacustrine deposits. New Mexico Museum of Natural History and Science Bulletin 28:185–248.

Morgan, G. S., S. G. Lucas, P. L. Sealey, and A. P. Hunt. 2001. A review of Pleistocene vertebrate faunas from northeastern New Mexico. Pages 265–284 *in* S. G. Lucas and D. S. Ulmer-Scholle, editors. Geology of the Llano Estacado. New Mexico Geological Society, Socorro, New Mexico. Guidebook 52. Available at http://nmgs.nmt.edu/publications/guidebooks/downloads/52/52_p0265_p0284.pdf (accessed January 2015).

National Park Service. 2006. Geologic resource evaluation scoping summary: Pecos National Historical Park, New Mexico. National Park Service, Geologic Resources Division, Denver, Colorado. Available at http://www.nature.nps.gov/geology/inventory/publications/s_summaries/PECO_scoping_summary_2006-0504.pdf (accessed January 2015).

NPS Geologic Resources Inventory Program. 2009. Digital Geologic Map of Pecos National Historical Park and Vicinity, New Mexico (NPS, GRD, GRI, PECO, PECO digital map). NPS Geologic Resources Inventory Program. Lakewood, Colorado. Geospatial Dataset-1047622. Available at https://irma.nps.gov/App/Reference/Profile/1047622 (accessed January 2015).

Newberry, J. S. 1861. Geological report. In J. C. Ives. Report upon the Colorado River of the West. U.S. 36th Congress, 1st Session, Senate Executive Document and House Executive Document 90(3). Available at https://archive.org/details/reportuponcolor00engigoog (accessed January 2015).

Newberry, J. S. 1876. Geological report. Pages 9–118 *in* J. N. Macomb. Report of the exploring expedition from Santa Fe, New Mexico, to the junction of the Grand and Green rivers of the Great Colorado of the West in 1859. Government Printing Office, Washington, D.C. U.S. Army Engineer Department. Available at https://archive.org/details/reportexploring00newbgoog (accessed January 2015).

Parker, W. G. 2004. Fossil pollen. Petrified Forest National Park. Available at http://www.nps.gov/pefo/naturescience/fossil-pollen-taxa.htm (accessed January 2015).

Parker, W. G. 2005. Faunal review of the Upper Triassic Chinle Formation of Arizona. Mesa Southwest Museum Bulletin 11:34–54.

Parker, W. G., and S. Ash. 2004. Kingdom Plantae (fossils). Petrified Forest National Park. Available at http://www.nps.gov/pefo/naturescience/kingdom-plantaea-fossils.htm (Accessed January 2015).

Parker, W. G., and J. W. Martz. 2011. The Late Triassic (Norian) Adamanian–Revueltian tetrapod faunal transition in the Chinle Formation of Petrified Forest National Park, Arizona. Earth and Environmental Science Transactions of the Royal Society of Edinburgh 101:231–260.

Parrish, J. M. 1989. Vertebrate paleoecology of the Chinle Formation (Late Triassic) of the southwestern United States. Palaeogeography, Palaeoclimatology, Palaeoecology 72(3–4):227–247.

Pipiringos, G. N., and R. B. O'Sullivan. 1978. Principal unconformities in Triassic and Jurassic rocks, Western Interior United States—a preliminary survey. U.S. Geological Survey, Reston, Virginia. Professional Paper 1035-A. Available t http://pubs.er.usgs.gov/publication/pp1035A (accessed January 2015).

Port, R. 2015. Pecos National Historical Park: geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2015/915. National Park Service, Fort Collins, Colorado. Available at http://www.nature.nps.gov/geology/inventory/publications/reports/peco_gri_rpt_view.pdf (accessed May 2015).

Ramezani, J., G. D. Hoke, D. E. Fastovsky, S. A. Bowring, F. Therrien, S. I. Dworkin, S. C. Atchley, and L. C. Nordt. 2011. High-precision U-Pb zircon geochronology of the Late Triassic Chinle Formation, Petrified Forest National Park (Arizona, USA): temporal constraints on the early evolution of dinosaurs. Geological Society of America Bulletin 123(11–12):2142–2159.

Rawling, G. C. 2010. Pecos National Historical Park. Pages 283–289 *in* L. G. Price, editor. The geology of northern New Mexico's parks, monuments, and public lands. New Mexico Bureau of Geology and Mineral Resources, Socorro, New Mexico.

Read, A., and G. Rawling. 2002. Geology of the Pecos 7.5-minute quadrangle, San Miguel and Santa Fe counties. New Mexico Bureau of Geology and Mineral Resources, Socorro, New Mexico. Open-File Geologic Map Series 52. Scale 1:24,000. Available at https://geoinfo.nmt.edu/publications/maps/geologic/ofgm/details.cfml?volume=52 (accessed January 2015).

Riggs, N. R., S. R. Ash, A. P. Barth, G. E. Gehrels, and J. L. Wooden. 2003. Isotopic age of the Black Forest Bed, Petrified Forest Member, Chinle Formation, Arizona: An example of dating a continental sandstone. Geological Society of America Bulletin 115(11):1315–1323.

Rinehart, L. F., and S. G. Lucas. 2011. Nonmarine bivalves (Unionoida, Anthracosiidae) from the Early Permian (Wolfcampian) Sangre de Cristo Formation in north-central New Mexico. New Mexico Museum of Natural History and Science Bulletin 53:143–148.

Rinehart, L. F., S. G. Lucas, and A. B. Heckert. 2003. An early eubrachyuran (Malacostraca, Decapoda) from the Upper Triassic Snyder Quarry, Petrified Forest Formation, north-central New Mexico. New Mexico Museum of Natural History and Science Bulletin 24:67–70.

Rinehart, L. F., S. Voigt, S. G. Lucas, A. Cantrell, and T. Suazo. 2010. Preliminary taphonomic analysis of a Middle Triassic (Perovkan) amphibian bonebed in northeastern New Mexico, USA. Abstracts with Programs - Geological Society of America 42(5):633.

Robertson, J. M., A. J. Budding, F. E. Kottlowski, H. L. James, and A. K. Armstrong. 1979. Third day: road log from Lamy Junction to Cowles via Glorieta, Pecos National Monument, Pecos, Tererro and Pecos Mine. Pages 29–41 *in* R. V. Ingersoll, L. A. Woodward, and H. L. James, editors. Santa Fe country. New Mexico Geological Society, Socorro, New Mexico. Guidebook 30.

Romer, A. S. 1960. The vertebrate fauna of the New Mexico Permian. Pages 48–54 *in* E. C. Beaumont and C. B. Read, editors. Rio Chama country. New Mexico Geological Society, Socorro, New Mexico. Guidebook 11. Available at https://nmgs.nmt.edu/publications/guidebooks/downloads/11/11_p0048_p0054.pdf (accessed January 2015).

Rowe, M. C., J. A. Wolff, J. N. Gardner, F. C. Ramos, R. Teasdale, and C. E. Heikoop. 2007. Development of a continental volcanic field: petrogenesis of pre-caldera intermediate and silicic rocks and origin of the Bandelier magmas, Jemez Mountains (New Mexico, USA). Journal of Petrology 48(11):2063–2091.

Santucci, V. L., and A. L. Koch. 2003. Paleontological resource monitoring strategies for the National Park Service. Park Science 22(1):22–25. Available at http://www.nature.nps.gov/ParkScience/archive/PDF/ParkScience22%281%29Fall2003.pdf (accessed January 2015).

Santucci, V. L., J. P. Kenworthy, and A. L. Mims. 2009. Monitoring in situ paleontological resources. Pages 189–204 *in* R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado.

Sayre, W. O., and M. H. Ort. 2011. A geologic study of the Capulin Volcano National Monument and surrounding areas, Union and Colfax counties, New Mexico. New Mexico Bureau of

Geology and Mineral Resources, Socorro, New Mexico. Open File Report 541. Available at http://geoinfo.nmt.edu/publications/openfile/details.cfml?Volume=541 (accessed January 2015).

Soegaard, K., and K. R. Caldwell. 1990. Depositional history and tectonic significance of alluvial sedimentation in the Permo-Pennsylvanian Sangre de Cristo Formation, Taos Trough, New Mexico. Pages 277–289 *in* P. W. Bauer, S. G. Lucas, C. K. Mawer, and W. C McIntosh, editors. Tectonic development of the southern Sangre de Cristo Mountains, New Mexico. New Mexico Geological Society, Socorro, New Mexico. Guidebook 41. Available at http://nmgs.nmt.edu/publications/guidebooks/downloads/41/41_p0277_p0289.pdf (accessed January 2015).

Spaulding, W. G. 1992. Late Quaternary and paleoclimates and sources of paleoenvironmental data in the vicinity of Los Alamos National Laboratory final report. University of California, Los Alamos National Laboratory, prepared by Dames and Moore, Las Vegas, Nevada.

Springer, A. 1902. On some living and fossil snails of the genus *Physa*, found at Las Vegas, N Mex. Proceedings of the Academy of Natural Sciences of Philadelphia 54:513–516. Available at http://www.jstor.org/stable/4062756 (accessed January 2015).

Stanesco, J. D. 1991. Sedimentology and depositional environments of the Lower Permian Yeso Formation, northwestern New Mexico. U.S. Geological Survey, Reston, Virginia. Bulletin 1808-M. Available at http://pubs.er.usgs.gov/publication/b1808M (accessed January 2015).

Stewart, J. H., F. G. Poole, and R. F. Wilson. 1972a. Stratigraphy and origin of the Chinle Formation and related Upper Triassic strata in the Colorado Plateau region. U.S. Geological Survey, Washington, D.C. Professional Paper 690. Available at http://pubs.er.usgs.gov/publication/pp690 (accessed January 2015).

Stewart, J. H., F. G. Poole, and R. F. Wilson. 1972b. Stratigraphy and origin of the Triassic Moenkopi Formation and related strata in the Colorado Plateau area. U.S. Geological Survey, Washington, D.C. Professional Paper 691. Available at http://pubs.er.usgs.gov/publication/pp691 (accessed January 2015).

Strickland, L. E., R. S. Thompson, and K. H. Anderson. 2001. USGS/NOAA North American packrat midden database data dictionary. U.S. Geological Survey, Reston, VA. Open File Report 01-022. Available at http://pubs.er.usgs.gov/publication/ofr0122 (accessed January 2015).

Sutherland, P. K., and F. H. Harlow. 1973. Pennsylvanian brachiopods and biostratigraphy in southern Sangre de Cristo Mountains, New Mexico. New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico. Memoir 27.

Tanke, D. H. 2005. Identifying lost quarries. Pages 34–53 *in* P. J. Currie and E. B. Koppelhus, editors. Dinosaur Provincial Park: a spectacular ancient ecosystem revealed. Indiana University Press, Bloomington and Indianapolis, Indiana.

Tapanila, L., and E. M. Roberts. 2012. The earliest evidence of holometabolan insect pupation in conifer wood. PLoS ONE 7(2):e31668. Available at http://www.plosone.org/article/info%3Adoi%2F10.1371%2Fjournal.pone.0031668 (accessed January 2015).

Tweet, J. S., V. L. Santucci, and A. P. Hunt. 2012. An inventory of packrat (*Neotoma* spp.) middens in National Park Service areas. New Mexico Museum of Natural History and Science Bulletin 57:355–368.

Vachard, D., K. Krainer, and S. G. Lucas. 2013. The Artinskian-Kungurian (upper Lower Permian) calcareous algae and smaller foraminifers of the Yeso Group and San Andres Formation (New Mexico, USA). New Mexico Museum of Natural History and Science Bulletin 59:347–348.

Vaughn, P. P. 1964. Evidence of aestivating lungfish from the Sangre de Cristo Formation, Lower Permian of northern New Mexico. Los Angeles County Museum Contributions in Science 80. Available at http://www.nhm.org/site/sites/default/files/pdf/contrib_science/CS80.pdf (accessed January 2015).

Voigt, S., S. G. Lucas, and L. F. Rinehart. 2012. Early Permian tetrapod ichnofauna from the Sangre de Cristo Formation of north-central New Mexico. New Mexico Geology 34(2):58.

Walker, M. V. 1938. Evidence of Triassic insects in the Petrified Forest National Monument, Arizona. U.S. National Museum Proceedings 85(3033):137–141.

Wilkinson, C. E., Jr., S. M. Ritter, L. L. Lambert, and G. L. Wilde. 1991. Stratigraphy and biostratigraphy of the lower and middle San Andres Formation in Last Chance Canyon, Guadalupe Mountains, New Mexico. Pages 99–110 *in* S. Meader-Roberts, M. P. Candelaria, and G. E. Moore, editors. Sequence stratigraphy, facies, and reservoir geometries of the San Andres, Grayburg, and Queen formations, Guadalupe Mountains, New Mexico and Texas. Society of Economic Paleontologists and Mineralogists, Permian Basin Chapter, West Texas Geological Society, Midland, Texas. Publication 91-32.

Additional References

Ash, S. R. 1972. Upper Triassic Dockum flora of eastern New Mexico and Texas. Pages 124–128 *in* V. C. Kelley and F. D. Trauger, editors. East-central New Mexico. New Mexico Geological Society, Socorro, New Mexico. Guidebook 23. Available at http://nmgs.nmt.edu/publications/guidebooks/downloads/23/23_p0124_p0128.pdf (accessed December 2014).

Baltz, E. H., and D. A. Myers. 1999. Stratigraphic framework of upper Paleozoic rocks, southeastern Sangre de Cristo Mountains, New Mexico, with a section on speculations and implications for regional interpretation of Ancestral Rocky mountains paleotectonics. New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico. Memoir 48.

Berman, D. S., and R. R. Reisz. 1980. A new species of Trimerorhachis (Amphibia, Temnospondyli) from the Lower Permian of New Mexico, with discussions of Permian faunal distribution in that state. Annals of the Carnegie Museum of Natural History 49:455–485.

Berman, D. S., and R. R. Reisz. 1986. Captorhinid reptiles from the Early Permian of New Mexico, with description of new genus and species. Annals of the Carnegie Museum of Natural History 55:1–28.

Berman, D. S., S. S. Sumida, and R. E. Lombard. 1992. Reinterpretation of the temporal and occipital regions in *Diadectes* and the relationships of diadectomorphs. Journal of Paleontology 66:481–499.

Brezinski, D. K. 1991. Permian trilobites from the San Andres Formation, New Mexico, and their relationship to species from the Kaibab Formation of Arizona. Journal of Paleontology 65(3):480–484.

Dean, J. S., W. J. Robinson, and M. R. Rose. 1982. Dendroclimatic reconstructions for Arroyo Hondo, New Mexico: A.D. 900-1970. Program and Abstracts - American Quaternary Association. Conference 7:89.

Drakos, P. G., S. L. Reneau, and G. S. Morgan. 2007. *Bison antiquus* occurrence and Pleistocene-Holocene stratigraphy, Canada del Buey, Pajarito Plateau, New Mexico. Pages 441–448 *in* B. S. Kues, S. A. Kelley, and V. W. Lueth, editors. Geology of the Jemez Region II. New Mexico Geological Society, Socorro, New Mexico. Guidebook 58. Available at http://nmgs.nmt.edu/publications/guidebooks/downloads/58/58_p0441_p0448.pdf (accessed January 2015).

Elias, S. A. 1997. The Ice Age history of southwestern National Parks. Smithsonian Institution Press, Washington, D.C.

Ellwood, B. B. 1996. Geology and America's National Park areas. Prentice Hall, Upper Saddle River, New Jersey.

Graham, R. W. 1987. Late Quaternary mammalian faunas and paleoenvironments of the southwestern Plains of the United States. Pages 24–86 *in* R. W. Graham, H. A. Semken, Jr., and M. A. Graham, editors. Late Quaternary mammalian biogeography and environments of the Great Plains and prairies. Illinois State Museum, Springfield, Illinois. Scientific Papers 22.

Harris, A. H. 1985. Late Pleistocene vertebrate paleoecology of the west. University of Texas Press, Austin, Texas.

Hay, O. P. 1924. The Pleistocene of the middle region of North America and its vertebrated animals. Carnegie Institute of Washington Publication 322A. Available at https://archive.org/details/pleistoceneofmid00hayo (accessed January 2015).

Hay, O. P. 1927. The Pleistocene of the western region of North America and its vertebrated animals. Carnegie Institute of Washington Publication 322B.

Heckert, A. B. 2007. *Colognathus obscurus* Case, an unusual vertebrate index fossil of Adamanian (St. Johnsian: latest Carnian) time, from the Upper Triassic of the American Southwest. Abstracts with Programs - Geological Society of America 39(2):30.

Heckert, A. B., S. G. Lucas, and R. M. Sullivan. 2000. Triassic dinosaurs in New Mexico. New Mexico Museum of Natural History and Science Bulletin 17:17–26.

Holliday, V. T. 1997. Paleoindian geoarchaeology of the southern High Plains. University of Texas Press, Austin, Texas.

Kelley, V. C. 1972. Outcropping Permian shelf formations of eastern New Mexico. Pages 72–78 *in* V. C. Kelley and F. D. Trauger, editors. East-central New Mexico. New Mexico Geological Society Guidebook 23. Available at http://nmgs.nmt.edu/publications/guidebooks/downloads/23/23_p0072_p0078.pdf (accessed January 2015).

Lang, R. W., and A. H. Harris. 1984. The faunal remains from Arroyo Hondo Pueblo, New Mexico: a study in short-term subsistence change. School of American Research Press, Santa Fe, New Mexico. Arroyo Hondo Archaeological Series 5.

Lucas, S. G., and A. P. Hunt. 1993. A dicynodont from the Upper Triassic of New Mexico and its biochronologic significance. New Mexico Museum of Natural History and Science Bulletin 3:321–325.

Lucas, S. G., and K. E. Zeigler. 2004. Permian stratigraphy in the Lucero Uplift, central New Mexico. New Mexico Museum of Natural History and Science Bulletin 25:71–82.

Mayor, A. 2005. Fossil legends of the first Americans. Princeton University Press, Princeton, New Jersey.

Morgan, G. S., and S. G. Lucas. 1999. Pliocene (Blancan) vertebrates from the Albuquerque Basin, north-central New Mexico. Pages 363–370 *in* F. J. Pazzaglia and S. G. Lucas, editors. Albuquerque geology. New Mexico Geological Society Guidebook 50. Available at http://nmgs.nmt.edu/publications/guidebooks/downloads/50/50_p0363_p0370.pdf (accessed January 2015).

Olsen, S. J. 1971. Zooarchaeology: animal bones in archaeology and their interpretation. Addison-Wesley Publishing Company, New York City, New York.

Strimple, H. L. 1980. Pennsylvanian crinoids from Sangre de Cristo and Sacramento Mountains of New Mexico. New Mexico Bureau of Geology and Mineral Resources, Socorro, New Mexico. Circular 178.

Tanner, W. F. 1963. Permian shoreline of central New Mexico. Bulletin of the American Association of Petroleum Geologists 47(8):1604–1610.

Data Sets

Pecos National Historical Park Paleontological Archives
5/1985–present. (hard copy data; reports; electronic data; photographs; maps; publications). Originated by Santucci, Vincent; status: Active.

Pecos National Historical Park Collections
1965–present. (museum specimens; associated specimen notes; collection records; maps; etc.). Originated by PECO staff; status: Active.

Pecos National Historical Park Digital Geologic Map
2009–present. (geologic map data; electronic files; GIS metadata; associated report). Originated by NPS-Geologic Resources Inventory staff; status: Active. Online. https://irma.nps.gov/App/Reference/Profile/1047622.

Robert S. Peabody Museum of Archaeology
1915–present. (museum specimens; associated specimen notes; collection records; maps; etc.). Originated by Robert S. Peabody Museum of Archaeology staff; status: Active.

University of California Museum of Paleontology
1930s–present. (museum specimens; associated specimen notes; collection records; maps; etc.). Originated by UCMP staff; status: Active.

Western Archeological and Conservation Center
1960s?–present. (museum specimens; associated specimen notes; collection records; maps; etc.). Originated by WACC staff; status: Active.

Sand Creek Massacre National Historic Site

Sand Creek Massacre National Historic Site (SAND) preserves the location of a historically significant incident which occurred during the Indian Wars (SAND Figure 1). On November 29, 1864, U.S. soldiers attacked a peaceful encampment of Cheyenne and Arapaho along Sand Creek (or Big Sandy Creek), killing over 150 people, mostly women, children, and the elderly. The Sand Creek Massacre had a profound influence on U.S.–Indian relations, and altered the Cheyenne and Arapaho cultures, which were already dealing with the effects of recent epidemics. SAND was authorized November 7, 2000, and established April 23, 2007. The site encompasses 5,092 ha (12,583 acres), 965.35 ha (2,385.43 acres) of which are federal.



SAND Figure 1. A view of intermittent Sand Creek from the bluffs (SAND/NPS).

Geologic Background

SAND is located in north-central Kiowa County, eastern Colorado. The historic site is within a relatively flat and sparsely-populated area of short-grass prairie. Sand Creek, a tributary of the Arkansas River which passes through SAND, is an intermittent stream. The small community of Eads is about 21 km (13 mi) southwest of SAND. Cheyenne Wells, Colorado is about 28 km (17 mi) north-northeast of SAND, Lamar, Colorado is about 60 km (37 mi) south of SAND, and Burlington, Colorado is about 80 km (50 mi) north-northeast of SAND. Primary documents on the geology and paleontology of the SAND area include Coffin (1967), Sharps (1976), De Vore (1999), Holmes and McFaul (1999), NPS (2000), Koch and Santucci (2003), Noon et al. (2005), Martin (2006, 2011), and Mensing (2007). Because SAND postdates the establishment of the Inventory & Monitoring program, it does not have the same coverage that the other units in the SOPN have, although it was included in the original SOPN paleontological resource inventory and summary (Koch and Santucci 2003).

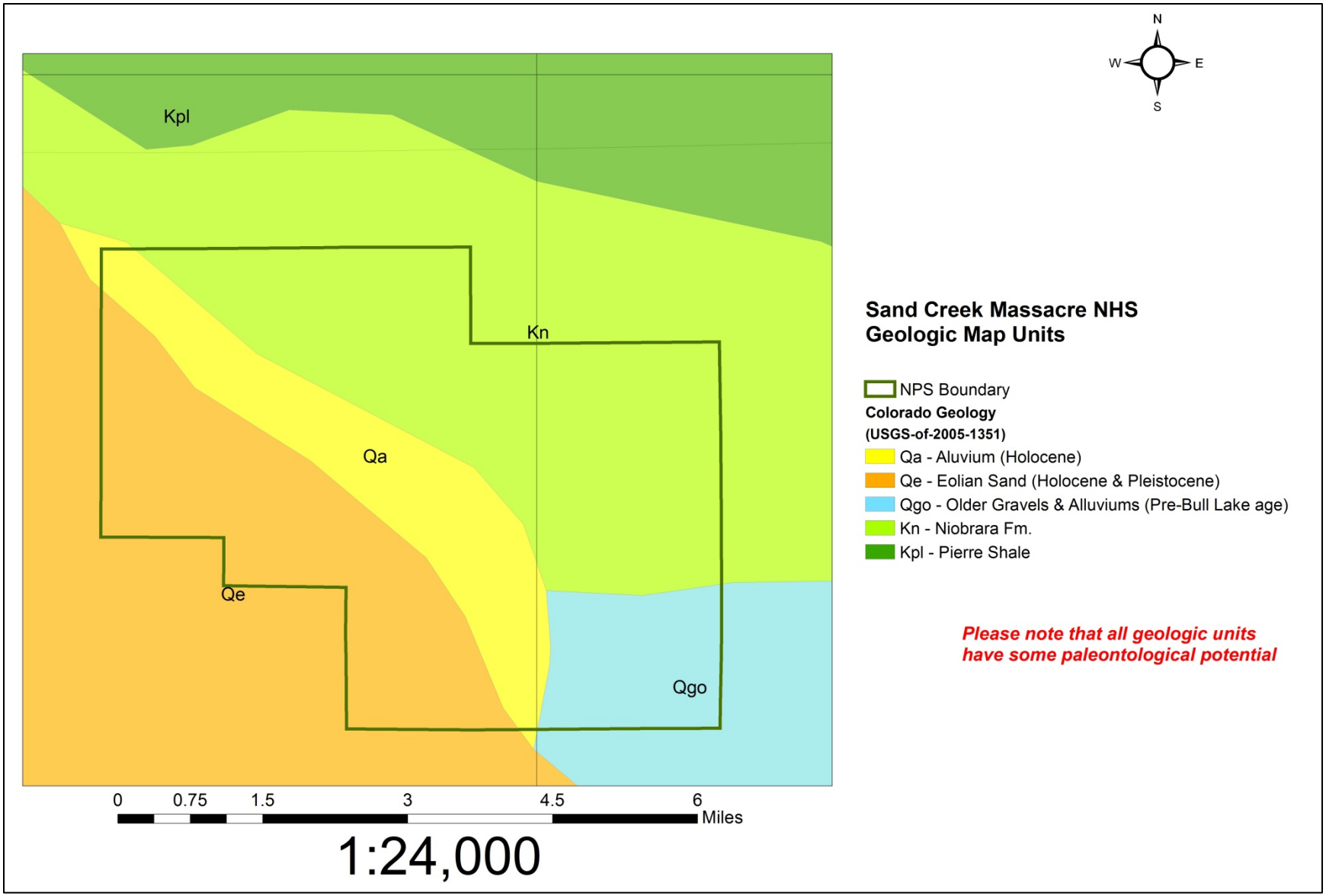
The rocks and sediments exposed at SAND and the immediate vicinity record Upper Cretaceous marine deposition and Quaternary deposition associated with Sand Creek (see Appendix A for a geologic time scale). Cretaceous rocks of the Niobrara Formation are present immediately beneath the surface of the historic site (Coffin 1967; Sharps 1976). These rocks were deposited in a shallow continental sea known as the Western Interior Seaway or Cretaceous Interior Seaway, which covered much of central North America from approximately 100 to 70 Ma (million years ago). At its greatest extent, the seaway extended from the Arctic to the Gulf of Mexico, bisecting North America (Elder and Kirkland 1993, 1994). Its advances (transgressions) and retreats (regressions) influenced the geology of numerous NPS units both within and outside of the Southern Plains Network (SOPN). Several major cycles of marine transgressions and regressions occurred (Kauffman et al. 1969; Scott et al. 1998), with smaller sea level rises and falls within them (Scott et al. 1998). Volcanoes to the west of the seaway introduced great quantities of ash, today preserved as bentonite layers (Hattin 1975). Stratification of the seawater, limiting oxygen in the depths, appears to have occurred over the course of the cycles (Hattin 1975; Kennedy et al. 1999; Da Gama et al. 2014). The cycles of transgressions and regressions ended after a mountain-building event toward the end of the Cretaceous, beginning roughly 75 Ma, uplifted the region far above sea level. This event, called the Laramide Orogeny, was the first step in the formation of the modern Rocky Mountains. Erosion wore down these peaks until tectonic activity resulted in renewed uplift during the past few million years (Sayre and Ort 2011).

Because of the absence of younger rocks, there is little direct evidence for geologic events that occurred at SAND during the approximately 70 million years that separate the Cretaceous seaway and the Quaternary, which began about 2.6 Ma. The Arkansas River was present to the south by the Quaternary, although its course has been steadily shifting (Sharps 1969). Sand Creek was also present by some point during the Pleistocene, as shown by the presence of multiple terraces. It eroded and reworked Pliocene and Pleistocene upland deposits composed of sediments from the Rocky Mountains (Coffin 1967). During the Late Pleistocene, western Kansas and the vicinity are interpreted as having had a taiga-like mix of conifer forest and aspen parkland, resembling the subalpine taiga of the modern Rockies (Wells and Stewart 1987). Fire events promoted parklands, which were replaced by forests within a century or two. The climate was more equable than present, with cooler, cloudier, and moister summers, and fewer droughts (Wells and Stewart 1987). Humans arrived in the region by the end of the Pleistocene (Hofman 2001).

Because of SAND's late entry into the I&M program, a geologic map has not yet been completed for the site by the Geologic Resources Division. At present, there are three geologic maps that are potential sources: the state geologic map by Tweto (1979); a map of the Lamar 1° x 2° topographic quadrangle by Sharps (1976); and a map of the Sand Creek valley by Coffin (1967). The state map has the advantages of being newest and in digital format, but is at the coarsest scale (1:500,000). The Lamar map is intermediate in age and scale (1:250,000), and is perhaps the most realistic for surficial geology in that it depicts the bedrock as buried rather than at the surface. The Sand Creek valley map is oldest, but has the best scale (1:125,000), shows the position of the township-range-section grid, and is narrowly focused on the Sand Creek valley. Therefore, it is probably the most optimal map of

the three for SAND, if the reader takes into account that the Cretaceous rocks of the area are poorly exposed when near the surface.

Geologic units exposed at the surface or present just beneath cover within SAND include the Upper Cretaceous Niobrara Formation (Smoky Hill Chalk Member), and Quaternary eolian (windblown), terrace, alluvial, and valley fill deposits (Coffin 1967; Sharps 1976) (SAND Figure 2). None of these units are known to be fossiliferous within the historic site at this time, but they have the potential to yield fossils (SAND Table 1).



SAND Figure 2. Schematic geologic map of SAND, based on a digital map derived from Tweto (1979).

SAND Table 1. Summary of SAND stratigraphy, fossils, and depositional settings in descending order of age, from youngest to oldest. Details and references can be found in the text.

Formation	Age	Fossils Within SAND	Depositional Environment
Quaternary sediments (alluvium, eolian, and older gravel)	Pleistocene–Holocene	None to date; pollen is most likely, given the historic pollen record	Windblown deposits and deposits associated with fluvial processes predominate
Niobrara Formation, Smoky Hill Chalk Member	Late Cretaceous	None to date; microfossils and bivalves are most likely	Marine

Potential Sources of Paleontological Resources

Fossils have not yet been documented from the following rock units within SAND. However, they are known to preserve fossils elsewhere, and future field investigations within the historic site may result in the discovery of fossils in one or more of them.

Niobrara Formation (Upper Cretaceous)

The Niobrara Formation is a widespread chalky and shaly formation on the Great Plains. This formation is often divided into two members: the Fort Hays Limestone Member and overlying Smoky Hill Chalk (or Shale) Member. The Smoky Hill Chalk Member is the unit immediately beneath the surface at SAND (Coffin 1967; Sharps 1976). Although depicted by Coffin (1967) as at the surface in eastern SAND, the author notes that it is poorly exposed and weathers quickly, so that it is usually concealed by a thin layer of silty clay. In this area, it is composed of thin-bedded chalky shale, more chalky in the upper section, more shaly in the middle section, and with harder limestone beds near the base (Sharps 1976). Although it is dark gray to black when freshly exposed (Coffin 1967), it weathers to a distinctive yellowish-gray color, which can be seen in the soil (Sharps 1976). It is between 150 and 210 m (500 and 700 ft) thick in the area (Sharps 1976), so any kind of deep drilling within the historic site should encounter a significant thickness of it. Thin bentonite beds are observed in some areas, and limestone concretions as much as a meter (3 ft) in diameter are common (Coffin 1967). The exact contact between the Smoky Hill Chalk Member and the overlying Pierre Shale is not known for certain in the area (Coffin 1967; Sharps 1976), but the two can be distinguished by the orange to yellow color of weathered Smoky Hill Chalk versus the drabber yellowish-brown color of weathered Pierre Shale, and the fact that the Pierre Shale is not calcareous (lacks calcium carbonate) (Coffin 1967).

Deposition of the Niobrara Formation occurred within an epicontinental sea over several million years. The age of the base of the formation becomes younger going north, east, and west from southern and central Colorado. According to the fossil content, deposition of the Niobrara Formation began shortly before 89 Ma in adjacent Hamilton County, Kansas (Merewether et al. 2007). Deposition of the Smoky Hill Chalk Member began shortly after, and continued to between 82 and 81 Ma (Da Gama et al. 2014). The first few million years of deposition occurred under relatively well-mixed and well-oxygenated water, with a warm surface temperature and high productivity. Water was drawn from both oceans to the north and south (Da Gama et al. 2014). The middle period of deposition saw the contribution of northern waters become less important, with an increase in terrestrial input and water stratification, and a decrease in oxygenation in the bottom waters. By the end of deposition, the surface water had become notably fresher from the terrestrial input, and the

water column was stagnant and strongly stratified, with the bottom water bordering on anoxia (Da Gama et al. 2014). Active volcanoes were present to the west, which provided the ash that eventually altered to form the bentonite beds (Diffendal and Voorhies 1994). The sea deepened throughout deposition (Hattin and Cobban 1977). The chalk of the Niobrara Formation is composed of fecal pellets, which in turn are made up of coccoliths (mineralized plates of plankton) (Da Gama et al. 2014). They may represent the feces of marine microorganisms like the tiny planktonic crustaceans known as copepods, which would have been feeding on coccolith-producing phytoplankton (Longman et al. 1998). Cyclic bedding of limestone with shale and marlstone in the underlying Fort Hays Limestone Member are attributed to climate and orbital variations, although mountain-building to the west and erosional events complicate the signal (Laferriere 1987).

The Niobrara Formation is famous for its fossils, which are found throughout the formation. The Smoky Hill Chalk Member will be the focus here because of its presence at SAND. Common fossils in the Smoky Hill Chalk Member of the Arkansas River region of eastern Colorado include the bivalve *Volviceramus* (formerly *Inoceramus*) *grandis*, oysters, ammonites, and fish fossils, especially scales (Dane et al. 1937). The fossil assemblage of the Smoky Hill Chalk Member over its entire depositional area is documented well enough that faunal changes can be observed over time (Everhart 2005). Microfossils, plant fossils, and invertebrate fossils from the Smoky Hill Chalk Member include nannofossils like coccoliths (Watkins et al. 1993; Shamrock and Watkins 2009), foraminifera (“amoebas with shells”) (Loetterle 1937; Frerichs and Gaskill 1988), dinoflagellates (single-celled organisms that move using one or more whip-like flagella), pollen, spores, algae, microscopic plant fragments (Da Gama et al. 2014), rare wood fragments (Everhart 2005), fragments of marine rushes (Simpson 1960), sponges (Everhart 2005), bivalves (including inoceramids and reef-forming rudists), ammonites, belemnites (squid-like cephalopods known from their bullet-shaped guards), squids, barnacles (Everhart 2005; Shimada et al. 2007), rare crustaceans, crinoids (sea lilies), worm tubes (Everhart 2005), invertebrate fecal pellets (Hattin and Cobban 1977), and burrows and trails (Scott and Cobban 1964).

The fossil vertebrate assemblage of the Smoky Hill Chalk Member includes diverse chondrichthyans (including guitarfish, ratfish, and sharks) and ray-finned fish (Everhart 2005; Shimada and Fielitz 2006; Shimada et al. 2007), rare coelacanths, several taxa of turtles, long-necked and large-skulled plesiosaurs, several mosasaur taxa (lizard-like marine reptiles), the marine lizard *Coniasaurus*, the pterosaurs (flying reptiles) *Nyctosaurus* and *Pteranodon*, rare dinosaurs (armored *Hierosaurus* and *Niobrarasaurus*, and the “duck-bill” *Claosaurus*), several birds (most famously the toothed seabirds *Hesperornis* and *Ichthyornis*, the former flightless) (Everhart 2005; Shimada et al. 2007), and coprolites (fossil feces), often containing invertebrate or vertebrate remains (Everhart 2005).

Quaternary rocks and sediments (Pleistocene–Holocene)

The Quaternary deposits of SAND include a combination of eolian (windblown) sand, alluvium, terrace, and valley fill deposits (Coffin 1967; Sharps 1976). The eolian sand deposits are particularly extensive on the west side of the creek (Coffin 1967; Sharps 1976), while loess and slopewash are more common on the east side (Sharps 1976). The deposits have not been formally dated, but may only be as old as the Pinedale glaciation (Sharps 1976), the regional representative of the most recent

major glacial advance (approximately 30,000 years maximum). A cross-section through southern SAND shows that the Quaternary deposits can be 15 to 30 m (50 to 100 ft) thick, although they would seem to thin to the north, because the Niobrara Formation is depicted as at the surface in much of eastern SAND (Coffin 1967). The valley fill and terrace deposits average 8 to 9 m (25 to 30 ft) thick, reaching as much as 21 m (70 ft) thick, and are composed of grains from gravel to clay size. The original source for most of the material was igneous and metamorphic rocks in the Rocky Mountains, which were eroded from the mountains during the Neogene and became part of upland deposits, and later reworked farther away by Sand Creek and other creeks. De Vore (1999) depicted three terraces above the modern floodplain and below the bluffs at SAND. Radiocarbon dates from soil show that the second terrace formed around 2000 years ago and the lowest terrace formed around 1000 years ago. The dune sand, which is generally sourced from valley fill, is composed of very fine to very coarse quartz sand grains. It is usually 3 to 6 m (10 to 20 ft) thick, but can be as much as 21 m (70 ft) thick (Coffin 1967).

Mensing (2007) described pollen from several sediment cores taken from two sites in SAND. A core from a creek site, with a depth of approximately 105 cm (41 in), included pollen-bearing sediment above 30 cm (12 in) and below approximately 90 cm (36 in). The upper pollen-bearing sediment has an extrapolated date of 1850 AD at the base, shortly before the massacre (Mensing 2007). The lower pollen-bearing sediment is undated, and so could be hundreds to thousands of years older. At this time, in the absence of dates, the older pollen-bearing sediment is most useful for showing the potential of discovering ancient pollen within SAND, which could be useful for climatological work at the historic site.

There are relatively few reports of Quaternary fossils within a 100 km (60 mi) radius of SAND. For example, the maps of Hay (1924) or the Neotoma paleoecology database (http://www.neotomadb.org/) show little for eastern Colorado and western Kansas. Terrestrial gastropods are a notable exception, with numerous faunas known from the Peorian loess of western Kansas. Small mammals (shrews, rodents) and conifer fragments are also fairly common (Wells and Stewart 1987). The most notable Quaternary site in the area is the Olsen-Chubbuck Bison Kill Site, about 12 km (7 mi) north of SAND. This site yielded the remains of at least 190 individuals of the extinct bison *Bison occidentalis*, killed about 10,150 ± 500 radiocarbon years before present (12,980 to 10,410 calibrated years before present) (Wheat 1972). (Note that radiocarbon dates are not the same as calendar dates, and must be calibrated to approximate calendar years. Dates can be calibrated using a calibration program such as Calib 7.1 [http://calib.qub.ac.uk/calib/] if error ranges are provided. “Present” in “before present” is 1950.) The hunters used tools made of a variety of materials, including bone, Alibates chert from Texas (see the Alibates Flint–Lake Meredith section of this report for more information), potentially fossiliferous Knife River flint from North Dakota, and petrified wood. The site also yielded ephedra, conifer, and angiosperm pollen (Wheat 1972). An archeological site of similar age has been found at Kanorado, Kansas, about 90 km (55 mi) northeast of SAND; interestingly, mammoth and camel bones were also found here at a lower horizon (Holen et al. 2004). Hay (1924) reported observing a Columbian mammoth tooth reputedly from Sharon Springs, Kansas, about 71 km (44 mi) northeast of SAND, on display in Portland, Oregon. Useful online paleontological resources for the southwestern United States include the Neotoma database

mentioned above, and Faunmap, which is the vertebrate element of Neotoma (http://www.ucmp.berkeley.edu/faunmap/).

Park Collections

No fossils are currently reported to be in SAND collections, and no SAND fossils are currently reported to be in the collections of other institutions.

Cultural Resource Connections

No fossils have been reported from cultural resource contexts at SAND, although such associations would not be unprecedented. The most likely type of cultural association for this area would be fossiliferous stone used for artifacts. For example, in the Southwest, petrified wood from the Upper Triassic Chinle Formation was often used for artifacts. The majority of parks in the neighboring Southern Colorado Plateau Network have examples (Tweet et al. 2009). Kenworthy and Santucci (2006) presented an overview and cited selected examples of National Park Service fossils found in cultural resource contexts.

Paleontological Resource Management, Preliminary Recommendations

- Staff from the historic site should be encouraged to observe exposed rocks and sedimentary deposits for fossil material while conducting their usual duties. To promote this, staff should also receive guidance regarding how to recognize common local fossils. When opportunities arise to observe paleontological resources in the field and take part in paleontological field studies with trained paleontologists, staff should take advantage of them, if funding and time permit.

- Staff should photodocument and monitor any occurrences of paleontological resources that may be observed in situ. Fossils and their associated geologic context (surrounding rock) should be documented but left in place unless they are subject to imminent degradation by artificially accelerated natural processes or direct human impacts. A Geologic Resource Monitoring Manual by the Geological Society of America and NPS Geologic Resources Division includes a section on paleontological resource monitoring (Santucci et al. 2009). Santucci and Koch (2003) present information on paleontologic resource monitoring.

- Fossils found in a cultural context should be documented like other fossils, but will also require the input of an archeologist or a cultural resource specialist. Any fossil which has a cultural context may be culturally sensitive as well (e.g., subject to NAGPRA) and should be regarded as such until otherwise established. The Geologic Resources Division can coordinate additional documentation/research of such material.

- Contact the NPS Geologic Resources Division for technical assistance with paleontological resource management issues.

References Cited

Coffin, D. L. 1967. Geology and ground-water resources of the Big Sandy Creek valley, Lincoln, Cheyenne, and Kiowa counties, Colorado. U.S. Geological Survey, Washington, D.C. Water-

Supply Paper 1843. Available at http://pubs.er.usgs.gov/publication/wsp1843 (accessed January 2015).

Da Gama, R. O. B. P., B. Lutz, P. Desjardins, M. Thompson, I. Prince, and I. Espejo. 2014. Integrated paleoenvironmental analysis of the Niobrara Formation: Cretaceous Western Interior Seaway, northern Colorado. Palaeogeography, Palaeoclimatology, Palaeoecology 413:66–80.

Dane, C. H., W. G. Pierce, and J. B. Reeside, Jr. 1937. The stratigraphy of the Upper Cretaceous rocks north of the Arkansas River in eastern Colorado. U.S. Geological Survey, Washington, D.C. Professional Paper 186-K. Available at http://pubs.er.usgs.gov/publication/pp186K (accessed January 2015).

De Vore, S. L. 1999. Geophysical investigations at the Sand Creek Massacre Site. National Park Service Intermountain Support Office, Santa Fe, New Mexico. Available at http://www.nps.gov/sand/naturescience/upload/Geophysical-Investigations.pdf (accessed January 2015).

Diffendal, R. F., Jr., and M. R. Voorhies. 1994. Geologic framework of the Niobrara River drainage basin and adjacent areas in South Dakota generally east of the 100th meridian west longitude and west of the Missouri River. Nebraska Geological Survey, Lincoln, NE. Report of Investigations 9. Available at http://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1093&context=geosciencefacpub (accessed January 2015).

Elder, W. P., and J. I. Kirkland. 1993. Cretaceous paleogeography of the Colorado Plateau and adjacent areas. Museum of Northern Arizona Bulletin 59:129–151.

Elder, W. P., and J. I. Kirkland. 1994. Cretaceous paleogeography of the southern Western Interior region. Pages 415–440 *in* M. V. Caputo, J. A. Peterson, and K. J. Franczyk, editors. Mesozoic System of the Rocky Mountain region, USA. Rocky Mountain Section, Society for Sedimentary Geology, Denver, Colorado.

Everhart, M. J. 2005. Oceans of Kansas: a natural history of the Western Interior Sea. Indiana University Press, Bloomington and Indianapolis, Indiana.

Frerichs, W. E., and C. Gaskill. 1988. Planktic foraminifera and age of the Niobrara Formation in its type area. Contributions to Geology 26(1):5–13.

Hattin, D. E. 1975. Stratigraphy and depositional environment of Greenhorn Limestone (Upper Cretaceous) of Kansas. Kansas Geological Survey, Lawrence, Kansas. Bulletin 209. Available at http://www.kgs.ku.edu/Publications/Bulletins/209/index.html (accessed January 2015).

Hattin, D. E., and W. A. Cobban. 1977. Upper Cretaceous stratigraphy, paleontology and paleoecology of western Kansas. Mountain Geologist 14(3–4):175–217.

Hay, O. P. 1924. The Pleistocene of the middle region of North America and its vertebrated animals. Carnegie Institute of Washington Publication 322A. Available at https://archive.org/details/pleistoceneofmid00hayo (accessed January 2015).

Hofman, J. L. 2001. Human occupations across the Pleistocene-Holocene transition on the Great Plains: geomorphic and regional patterns. Abstracts with Programs - Geological Society of America 33(6):287.

Holen, S. R., R. D. Mandel, and J. L. Hofman. 2004. Preliminary evidence of stratified Clovis campsites on the High Plains of northwestern Kansas. Program and Abstracts - American Quaternary Association. Conference 18:144–145.

Holmes, A. M., and M. McFaul. 1999. Geoarchaeological assessment of the Sand Creek Massacre Site, Kiowa County, Colorado. Laramie Soils Service, Laramie, Wyoming. Available at http://www.nps.gov/sand/naturescience/upload/geoarchaeological-assessment_1999-10-18.pdf (accessed January 2015).

Kauffman, E. G., J. D. Powell, and D. E. Hattin. 1969. Cenomanian-Turonian facies across the Raton Basin. The Mountain Geologist 6(3):93–118.

Kennedy, W. J., W. A. Cobban, W. P. Elder, and J. I. Kirkland. 1999. Lower Turonian (Upper Cretaceous) *Watinoceras devonense* Zone ammonite fauna in Colorado, USA. Cretaceous Research 20(5):629–639.

Kenworthy, J. P., and V. L. Santucci. 2006. A preliminary investigation of National Park Service paleontological resources in cultural resource contexts, Part 1: general overview. New Mexico Museum of Natural History and Science Bulletin 34:70–76. Available at http://nature.nps.gov/geology/paleontology/pub/fossil_conference_7/9%20Kenworthy.pdf (accessed December 2014).

Koch, A. L., and V. L. Santucci. 2003. Sand Creek Massacre National Historic Site. Page 30 *in* A. L. Koch and V. L. Santucci. Paleontological resource inventory and monitoring: Southern Plains Network. TIC# D-107. National Park Service, Denver, Colorado.

Laferriere, A. P. 1987. Cyclic sedimentation in the Fort Hays Limestone Member, Niobrara Formation (Upper Cretaceous) in northeastern New Mexico and southeastern Colorado. Pages 249–254 *in* S. G. Lucas and A. P. Hunt, editors. Northeastern New Mexico. New Mexico Geological Society, Socorro, New Mexico. Guidebook 38. Available at https://nmgs.nmt.edu/publications/guidebooks/downloads/38/38_p0249_p0254.pdf (accessed January 2015).

Loetterle, G. J. 1937. The micropaleontology of the Niobrara Formation in Kansas, Nebraska, and South Dakota. Nebraska Geological Survey, Lincoln, Nebraska. Bulletin 12.

Longman, M. W., B. A. Luneau, and S. M. Landon. 1998. Nature and distribution of Niobrara lithologies in the Cretaceous Western Interior Seaway of the Rocky Mountain region. The Mountain Geologist 35(4):137–170.

Martin, L. 2006. Potential groundwater sources for a potable water supply, Sand Creek Massacre Site, Kiowa County, Colorado. National Park Service, Water Resources Division, Fort Collins, Colorado. Available at http://www.nps.gov/sand/naturescience/upload/potential-groundwater-sources-for-potable-water_SAND_2006-06.pdf (accessed January 2015).

Martin, M. 2011. Travel report – Geomorphic assessment of Big Sandy Creek, Sand Creek Massacre National Historic Site (SAND), May 18-20, 2011. Memorandum to Super-Superintendent Alexa Roberts of Sand Creek Massacre National Historic Site. L54(2380). Available at http://www.nps.gov/sand/naturescience/upload/geomorphic-assessment-of-big-sandy-creek_travel-report_2011.pdf (accessed January 2015).

Mensing, S. 2007. Pollen analysis of sediment cores recovered from the Sand Creek Massacre National Historic Site. Final report. Department of Geography, University of Nevada, Reno, Nevada. Available at http://www.nps.gov/sand/naturescience/upload/pollen-analysis-of-sediment-cores_2007-05.pdf (accessed January 2015).

Merewether, E. A., W. A. Cobban, and J. D. Obradovich. 2007. Regional disconformities in Turonian and Coniacian (Upper Cretaceous) strata in Colorado, Wyoming, and adjoining states: biochronological evidence. Rocky Mountain Geology 42(2):95–122.

National Park Service. 2000. Sand Creek Massacre Project, Volume 2: Special Resource Study (SRS) and Environmental Assessment (EA). National Park Service, Intermountain Region, Denver, Colorado.

Noon, K., M. Martin, J. Wagner, L. Martin, and A. Roberts. 2005. A preliminary assessment of wetland, riparian, geomorphology, and floodplain conditions at Sand Creek Massacre National Historic Site, Colorado. National Park Service, Fort Collins, Colorado. Technical Report NPS/NRWRD/NRTR-2005-335. Available at http://www.nps.gov/sand/naturescience/upload/prelim-assessment-of-wetland-riparian-geomorphology-and-f-2.pdf (accessed January 2015).

Santucci, V. L., and A. L. Koch. 2003. Paleontological resource monitoring strategies for the National Park Service. Park Science 22(1):22–25. Available at http://www.nature.nps.gov/ParkScience/archive/PDF/ParkScience22%281%29Fall2003.pdf (accessed January 2015).

Santucci, V. L., J. P. Kenworthy, and A. L. Mims. 2009. Monitoring in situ paleontological resources. Pages 189–204 *in* R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado.

Sayre, W. O., and M. H. Ort. 2011. A geologic study of the Capulin Volcano National Monument and surrounding areas, Union and Colfax counties, New Mexico. New Mexico Bureau of Geology and Mineral Resources, Socorro, New Mexico. Open File Report 541. Available at http://geoinfo.nmt.edu/publications/openfile/details.cfml?Volume=541 (accessed January 2015).

Scott, G. R., and W. A. Cobban. 1964. Stratigraphy of the Niobrara Formation at Pueblo, Colorado. U.S. Geological Survey, Washington, D.C. Professional Paper 454-L. Available at http://pubs.er.usgs.gov/publication/pp454L (accessed January 2015).

Scott, R. W., P. C. Franks, M. J. Evetts, J. A. Bergen, and J. A. Stein. 1998. Timing of Mid-Cretaceous relative sea level changes in the Western Interior: Amoco No. 1 bounds core. Concepts in Sedimentology and Paleontology 6:11–34.

Shamrock, J. L,. and D. K. Watkins. 2009. Evolution of the Cretaceous calcareous nannofossil genus *Eiffellithus* and its biostratigraphic significance. Cretaceous Research 30(5):1083–1102.

Sharps, J. A. 1969. Lateral migrations of the Arkansas River during the Quaternary: Fowler, Colorado, to the Colorado-Kansas state line. Pages C66–C70 *in* Geological Survey research 1969, Chapter C. U.S. Geological Survey, Washington, D.C. Professional Paper 650-C. Available at http://pubs.er.usgs.gov/publication/pp650C (accessed January 2015).

Sharps, J. A. 1976. Geologic map of the Lamar Quadrangle, Colorado and Kansas. U.S. Geological Survey, Washington, D.C. Miscellaneous Investigations Series 944. Scale 1:250,000. Available at http://pubs.er.usgs.gov/publication/i944 (accessed January 2015).

Shimada, K., and C. Fielitz. 2006. Annotated checklist of fossil fished from the Smoky Hill Chalk of the Niobrara Chalk (Upper Cretaceous) in Kansas. New Mexico Museum of Natural History and Science Bulletin 35:193–213.

Shimada, K., M. J. Everhart, and K. Ewell. 2007. A unique reptilian (large dolichosaurid lizard?) tooth from the Upper Cretaceous Niobrara Chalk of western Kansas. Transactions of the Kansas Academy of Science 110(3–4):213–219.

Simpson, H. E. 1960. Geology of the Yankton area, South Dakota and Nebraska. U.S. Geological Survey, Washington, D.C. Professional Paper 328. Available at http://pubs.er.usgs.gov/publication/pp328 (accessed January 2015).

Tweet, J., V. L. Santucci, J. P. Kenworthy, and A. L. Mims. 2009. Paleontological resource inventory and monitoring: Southern Colorado Plateau Network. Natural Resource Technical Report NPS/NRPC/NRTR—2009/245. TIC# D-59. National Park Service, Fort Collins, Colorado.

Tweto, O. 1979. Geologic map of Colorado. U.S. Geological Survey, Washington, D.C. Special Geologic Map. Scale 1:500,000.

Watkins, D. K., T. J. Bralower, J. M. Covington, and C. G. Fisher. 1993. Biostratigraphy and paleoecology of the Upper Cretaceous calcareous nannofossils in the Western Interior Basin,

North America. Pages 521–537 *in* W. G. E. Caldwell and E. G. Kauffman, editors. Evolution of the Western Interior Basin. Geological Association of Canada, Toronto, Canada. Special Paper 39.

Wells, P. V., and J. D. Stewart. 1987. Spruce charcoal, conifer macrofossils, and landsnail and small-vertebrate faunas in Wisconsinan sediments on the High Plains of Kansas. Pages 129–140 in W. C. Johnson, editor. Quaternary environments of Kansas. Kansas Geological Survey, Lawrence, Kansas. Guidebook Series 5. Available at http://www.kgs.ku.edu/Publications/Bulletins/GB5/ (accessed January 2015).

Wheat, J. B. 1972. The Olsen-Chubbuck site: a Paleoindian bison kill. Memoirs of the Society for American Antiquity 26.

Additional References

Cobban, W. A., I. Walaszczyk, J. D. Obradovich, and K. C. McKinney. 2006. A USGS zonal table for the Upper Cretaceous Middle Cenomanian-Maastrichtian of the Western Interior of the United States based on ammonites, inoceramids, and radiometric ages. U.S. Geological Survey, Reston, Virginia. Open-File Report 2006-1250. Available at http://pubs.usgs.gov/of/2006/1250/ (accessed January 2015).

Elias, S. A. 1997. The Ice Age history of southwestern National Parks. Smithsonian Institution Press, Washington, D.C.

Ellwood, B. B. 1996. Geology and America's National Park areas. Prentice Hall, Upper Saddle River, New Jersey.

Fielitz, C., and K. Shimada. 2009. A new species of *Apateodus* (Teleostei, Aulopiformes) from the Upper Cretaceous Niobrara Chalk of western Kansas, U. S. A. Journal of Vertebrate Paleontology 29(3):650–658.

Graham, R. W. 1987. Late Quaternary mammalian faunas and paleoenvironments of the southwestern Plains of the United States. Pages 24–86 *in* R. W. Graham, H. A. Semken, Jr., and M. A. Graham, editors. Late Quaternary mammalian biogeography and environments of the Great Plains and prairies. Illinois State Museum, Springfield, Illinois. Scientific Papers 22.

Hanna, G. D. 1920. Pleistocene mollusks from Wallace County, Kansas. University of Kansas Science Bulletin 13(2):17–19. Available at http://biodiversitylibrary.org/page/4397894 (accessed January 2015).

Harris, A. H. 1985. Late Pleistocene vertebrate paleoecology of the west. University of Texas Press, Austin, Texas.

Hattin, D. E., C. T. Siemers, and G. F. Stewart. 1978. Upper Cretaceous stratigraphy and depositional environments of western Kansas. Kansas Geological Survey, Lawrence, Kansas. Guidebook Series 3. Available at http://www.kgs.ku.edu/Publications/Bulletins/GB3/ (accessed January 2015).

Hay, O. P. 1927. The Pleistocene of the western region of North America and its vertebrated animals. Carnegie Institute of Washington Publication 322B.

Hibbard, C. W. 1951. *Thomomys talpoides* (Richardson) from a late Pleistocene deposit in Kansas. Journal of Mammalogy 32(2):229–230.

Liggett, G. A. 2005. A review of the dinosaurs from Kansas. Transactions of the Kansas Academy of Science 108(1–2):1–14.

Mayor, A. 2005. Fossil legends of the first Americans. Princeton University Press, Princeton, New Jersey.

Olsen, S. J. 1971. Zooarchaeology: animal bones in archaeology and their interpretation. Addison-Wesley Publishing Company, New York City, New York.

Data Sets

Sand Creek Massacre National Historic Site Paleontological Archives
2000–present. (hard copy data; reports; electronic data; photographs; maps; publications). Originated by Santucci, Vincent; status: Active.

Washita Battlefield National Historic Site

Washita Battlefield National Historic Site (WABA) preserves the site of a controversial attack by the 7th U.S. Cavalry on the village of Cheyenne chief Black Kettle. This attack, on November 27, 1868, resulted in the death of Black Kettle and the death or capture of over 100 other Cheyenne. WABA was authorized as a unit of the National Park Service November 12, 1996. The site encompasses 127.56 ha (315.20 acres), 126.34 ha (312.20 acres) of which are federal.

Geologic Background

WABA is located in central Roger Mills County, in western Oklahoma. It is surrounded by Black Kettle National Grassland. The Washita River flows through the historic site from west to east (WABA Figure 1). WABA is just outside of Cheyenne, Oklahoma, and Elk City, Oklahoma, is about 33 km (21 mi) to the southeast. In general, the region is sparsely populated. The geology of WABA has been described in documents including NPS (undated, 2013), Brown (2001), Koch and Santucci (2003), Fay (2010), KellerLynn (2011), Stahl (2012), and Stahl and Simms (2013). The NPS Geologic Resources Division coordinated a Geologic Resource Inventory scoping meeting for WABA in May 2011 (KellerLynn 2011), and produced a digital map of the historic site in 2013 (NPS 2013). Koch and Santucci (2003) prepared the original paleontologic resource inventory and summary for WABA.



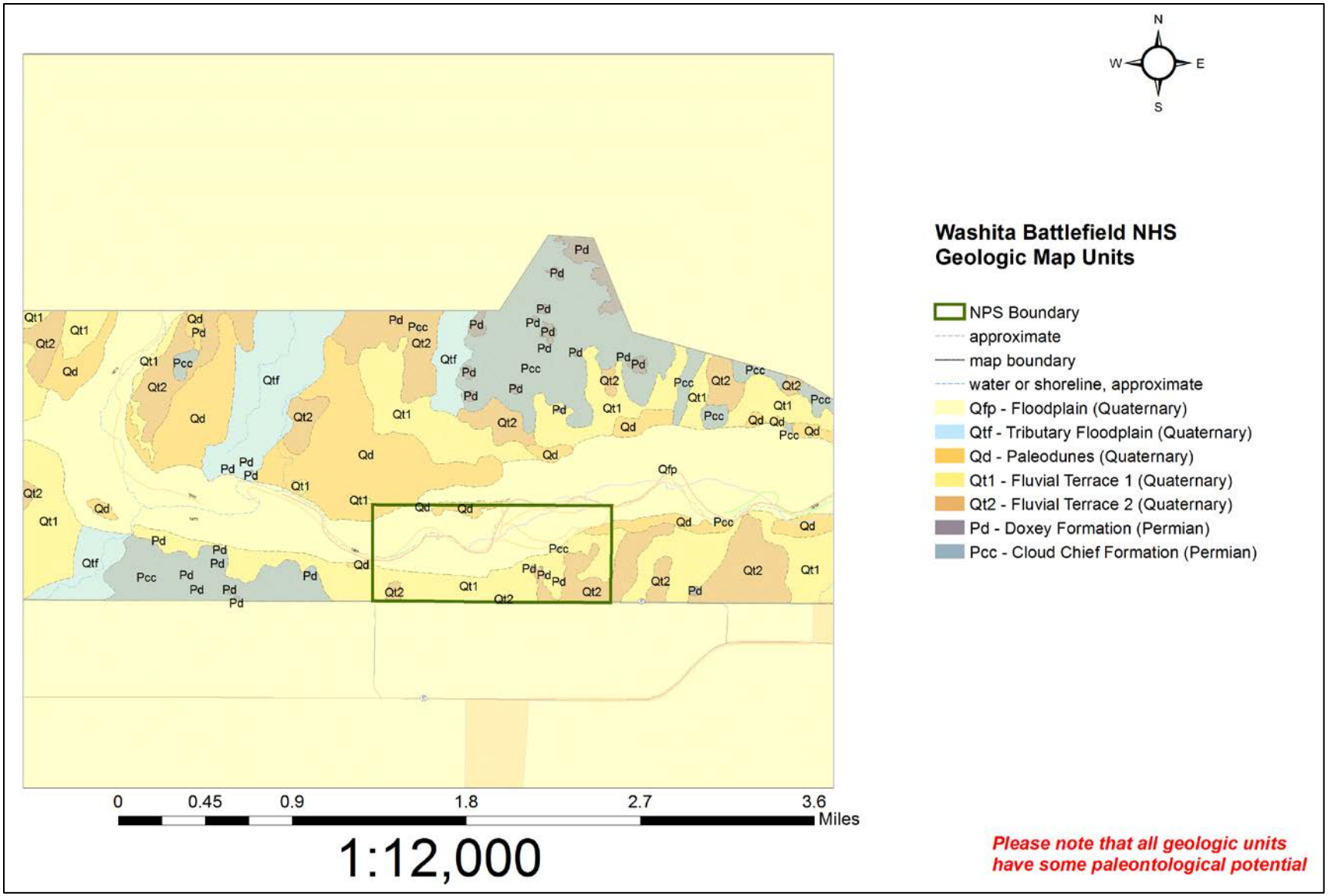
WABA Figure 1. The Washita River is responsible for much of the present geomorphology of WABA, including the modern river and floodplain, and older terraces flanking them (WABA/NPS).

The geologic units exposed in WABA were formed during the Permian and Quaternary, with nearly 250 million years separating these rock units (see the Appendix for a geologic time scale). WABA, and much of western Oklahoma, are within a feature called the Anadarko Basin (Fay and Hart 1978;

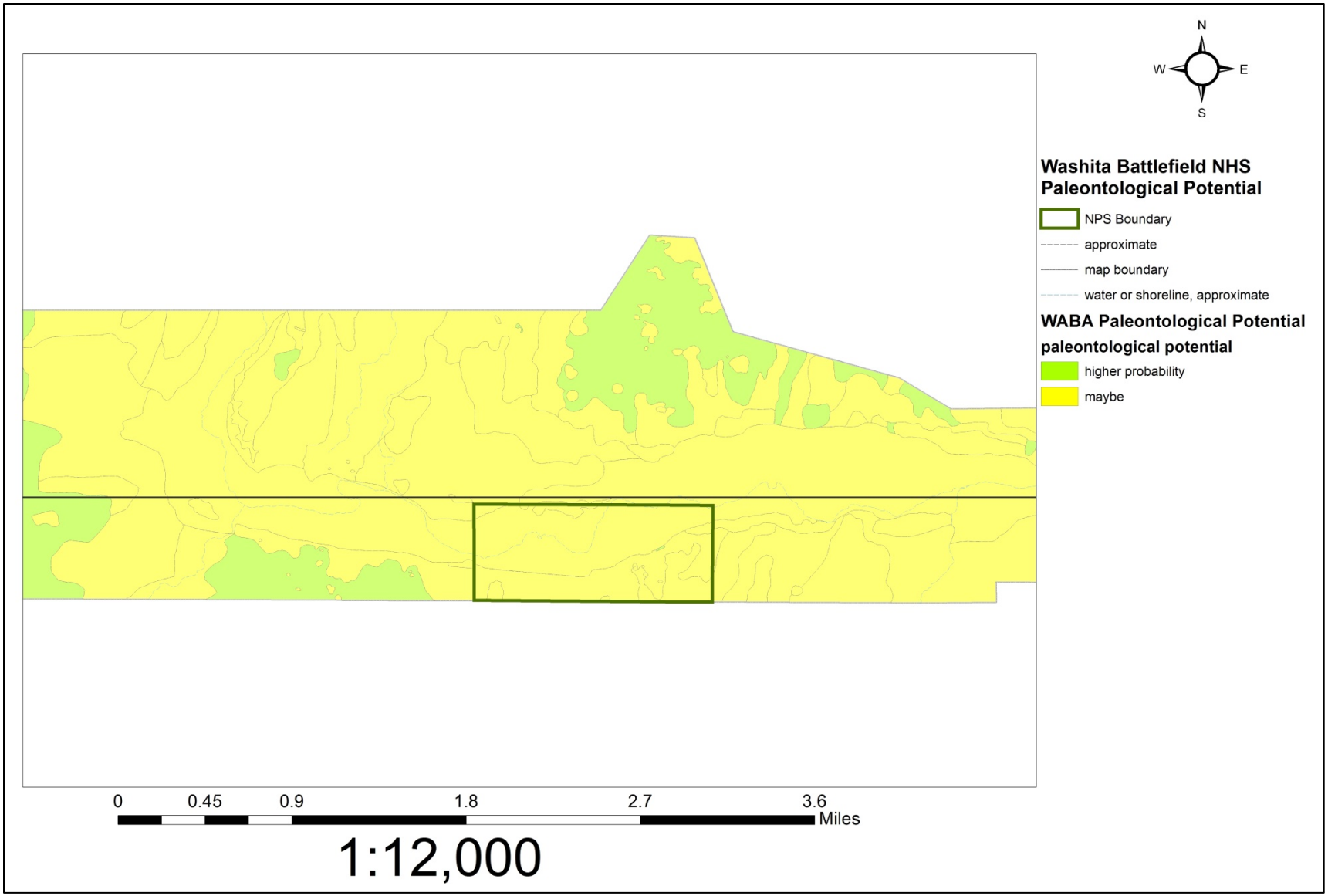
KellerLynn 2011). This basin may have begun forming as early as the Mississippian (Nicholson 1960), approximately one hundred million years before the historic site's Permian rocks, and was a place of shallow marine deposition. The Permian rocks of WABA, belonging to the Cloud Chief and overlying Doxey formations, record the final regression of the shallow continental sea (Zabawa 1976; KellerLynn 2011).

There are few remnants of Mesozoic or pre-Quaternary Cenozoic rocks in the region, indicating a lack of deposition, extensive erosion, or a combination of both. One notable exception is the Miocene–Pliocene Ogallala Formation, which is found in the uplands to the north and west of WABA. The Ogallala Formation of western Oklahoma preserves remains of a variety of plants and animals, including seeds, tortoises, snakes, rodents, canids, felids, skunks, gomphotheres, horses, rhinos, peccaries, oreodonts, camels, and pronghorns (Kitts 1957, 1959; Kitts and Black 1959). During this time a channel flowed from west to east across northern Roger Mills County (Kitts 1959). Fluvial processes and deposition have been major features of the Quaternary (2.58 million years ago to the present) of the WABA area, with windblown deposition as well (KellerLynn 2011). Humans arrived near the end of the Pleistocene, with evidence of the Clovis (Wyckoff and Czaplewski 1997) and Folsom cultures (Hofman et al. 1991) in western Oklahoma and northern Texas. The Clovis tradition existed between approximately 11,200 and 10,900 radiocarbon years before present, and the Folsom tradition existed between approximately 10,900 and 10,200 radiocarbon years before present (Holliday 2000). (Note that radiocarbon dates are not the same as calendar dates, and must be calibrated to approximate calendar years. Dates can be calibrated using a calibration program such as Calib 7.1 [http://calib.qub.ac.uk/calib/] if error ranges are provided. "Present" in "before present" is 1950.)

The bedrock and surficial geology of WABA includes, in ascending order, the Cloud Chief Formation (middle?–upper? Permian), the Doxey Formation (upper? Permian), and Quaternary sediments (Pleistocene–Holocene) (Fay 2010; Stahl 2012; NPS 2013) (WABA Figure 2, 3). None of these geologic units is known to be fossiliferous within WABA at this time (WABA Table 1), but there is some possibility for each of them to yield fossils, and the Cloud Chief Formation is fossiliferous just outside of WABA.



WABA Figure 2. Schematic geologic map of WABA. Map graphic adapted from digital geologic map data available at the following URL: https://irma.nps.gov/App/Reference/Profile/2194279.



WABA Figure 3. Paleontological potential map of WABA, showing the distribution of geologic units where fossils have been found and may be found. Map graphic adapted from digital geologic map data available at the following URL: https://irma.nps.gov/App/Reference/Profile/2194279.

WABA Table 1. Summary of WABA stratigraphy, fossils, and depositional settings in descending order of age, from youngest to oldest. Details and references can be found in the text.

Formation	Age	Fossils Within WABA	Depositional Environment
Quaternary sediments	Pleistocene–Holocene	None to date; mollusks and isolated vertebrate remains are most likely	Fluvial terraces and floodplains, and dunes
Doxey Formation	late? Permian	None to date; fossils are rare	Coastal mudflat
Cloud Chief Formation	middle?–late? Permian	None to date; fossils are rare, but corals, cephalopods, and invertebrate trace fossils have been reported from just outside of WABA	Shallow evaporative marine

Potential Sources of Paleontological Resources

Fossils have not yet been documented from the following geologic units within WABA. However, they are known to preserve fossils elsewhere, and future field investigations within the historic site may result in the discovery of fossils in one or more of them.

Cloud Chief Formation (middle?–late? Permian)

The Cloud Chief Formation is the distinctive red formation that forms most of the underlying bedrock of WABA (KellerLynn 2011). The formation is visible in a few areas of the historic site (KellerLynn 2011; NPS 2013), but this easily eroded formation is generally poorly exposed, so mapping has been done on the basis of weathered Cloud Chief Formation sediments in the soil (Stahl 2012). In and around WABA, it is mostly composed of yellow red claystone and siltstone, with meter- (yard-) scale gypsum beds and discontinuous beds of gypsum and green and gray shale (Stahl 2012). Siltstone and sandstone are prominent in the middle, and dolomite and gypsum are common in the lower part (Fay 2010). In central Roger Mills County, it is approximately 58 m (190 ft) thick, and is occasionally divided into four units. For reference, in ascending order they are the Moccasin Creek Bed, the Kiger Member, the Day Creek Bed, and the Big Basin Member (Fay and Hart 1978). The Moccasin Creek and Day Creek beds are thin (less than 2 m or 7 ft thick) and identified by the presence of gypsum beds. The Kiger and Big Basin members are mostly made of orange-brown to red-brown shale, siltstone, and sandstone. The Kiger Member is about 15 m (51 ft) thick, and the Big Basin Member is about 39 m (127 ft) thick. They are only differentiated where the Day Creek Bed is present to separate them (Fay and Hart 1978). The contact with the overlying Doxey Formation is gradational (Green 1936).

The nomenclature of the middle–upper Permian interval in western Oklahoma and the Oklahoma and Texas panhandles can be confusing. For example, the Cloud Chief Formation was established in 1924 (Gould 1924), and since that time has been abandoned (e.g., Clifton 1930), reinstated, classified as a member of the Whitehorse Formation (e.g., Evans 1931) or the Quartermaster Formation (e.g., Green 1936), and so forth. Furthermore, the interval has also been called the Greer Formation or Taloga Formation (Fay and Hart 1978). Part of the difficulty is that the formation was originally named as a gypsum unit, but the stratigraphic interval was later found to be predominantly sandstone on a regional scale (Green 1936).

In the WABA area, the Cloud Chief Formation is interpreted as having been deposited in a shallow-marine setting along an inland sea, probably under an arid climate (KellerLynn 2011). Evaporation

was a major process (Zabawa 1976). Sediment came from the east, perhaps from the Ozark region (Fay and Hart 1978). The age of the Cloud Chief Formation is uncertain, because few fossils have been found to date. The formation is thought to be middle Permian (Guadalupian) in age based on correlation to better-dated rocks in Texas and New Mexico (Fay and Hart 1978), and may extend into the late Permian (Johnson 1978).

The Cloud Chief Formation is fossiliferous at a locality adjacent to WABA, just beyond the eastern boundary. Fossils found here include cup (or horn) corals, coiled cephalopods, and worm trails (Brown 2001; Koch and Santucci 2003; KellerLynn 2011). This is unusual because the Cloud Chief Formation is not noted for its fossils; in fact, this is the only report known to the lead author (JST). It may represent an isolated fossiliferous bed, similar to that reported from the Doxey Formation in Texas (Roth et al. 1941; see below). The rarity of such a find indicates the need for further study. In general, evaporative shallow-marine settings under arid climates are unfavorable to many forms of life.

Doxey Formation (upper? Permian)

The Doxey Formation is found at relatively high elevations away from the floodplain, in knolls and bluffs (KellerLynn 2011). One area within southern WABA is large enough to be mapped (NPS 2013). This formation also fills collapse features in the underlying Cloud Chief Formation, which formed after the dissolution of gypsum (KellerLynn 2011; Stahl and Simms 2013). The Doxey Formation is composed of interbedded cm-scale shale layers and sub-meter-scale siltstone and fine sandstone beds (Stahl 2012). The coarser beds sometimes form ledges (Fay and Hart 1978). The Doxey Formation in the area is about 59 m (195 ft) thick, and sometimes has a gypsum or carbonate zone at the base, interpreted as correlative to the Alibates Dolomite (see the Alibates Flint Quarries National Monument–Lake Meredith National Recreation Area chapter of this document for more details) (Fay and Hart 1978).

The Doxey and Cloud Chief formations are quite similar, differing mainly by color (the Cloud Chief Formation is lighter in color) and the presence of coarser-grained rocks in the Cloud Chief Formation (Ham and Jordan 1961). As with the Cloud Chief Formation, nomenclature has varied for this unit, with many sources calling it the Doxey Member or Shale of the Quartermaster Formation. For example, the historic site sometimes identifies this unit as the Doxey Member of the Quartermaster Formation (NPS undated).

The Doxey Formation records the continued regression of the sea that deposited the Cloud Chief Formation. In the WABA area, it is interpreted as having been deposited on a coastal mudflat (KellerLynn 2011). The age of the formation is regarded as the later part of the Permian (Fay and Hart 1978), but again there is little direct evidence. If the Doxey Formation is regarded as equivalent to at least the lower Quartermaster Formation, as implied by its occasional use as a member of that formation, a late Permian age is likely. Ash in the lower Quartermaster Formation has been dated to 252.2 ± 0.6 Ma (million years ago) and 252.3 ± 0.6 Ma (Tabor et al. 2011), more or less the same as the modern date for the end of the Permian (252.2 Ma).

Fossils are rare in the Doxey Formation and have not been reported from WABA. One of the few reports comes from Briscoe County, Texas, over 150 km (90 mi) southwest of WABA. The fossils from this site include bivalves and gastropods in a thin dolomite bed near the base of the formation, and invertebrate burrows in shales below (Roth et al. 1941). Plant spores may be present in the Doxey Formation of Oklahoma (Ham and Jordan 1961).

Quaternary rocks and sediments (Pleistocene–Holocene)

The Quaternary deposits of WABA include ancient dunes, fluvial terraces, and floodplain sediments (NPS 2013). The terrace deposits, flanking the floodplain, include coarse material (pebbles and gravel), while the floodplain is composed of finer sediments. The paleodunes are composed of light gray to salmon-colored medium to coarse quartz-rich sand (Stahl 2012). They are mostly mapped in the northwestern part of the historic site (NPS 2013).

Fossils have not yet been reported from WABA's Quaternary deposits, but similar deposits have yielded fossils within about 100 km (60 mi) of the historic site. Useful online paleontological resources for this area include the Neotoma paleoecology database (http://www.neotomadb.org/), and Faunmap, which is the vertebrate element of Neotoma (http://www.ucmp.berkeley.edu/faunmap/). The most common fossils within the 100 km radius are mollusks, particularly snails, which are noted from the various terraces (Kitts 1959, 1965; Fay and Hart 1978). Numerous sites are reported in Neotoma, although the great majority of these sites are archeological sites yielding bison remains dating back approximately 1,000 years or less (Baugh 1986). An example of a relatively young archeological site with extensive floral and faunal remains is the Linville II site, about 30 km (20 mi) east-southeast of WABA. This site dates from about 1040 to 1360 AD, and includes corn and other angiosperm remains, mussels, and bones of fish, turtles, snakes, birds, rodents, rabbits, mustelids, raccoons, canids, deer, and bison. Artifacts of note include lithics composed of petrified wood and Alibates flint, bone tools, and cord-marked pottery with fossiliferous shale tempering. The faunal assemblage is typical for the area; some sites in the vicinity also have remains of opossums and pronghorns (Drass and Moore 1987). The antiquity of human occupation in the area goes back much father, though, with Clovis points in western Oklahoma (Wyckoff and Czaplewski 1997) and a Folsom site in Lipscomb County, Texas, where at least 23 individuals of the extinct bison *Bison antiquus* were butchered by Paleoindians (Hofman et al. 1991).

The Neotoma listing does not include all of the Pleistocene vertebrate sites of the area. A handful of Pleistocene vertebrate finds are reported for the vicinity of WABA in Smith and Cifelli (2000). The nearest finds are from north of Cheyenne, where a possible grizzly bear skull was found in river gravels 1 m (3 ft) below the surface, and in the Durham area, about 32 km (20 mi) northwest of WABA. The Durham specimen is a bison fossil that previously was thought to represent a Miocene camel from the site's better known Ogallala Formation fauna (Smith and Cifelli 2000). The most diverse nearby assemblage is the Washita local fauna, from near Weatherford, Oklahoma, over 80 km (50 mi) to the east (Kirkland et al. 1991, 1997; Kirkland and Norris 1999; Smith and Cifelli 2000). Fossils of snails, shrews, rodents, rabbits, horses, bison, and shruboxen have been found here, with an age of 18,295 ± 190 radiocarbon years before present (22,520 to 21,680 calibrated years before present) (Smith and Cifelli 2000). Other Pleistocene vertebrates that have been found in the

vicinity include frogs, birds, turtles, sloths, canids, and mammoths (Smith and Cifelli 2000). Mammoth remains are fairly common in the Pleistocene of Oklahoma (Wyckoff and Czaplewski 1997; Smith and Cifelli 2000).

Park Collections

No fossils are currently reported to be in WABA collections, and no WABA fossils are currently reported to be in the collections of other institutions.

Cultural Resource Connections

No fossils have been reported from cultural resource contexts at WABA, although such associations would not be unprecedented. The most likely type of cultural association for this area would be fossiliferous stone used for artifacts. For example, in the Southwest, petrified wood from the Upper Triassic Chinle Formation was often used for artifacts. The majority of parks in the neighboring Southern Colorado Plateau Network have examples (Tweet et al. 2009). Kenworthy and Santucci (2006) presented an overview and cited selected examples of National Park Service fossils found in cultural resource contexts.

Paleontological Resource Management, Preliminary Recommendations

- Staff from the historic site should be encouraged to observe exposed rocks and sedimentary deposits for fossil material while conducting their usual duties. To promote this, they should also receive guidance regarding how to recognize common local fossils. When opportunities arise to observe paleontological resources in the field and take part in paleontological field studies with trained paleontologists, staff should take advantage of them, if funding and time permit.

- The report of an adjoining Cloud Chief Formation fossil locality should be investigated further, due to the rarity of such occurrences and because the fossiliferous occurrence may extend into the historic site.

- Staff should photodocument and monitor any occurrences of paleontological resources that may be observed in situ. Fossils and their associated geologic context (surrounding rock) should be documented but left in place unless they are subject to imminent degradation by artificially accelerated natural processes or direct human impacts. A Geologic Resource Monitoring Manual by the Geological Society of America and NPS Geologic Resources Division includes a section on paleontological resource monitoring (Santucci et al. 2009). Santucci and Koch (2003) present information on paleontologic resource monitoring.

- Fossils found in a cultural context should be documented like other fossils, but will also require the input of an archeologist or a cultural resource specialist. Any fossil which has a cultural context may be culturally sensitive as well (e.g., subject to NAGPRA) and should be regarded as such until otherwise established. The Geologic Resources Division can coordinate additional documentation/research of such material.

- Contact the NPS Geologic Resources Division for technical assistance with paleontological resource management issues.

References Cited

Baugh, S. T. 1986. Late Prehistoric bison distributions in Oklahoma. Plains Anthropologist Memoir 21:83-96.

Brown, J. 2001. Washita Battlefield geology. Site Bulletin. National Park Service, Washita Battlefield National Historic Site, Cheyenne, Oklahoma.

Clifton, R. L. 1930. Permian structure and stratigraphy of northwestern Oklahoma and adjacent areas. Bulletin of the American Association of Petroleum Geologists 14(2):161–173.

Drass, R. R., and M. C. Moore. 1987. The Linville II site (34RM492) and Plains Village manifestations in the mixed grass prairie. Plains Anthropologist 32:404–419.

Evans, N. 1931. Stratigraphy of Permian beds of northwestern Oklahoma, with discussion by Horace L. Griley and Sherwood Buckstaff. Bulletin of the American Association of Petroleum Geologists 15(4):405–439.

Fay, R. O. 2010. Preliminary geologic map of the Foss Reservoir 30’ x 60’ Quadrangle, Oklahoma. Oklahoma Geological Survey, Norman, Oklahoma. Geologic Quadrangle Map 78a. Scale 1:100,000.

Fay, R. O., and D. L. Hart, Jr. 1978. Geology and mineral resources (exclusive of petroleum) of Custer County, Oklahoma. Oklahoma Geological Survey, Norman, Oklahoma. Bulletin 114. Available at http://www.ogs.ou.edu/pubsscanned/BULLETINS/Bulletin114wm.pdf (accessed January 2015).

Gould, C .N. 1924. A new classification of the Permian red beds of southwestern Oklahoma. American Association of Petroleum Geologists Bulletin 8(3):322–341.

Green, D. A. 1936. Permian and Pennsylvanian sediments exposed in central and west-central Oklahoma. Bulletin of the American Association of Petroleum Geologists 20(11):1454–1475.

Ham, W. E., and L. Jordan. 1961. A Permian stratigraphic section in west-central Oklahoma. Oklahoma Geology Notes 21(1):4–9. Available at http://www.ogs.ou.edu/pubsscanned/NOTES/1961Vol21P.pdf (accessed January 2015).

Hofman, J. L., L. C. Todd, C. B. Shultz, and W. Hendy. 1991. The Lipsomb Bison Quarry: continuing investigation at a Folsom kill-butchery site on the southern plain. Bulletin of the Texas Archeological Society 60:149–191. Available at http://www.greybull.org/hofman_etal_1989_tas_lipscomb.pdf (accessed January 2015).

Holliday, V. T. 2000. Folsom drought and episodic drying on the Southern High Plains from 10,900-10,200 ^{14}C yr B.P. Quaternary Research 53(1):1–12. Available at http://www.argonaut.arizona.edu/articles/holliday2000_2.pdf (accessed January 2015).

Johnson, K. S. 1978. Stratigraphy and mineral resources of Guadalupian and Ochoan rocks in the Texas Panhandle and western Oklahoma. Pages 57–62 in G. S. Austin, compiler. Geology and mineral deposits of Ochoan rocks in Delaware Basin and adjacent areas. New Mexico Bureau of Geology & Mineral Resources, Socorro, New Mexico. Circular 159.

KellerLynn, K. 2011. Geologic resource inventory scoping summary: Washita Battlefield National Historic Site, Oklahoma. National Park Service, Geologic Resources Division, Denver, Colorado. Available at http://www.nature.nps.gov/geology/inventory/publications/reports/WABA_GRI_scoping_summary_2011-0919.pdf (accessed January 2015).

Kenworthy, J. P., and V. L. Santucci. 2006. A preliminary investigation of National Park Service paleontological resources in cultural resource contexts, Part 1: general overview. New Mexico Museum of Natural History and Science Bulletin 34:70–76. Available at http://nature.nps.gov/geology/paleontology/pub/fossil_conference_7/9%20Kenworthy.pdf (accessed December 2014).

Kirkland, H., Jr., and S. Norris. 1999. Two late Pleistocene fossils from the Washita local fauna. Proceedings of the Oklahoma Academy of Science 79:97–98. Available at http://digital.library.okstate.edu/oas/oas_pdf/v79/p97_98.pdf (accessed January 2015).

Kirkland, H., Jr., J. Dill, and W. Selfridge. 1991. Some late Pleistocene vertebrates from western Oklahoma. Proceedings of the Oklahoma Academy of Science 71:55. Available at http://digital.library.okstate.edu/oas/oas_pdf/v71/p55.pdf (accessed January 2015).

Kirkland, H., Jr., M. Davis, J. Wood, D. Devine, and K. Giblet. 1997. Some late Pleistocene fossils from Washita local fauna. Proceedings of the Oklahoma Academy of Science 77:113–115. Available at http://digital.library.okstate.edu/oas/oas_pdf/v77/p113_115.pdf (accessed January 2015).

Kitts, D. B. 1957. A Pliocene vertebrate fauna from Ellis County, Oklahoma. Oklahoma Geological Survey, Norman, Oklahoma. Circular 45. Available at http://www.ogs.ou.edu/pubsscanned/Circulars/circular45.pdf (accessed January 2015).

Kitts, D. B. 1959. Cenozoic geology of northern Roger Mills County, Oklahoma. Oklahoma Geological Survey, Norman, Oklahoma. Circular 48:5–26. Available at http://www.ogs.ou.edu/pubsscanned/Circulars/circular48mm.pdf, http://www.ogs.ou.edu/pubsscanned/CircularsPlates/C48PI.pdf (accessed January 2015).

Kitts, D. B. 1965. Geology of the Cenozoic rocks of Ellis County, Oklahoma. Oklahoma Geological Survey, Norman, Oklahoma. Circular 69. Available at

http://www.ogs.ou.edu/pubsscanned/Circulars/circular69mm.pdf, http://www.ogs.ou.edu/pubsscanned/CircularsPlates/C69PI.pdf (accessed January 2015).

Kitts, D. B., and C. C. Black. 1959. A Pliocene vertebrate local fauna from Roger Mills County, Oklahoma. Oklahoma Geological Survey, Norman, Oklahoma. Circular 48:27–47. Available at http://www.ogs.ou.edu/pubsscanned/Circulars/circular48mm.pdf (accessed January 2015).

Koch, A. L., and V. L. Santucci. 2003. Washita Battlefield National Historic Site. Pages 31–32 *in* A. L. Koch and V. L. Santucci. Paleontological resource inventory and monitoring: Southern Plains Network. TIC# D-107. National Park Service, Denver, Colorado.

National Park Service. Undated. Washita Battlefield: geology. Pamphlet, on file at Washita Battlefield National Historic Site, Cheyenne, Oklahoma.

National Park Service Geologic Resources Inventory. 2013. Unpublished Digital Geologic Map of Washita Battlefield National Historic Site and Vicinity, Oklahoma (NPS, GRD, GRI, WABA, WABA digital map) adapted from a Geological Society of America GeoCorps unpublished map by Stahl (2012). National Park Service Geologic Resources Inventory. Geospatial Dataset-2194279. Available at https://irma.nps.gov/App/Reference/Profile/2194279 (accessed January 2015).

Nicholson, J. H. 1960. Geology of the Texas Panhandle. University of Texas at Austin, Austin, Texas. Publication 6017:51–64.

Roth, R. I., N. D. Newell, and B. H. Burma. 1941. Permian pelecypods in the lower Quartermaster Formation, Texas. Journal of Paleontology 15(3):312–317. Available at http://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1324&context=geosciencefacpub (accessed January 2015).

Santucci, V. L., and A. L. Koch. 2003. Paleontological resource monitoring strategies for the National Park Service. Park Science 22(1):22–25. Available at http://www.nature.nps.gov/ParkScience/archive/PDF/ParkScience22%281%29Fall2003.pdf (accessed January 2015).

Santucci, V. L., J. P. Kenworthy, and A. L. Mims. 2009. Monitoring in situ paleontological resources. Pages 189–204 *in* R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado.

Smith, K. S., and R. L. Cifelli. 2000. A synopsis of the Pleistocene vertebrates of Oklahoma. Oklahoma Geological Survey Bulletin 147. Available at http://www.ogs.ou.edu/pubsscanned/BULLETINS/Bulletin147.pdf (accessed January 2015).

Stahl, J. 2012. Geologic map of the Washita Battlefield National Historic Site, Cheyenne, Oklahoma. Geological Society of America GeoCorps, unpublished. Scale 1:24,000.

Stahl, J., and A. Simms. 2013. Topographic inversion in karst terrains: the breccia-pipe hills of the Washita Battlefield National Historic Site, Oklahoma, USA. Abstracts with Programs - Geological Society of America 45(7):372.

Tabor, N. J., T. S. Myers, G. H. Mack, C. V. Looy, P. R. Renne, R. Mundil, and J. W. Geissman. 2011. “Ochoan” Quartermaster Formation of north Texas, USA: Part I, Litho- and chemostratigraphy. Abstracts with Programs - Geological Society of America 43(5):383.

Tweet, J., V. L. Santucci, J. P. Kenworthy, and A. L. Mims. 2009. Paleontological resource inventory and monitoring: Southern Colorado Plateau Network. Natural Resource Technical Report NPS/NRPC/NRTR—2009/245. TIC# D-59. National Park Service, Fort Collins, Colorado.

Wyckoff, D. G., and N. J. Czaplewski. 1997. Paleontological and archaeological perspectives of fossil proboscideans in Oklahoma. Oklahoma Geology Notes 57(3):72–101. Available at http://www.ogs.ou.edu/pubsscanned/NOTES/GN-V57N3.pdf (accessed January 2015).

Zabawa, P. J. 1976. Investigation of surficial structural geology of portions of Beckham, Custer, Roger Mills, and Washita counties, Oklahoma. The Shale Shaker Digest 27:249–276.

Additional References

Bowers, J. R. 1967. Areal geology of the Cheyenne area, Roger Mills County, Oklahoma. Thesis. University of Oklahoma, Norman, Oklahoma.

Elias, S. A. 1997. The Ice Age history of southwestern National Parks. Smithsonian Institution Press, Washington, D.C.

Ellwood, B. B. 1996. Geology and America’s National Park areas. Prentice Hall, Upper Saddle River, New Jersey.

Ennen, C. M., R. A. Marston, and T. Halihan. 2005. Historic river changes in the Washita Battlefield National Historic Site. Abstracts with Programs - Geological Society of America 37(3):15.

Ennen, C., and R. Marston. 2004. Watershed restoration feasibility for the Washita Battlefield National Historic Site. Abstracts with Programs - Geological Society of America 36(5):285.

Graham, R. W. 1987. Late Quaternary mammalian faunas and paleoenvironments of the southwestern Plains of the United States. Pages 24–86 *in* R. W. Graham, H. A. Semken, Jr., and M. A. Graham, editors. Late Quaternary mammalian biogeography and environments of the Great Plains and prairies. Illinois State Museum, Springfield, Illinois. Scientific Papers 22.

Harris, A. H. 1985. Late Pleistocene vertebrate paleoecology of the west. University of Texas Press, Austin, Texas.

Hay, O. P. 1924. The Pleistocene of the middle region of North America and its vertebrated animals. Carnegie Institute of Washington Publication 322A. Available at https://archive.org/details/pleistoceneofmid00hayo (accessed January 2015).

Hay, O. P. 1927. The Pleistocene of the western region of North America and its vertebrated animals. Carnegie Institute of Washington Publication 322B.

Kitts, D. B. 1958. Cenozoic stratigraphy of Roger Mills County, Oklahoma: a preliminary report. Proceedings of the Oklahoma Academy of Science 38:87. Available at http://digital.library.okstate.edu/oas/oas_pdf/v38/p87.pdf (accessed January 2015).

Mayor, A. 2005. Fossil legends of the first Americans. Princeton University Press, Princeton, New Jersey.

Olsen, S. J. 1971. Zooarchaeology: animal bones in archaeology and their interpretation. Addison-Wesley Publishing Company, New York City, New York.

Shaeffer, J. B. 1965. Salvage archaeology in Oklahoma. Bulletin of the Oklahoma Anthropological Society 13:77–152.

Stovall, J. W., and W. N. McAnulty. 1939. Cyprinodontidae from the Pliocene in Roger Mills County, Oklahoma. American Midland Naturalist 22(3):749–752.

Wayne, W. J., J. S. Aber, S. S. Agard, R. N. Bergantino, J. P. Bluemle, D. A. Coates, M. E. Cooley, R. F. Madole, J. E. Martin, B. Mears, Jr., and W. M. Sutherland. 1991. Quaternary geology of the Northern Great Plains. Pages 441–476 *in* R. B. Morrison, editor. Quaternary nonglacial geology, conterminous U.S. Geological Society of America, Boulder, Colorado. The geology of North America K-2.

Data Sets

Washita Battlefield National Historic Site Paleontological Archives
1996–present. (hard copy data; reports; electronic data; photographs; maps; publications). Originated by Santucci, Vincent; status: Active.

Washita Battlefield National Historic Site Digital Geologic Map
2013–present. (geologic map data; electronic files; GIS metadata; associated report). Originated by NPS-Geologic Resources Inventory staff; status: Active. Online.
https://irma.nps.gov/App/Reference/Profile/2194279.

Non-I&M network units within the SOPN

There are several NPS units and affiliated areas geographically within the SOPN, but not included among the 270 parks in the Inventory and Monitoring Program. Most of these units are historic trails that pass through the SOPN, including El Camino Real de Tierra Adentro National Historic Trail (ELCA), El Camino Real de los Tejas National Historic Trail (ELTE), Old Spanish National Historic Trail (OLSP) and Trail of Tears National Historic Trail. There is also one trail, Santa Fe National Historic Trail (SAFE), which is mostly within the SOPN, and which has historical connections to many of the SOPN I&M units. The geology and paleontology of the historic and scenic trails of the National Park Service have received little attention to date, but they often include or pass near known paleontological localities. It is beyond the scope of this document to provide a full accounting for the trails mentioned above, but a short discussion of SAFE is included below. This historic trail is associated with a number of fossil localities.

Two other units are geographically within the SOPN: Nicodemus National Historic Site (NICO) and Oklahoma City National Memorial (OKCI), an affiliated site. NICO, in northwestern Kansas, has good potential for the occurrence of fossils within building stones. The NPS portion of OKCI consists of 1.26 ha (3.12 acres) in Oklahoma City, Oklahoma, and is unlikely to produce fossils.

Nicodemus National Historic Site

Nicodemus National Historic Site (NICO) commemorates the town of Nicodemus, Kansas, the last remaining example of a group of towns established by African Americans in the West during Reconstruction. Several of the town's important buildings are preserved. NICO was established November 12, 1996. The historic site encompasses 1.7 ha (4.3 acres), 0.21 ha (0.51 acres) of which are federal. It is located in far eastern Graham County, north-central Kansas, north of the south fork of the Solomon River.

Fossils are not currently known from NICO, but the building stones used for the town's buildings have good potential for containing fossils. Several of NICO's buildings are made of local limestone, including the St. Francis Hotel, African Methodist Episcopal Church, First Baptist Church, and Nicodemus Town Hall, which now serves as the visitor center. The town hall was built by the Works Progress Administration in 1937–1939 from rock quarried near Webster Reservoir in Rooks County. Additionally, there is a pile of building stone near the Nicodemus School District No. 1 building, possibly from the G. M. Sayers general store. Limestone was quarried as near as 3 km (2 mi) away from the town, in nearby bluffs (Burden et al. 2011). From the maps and discussion in Byrne et al. (1949, 1951), the best local candidate for the building material is the Fort Hays Limestone Member of the Upper Cretaceous Niobrara Formation (see the Appendix for a geologic time scale). Although the Fort Hays Limestone Member is apparently not exposed at the surface in Graham County (Byrne et al. 1951; Prescott 1955), it is exposed in adjoining Rooks County to the east (Byrne et al. 1949). This unit is considered to be good building material, albeit perhaps not as high-quality as the famous "fencepost limestone" of the Greenhorn Limestone used widely in counties to the east (Muilenburg and Swineford 1975). Thicker beds of the Smoky Hill Chalk Member of the Niobrara Formation are also a possibility (Byrne et al. 1951; Prescott 1955).

The Fort Hays Limestone Member in Graham County is composed of chalk or chalky limestone beds alternating with thin beds of chalky shale. It is perhaps 17 m (55 ft) thick on average, and is light to dark gray when unweathered, but weathers to lighter tan to white colors (Prescott 1955). The bivalves *Inoceramus deformis* and *Ostrea congesta* are common (Byrne et al. 1949). In neighboring Rooks County, this unit forms bluffs along the South Fork of the Solomon River (Byrne et al. 1949). The overlying Smoky Hill Chalk Member is mostly composed of chalk and chalky shale. This member is light to dark gray in color when unweathered, but weathers to yellow, orange, tan, or pink. Thin beds of bentonite (altered volcanic ash) and concretions of iron minerals are also present. This member can be as much as 170 m (550 ft) thick, but is usually thinner due to erosion at the surface. This member commonly has fossils of the large bivalve *Inoceramus grandis* and smaller bivalve *Ostrea congesta* (Prescott 1955).

Deposition of the Niobrara Formation occurred within an epicontinental sea over several million years. The age of the base of the formation becomes younger going north, east, and west from southern and central Colorado. According to the fossil content, deposition of the Niobrara Formation began between 88.9 and 88.1 million years ago in north-central Kansas (Merewether et al. 2007). The first few million years of deposition occurred under relatively well-mixed and well-oxygenated water, with a warm surface temperature and high productivity. Water was drawn from both oceans to the north and south. The middle period of deposition saw the contribution of northern waters become less important, with an increase in terrestrial input and water stratification, and a decrease in oxygenation in the bottom waters. By the end of deposition, the surface water had become notably fresher from the terrestrial input, and the water column was stagnant and strongly stratified, with the bottom water bordering on anoxia (Da Gama et al. 2014). Active volcanoes were present to the west, which provided the ash that eventually altered to form the bentonite beds (Diffendal and Voorhies 1994). The chalk of the Niobrara Formation is composed of fecal pellets, which in turn are made up of coccoliths (mineralized plates of plankton) (Da Gama et al. 2014). They may represent the feces of marine microorganisms like the tiny planktonic crustaceans known as copepods, which would have been feeding on coccolith-producing phytoplankton (Longman et al. 1998). Cyclic bedding of limestone with shale and marlstone in the underlying Fort Hays Limestone Member are attributed to climate and orbital variations, although mountain-building to the west and erosional events complicate the signal (Laferriere 1987).

The Niobrara Formation is famous for its fossils, which are found throughout the formation. The Fort Hays Limestone Member has a much less diverse assemblage than the Smoky Hill Chalk Member, including nannofossils (Watkins et al. 1993; Shamrock and Watkins 2009), foraminifera (“amoebas with shells”) (Frerichs and Gaskill 1988), bryozoans (moss animals) (Hattin et al. 1978), bivalves (Loetterle 1937), ammonites (Scott and Cobban 1964), squids (Everhart 2005a), serpulid worms, barnacles (Hattin et al. 1978), ostracodes (seed shrimp) (Loetterle 1937), burrows (Longman et al. 1998), cartilaginous fish (Shimada 1996), bony fish (Simpson 1960), elasmosaurs (Everhart 2005a), and mosasaurs (lizard-like marine reptiles) (Everhart 2005b). The fossil assemblage of the Smoky Hill Chalk Member is documented well enough that faunal changes can be observed over time (Everhart 2005a). Microfossils, plant fossils, and invertebrate fossils from the Smoky Hill Chalk Member include nannofossils like coccoliths (Watkins et al. 1993; Shamrock and Watkins 2009),

foraminifera (Loetterle 1937; Frerichs and Gaskill 1988), dinoflagellates (single-celled organisms that move using one or more whip-like flagella), pollen, spores, algae, microscopic plant fragments (Da Gama et al. 2014), rare wood fragments (Everhart 2005a), fragments of marine rushes (Simpson 1960), sponges (Everhart 2005a), bivalves, ammonites, belemnites (squid-like cephalopods known from their bullet-shaped guards), squids, barnacles (Everhart 2005a; Shimada et al. 2007), rare crustaceans, crinoids (sea lilies), worm tubes (Everhart 2005a), invertebrate fecal pellets (Hattin and Cobban 1977), and burrows and trails (Scott and Cobban 1964).

The fossil vertebrate assemblage of the Smoky Hill Chalk Member includes diverse chondrichthyans (including guitarfish, ratfish, and sharks) and ray-finned fish (Everhart 2005a; Shimada and Fielitz 2006; Shimada et al. 2007), rare coelacanths, several taxa of turtles, long-necked and large-skulled plesiosaurs, several mosasaur taxa, the marine lizard *Coniasaurus*, the pterosaurs (flying reptiles) *Nyctosaurus* and *Pteranodon*, rare dinosaurs (armored *Hierosaurus* and *Niobrarasaurus*, and the "duck-bill" *Claosaurus*), several birds (most famously the toothed seabirds *Hesperornis* and *Ichthyornis*, the former flightless) (Everhart 2005a; Shimada et al. 2007), and coprolites (fossil feces), often containing remains of invertebrates or vertebrates (Everhart 2005a).

Santa Fe National Historic Trail

The Santa Fe National Historic Trail (SAFE) was created in recognition of the 19th century trade route that connected northwestern Missouri to Santa Fe, New Mexico. Most of the route followed a west-southwest/east-northeast path between Missouri and western Kansas. In the vicinity of Fort Dodge, it split into two sub-routes, a northerly Mountain Route that entered what is now Colorado and turned south as it drew close to the Rocky Mountains, and a southerly Cimarron Route that continued on the west-southwest/east-northeast path through arid country in what is now southwestern Kansas, western Oklahoma, and northeastern New Mexico. The two routes converged near Fort Union before reaching Santa Fe. When first in use in the 1820s, the trail connected the United States frontier with northwestern Mexico, crossing the lands of several tribes. Following wars and expulsions, the entire area eventually was annexed into the United States. The spread of railroads eventually made the Santa Fe Trail obsolete, its utility ended for good by 1880 when rail reached Santa Fe. The trail is approximately 950 mi long (over 1,500 km), but the presence of two main branches for part of the route means that approximately 1,203 mi (1,936 km) are recognized as part of SAFE. Several units of the SOPN are associated with the trail, including Bent's Old Fort National Historic Site (BEOL), Fort Larned National Historic Site (FOLS), Fort Union National Historic Site (FOUN), and Pecos National Historical Park (PECO). Like other national historic and scenic trails, the federal government owns very little land, and the trail does not have boundaries in the same sense as a national park or monument, which makes determining the occurrence of paleontological resources a challenge. There is, however, a clear example of fossiliferous building stone within NPS property. The trail is also historically associated with abundant paleontological resources (SAFE Table 1).

The paleontology and geology of the trail are described in detail in several publications from the middle 19th century, during the time of the great pre-USGS surveys. In broad strokes, the trail crosses several general types of rocks and deposits (SAFE Table 1). From western Missouri through

eastern Kansas, the dominant bedrock is composed of Upper Paleozoic (Pennsylvanian and Permian) sedimentary rocks. Going further into Kansas, Quaternary surficial deposits predominate, including dune sands and loess. The northern trail enters Colorado before turning almost due south against the Rocky Mountains; this route is primarily over Cretaceous sedimentary rocks deposited in the Western Interior Seaway. The southern route passes through the western end of Oklahoma before entering New Mexico, and passes over a combination of Jurassic, Cretaceous, and Neogene sedimentary rocks and deposits. Both routes also pass over Neogene volcanic rocks once in New Mexico. The geology is most complex in the vicinity of Santa Fe, a mountainous region; otherwise, much of the trail passes over plains that have been little altered by faulting, mountain building, and other dramatic geologic events for hundreds of millions of years.

SAFE Table 1. A thumbnail of the geologic units crossed by SAFE, and fossils reported from them on or near the trail.

Formation	Age	Fossils Within or Adjacent to SAFE
Various Quaternary deposits	Pleistocene–Holocene	None to date; gastropod shells and isolated mammal fossils are most likely
Ogallala Group	Miocene–Pliocene	None to date; isolated mammal fossils are most likely
Western Interior Seaway rocks	Late Cretaceous	Angiosperm leaves, woody material, plant impressions, bivalves, ammonites, shark teeth, invertebrate burrows (some perhaps late Early Cretaceous)
Dakota Sandstone	Early–Late Cretaceous	Angiosperm leaves
Jurassic rocks	Jurassic	None to date
Permian rocks	Permian	Corals, brachiopods, bivalves, echinoids
Pennsylvanian rocks (“coal measures”)	Pennsylvanian	Brachiopods, bivalves, ammonites, gastropods, trilobites, echinoids, fusulinid foraminifera

In the 1850s, the trail and its fossils attracted the attention of several notable American geologists of the day, among them Timothy Abbott Conrad, Ferdinand Vandeveer Hayden, Jules Marcou, Fielding Bradford Meek, John Strong Newberry, George Clinton Swallow, and Benjamin Shumard. Primary descriptions of fossils from along the trail were published in over a dozen works (Hall 1856; Conrad 1857; Marcou 1858; Meek and Hayden 1858, 1859, 1860, 1864 or 1865; Shumard and Swallow 1858; Swallow and Hawn 1858; Swallow 1860; Newberry 1861, 1876, 1898; Geinitz 1866; Meek 1876). The most detailed and useful publications are Newberry (1861) and (1876). These two works constitute what is essentially a geologic trail guide covering the Cimarron Route and the main route. The 1861 work represents his travel on the trail heading east on the return leg of the Ives expedition of 1857–1858 to the Colorado River, and the more detailed 1876 work goes in the opposite direction on the Macomb expedition of 1859, back to the same general region. The only drawbacks, aside from Newberry not having the opportunity to describe the Mountain Route, are the archaic geologic and geographic terminology.

Newberry reported about a dozen notably fossiliferous localities along the route, regretting that he did not have the opportunity or logistics to collect them thoroughly (Newberry 1876). They include the following, going east to west (many locations are denoted on modern SAFE maps, but others

have been estimated using Madsen [2010], an account of the Macomb expedition): Pennsylvanian rocks near Uniontown, at Rockhouse, Walter's Station, and Burlingame; Pennsylvanian–Permian rocks at Dragoon Creek and Wilmington; Permian rocks in the hill tops east of Council Grove and on Cottonwood Creek; Lower Cretaceous rocks at the Pawnee Fork crossing, Cedar Springs, Cottonwood Spring, and Whetstone Creek (later researched by Lucas et al. [1987]); and "Middle Cretaceous" rocks at the valley of the Red Fork of the Canadian River/"breaks of the Red River" (later researched by Hook and Cobban [1980] and found to be from two areas in Sections 12 and 22 of Township 24 North, Range 23 East in Colfax County, New Mexico). Uniontown appears to be a former town in the vicinity of Topeka, across the Kansas River from Rossville, and associated with the emigrant trails instead of the Santa Fe Trail. "Rockhouse" appears to be a reference to an actual rock house, 37 km (23 mi) northeast on the road from Dragoon Creek. Walter's Station is unclear. Burlingame is in Osage County, Kansas. Dragoon Creek is a reference to the Dragoon Creek crossing, east of Wilmington in Wabaunsee County, Kansas. Council Grove is in Morris County, Kansas. "Cottonwood Creek" is probably a reference to the Cottonwood River Crossing area near Durham in Marion County, Kansas. The Pawnee Fork crossing is near Larned in Pawnee County. Cedar Spring is in Cimarron County, Oklahoma. Cottonwood Spring is about 13 km (8 mi) east of Round Mound in Union County, New Mexico. "Whetstone Creek" is somewhere along Palo Blanco Creek in Union County, New Mexico (Lucas et al. 1987).

Newberry reported collecting at several other localities as well. From Independence in Missouri to Dragoon Creek in Kansas, the route crossed the "coal measures" (Pennsylvanian rocks), which had yielded a few plant taxa and some marine fossils (mollusks, echinoids [sea urchins], and foraminifera ["amoebas with shells"]) in the region. At about Dragoon Creek the rocks and fossils became what he described as Permo-Carboniferous, and the hills bordering Dragoon Creek yielded bivalves and snails. He collected a fauna dominated by brachiopods (lamp shells) and echinoids from Council Grove, Diamond Spring (Morris County, Kansas), Lost Spring (Marion County, Kansas), and Cottonwood Creek with Meek, Hayden, and Major Hawn. True Permian rocks appeared near Cottonwood Creek, with a fauna of abundant bivalves collected by Meek and Hayden. The rocks from west of Cottonwood Creek to Walnut Creek (near Great Bend in Barton County) were unfossiliferous. In the area of Walnut Creek, basal Cretaceous sandstones appeared, and occasionally included abundant plant impressions and angiosperm leaves, including at the Pawnee Fork crossing. From Pawnee Fork to the Cimarron crossing he passed through what he interpreted as a dissected Tertiary basin, with unfossiliferous tuffaceous deposits (tuff is consolidated volcanic ash). Fossils were not reported again until a locality he identified as Enchanted Spring (Upper Cimarron Spring or Flag Spring of others, in Cimarron County, Oklahoma), where he found Cretaceous rocks with angiosperm leaves at the summits of hills. Cretaceous sandstone bluffs and patches of tuffaceous Tertiary limestone dominated from there to a location he identified as Cottonwood Spring, with the only fossils of note being angiosperm leaves and "fucoid" (invertebrate trace fossil) impressions at Cedar Springs. From Cottonwood Spring to the Red Fork of the Canadian River, igneous rocks, tuffaceous rocks, and Cretaceous rocks were prominent. Cretaceous rocks at Whetstone Creek yielded angiosperm leaves, and the Red Fork area yielded Lower Cretaceous rocks with leaves, "middle Cretaceous" rocks with marine shells and fish, and Upper Cretaceous rocks with leaves and tree fossils. The only fossil locality noted on the rest of the route was at Las Vegas, New Mexico,

where the bivalve *Inoceramus* was present in "Middle Cretaceous" rocks. In his previous work (Newberry 1861), he also reported the presence of Carboniferous brachiopods in limestone near Pecos Village, also discussed by Marcou (1858); the sites are apparently north of SAFE and PECO (Sutherland and Harlow 1973). An additional fossiliferous area in the vicinity of the trail is Lexington, Missouri, the source of several fossils described in Shumard and Swallow (1858) and Swallow and Hawn (1858).

With the main route and Cimarron Route well-described, only the Mountain Route is relatively poorly described, and it too probably crosses fossiliferous rocks, given that much of its route is over Western Interior Seaway rocks. Interestingly, property for sale in the area of the trail in Trinidad, Colorado, is being sold with fossils as a point of interest (http://www.rockymtnprop.com/properties/santa_fe_trail/C9.html, with a photo showing fossil leaves).

The previously mentioned fossiliferous building stone was noted in a newspaper article (Fairchild 2007). Two NPS trail markers, one placed in Marshall, Missouri, the other in Arrow Rock, Missouri, were fashioned from former farm boundary stones from north-central Kansas. The stones are fossiliferous limestones, and a photo of one was included, featuring an obvious bivalve. From the description, the stone is probably an example of the "Fencepost Limestone" of the Upper Cretaceous Greenhorn Limestone, the defining feature of "fencepost country" (Muilenburg and Swineford 1975).

As noted, a number of fossil taxa were named from sites on or near the trail (SAFE Table 2). Because scientific practices of the mid-19th century were not as rigorous as the present concerning reporting of localities, designation of type material, or specification of repositories, it is a challenge to reconstruct the authors' intentions and determine the actual localities. Hook and Cobban (1980) were able to establish the location of several fossils from the Red Fork area, but in many cases it is unlikely that we will be able to improve upon the original descriptions, meager as they often are.

SAFE Table 2. Fossil taxa named from localities in the vicinity of the trail (*=trail mentioned in original description, or otherwise known to be from near the trail).

Taxon	Citation	General locality	Age of rocks (per describer)	General taxonomic group
**Ostrea lugubris*	Conrad 1857	"Breaks of the Red River" in New Mexico, N1/2 SW1/4 sec 12, T24N, R23E (Hook and Cobban 1980)	Late Cretaceous	Bivalve
**Prionocyclus macombi*	Meek 1876	"Breaks of the Red River" in New Mexico, N1/2 SW1/4 sec 12, T24N, R23E (Hook and Cobban 1980)	Late Cretaceous	Ammonite
Axinus (*Schizodus*) *ovatus*	Meek and Hayden 1858	Cottonwood Creek	Pennsylvanian	Bivalve
Discina tenuilineata	Meek and Hayden 1859	Cottonwood Creek	Pennsylvanian?	Bivalve
Myalina aviculoides	Meek and Hayden 1860	Cottonwood Creek	Permian	Bivalve
Aviculopecten mccoyi	Meek and Hayden 1864	South Cottonwood Creek	Permian	Bivalve

SAFE Table 2 (continued). Fossil taxa named from localities in the vicinity of the trail (*=trail mentioned in original description, or otherwise known to be from near the trail).

Taxon	Citation	General locality	Age of rocks (per describer)	General taxonomic group
**Eumicrotis hawni* var. *ornate*	Meek and Hayden 1864	Near Cottonwood Creek, "south of the Santa Fe road"	Permian	Bivalve
*"*Ostrea elongatula*"	Newberry 1876	"Breaks of the Red River" in New Mexico, N1/2 SW1/4 sec 12, T24N, R23E (Hook and Cobban 1980)	Late Cretaceous	Bivalve (appears to have been named by mistake)
**Goniatites parvus*	Shumard in Shumard and Swallow 1858	Willow Spring, on Santa Fe road	Pennsylvanian	Ammonite
Goniatites minimus	Shumard in Shumard and Swallow 1858	Above Dover's Landing on the Missouri	Pennsylvanian	Ammonite
Goniatites politus	Shumard in Shumard and Swallow 1858	Lexington	Pennsylvanian	Ammonite
**Myalina kansasensis*	Shumard in Shumard and Swallow 1858	Locations including on the Santa Fe road south of Lecompton, Missouri and 9 mi SW of Council Grove	Pennsylvanian	Bivalve
Cardiomorpha missouriensis	Shumard in Shumard and Swallow 1858	Locations including Lexington	Pennsylvanian	Bivalve
**Retzia punctilifera*	Shumard in Shumard and Swallow 1858	Locations including Willow Spring and on the Santa Fe road	Pennsylvanian	Brachiopod
Discina missouriensis	Shumard in Shumard and Swallow 1858	Locations including Lexington	Pennsylvanian	Brachiopod
Poteriocrinus hemisphericus	Shumard in Shumard and Swallow 1858	Locations including Missouri River near Lexington and 9 mi SW of Council Grove	Pennsylvanian	Crinoid
**Archaeocidaris aculeatus*	Shumard in Shumard and Swallow 1858	Locations including on the Santa Fe road near Rock Creek and 25 mi W of Council Grove in Cottonwood valley	Pennsylvanian	Echinoid
Archaeocidaris biangulatus	Shumard in Shumard and Swallow 1858	Lexington	Pennsylvanian	Echinoid
Archaeocidaris megastylus	Shumard in Shumard and Swallow 1858	Locations including Cottonwood valley	Pennsylvanian	Echinoid
Naticopsis (*Nerita*) *pricei*	Shumard in Shumard and Swallow 1858	Locations including Cottonwood valley	Pennsylvanian	Gastropod
**Phillipsia major*	Shumard in Shumard and Swallow 1858	Locations including 12 mi south of Lecompton on the Santa Fe road	Pennsylvanian	Trilobite
Phillipsia missouriensis	Shumard in Shumard and Swallow 1858	Lexington	Pennsylvanian	Trilobite

SAFE Table 2 (continued). Fossil taxa named from localities in the vicinity of the trail (*=trail mentioned in original description, or otherwise known to be from near the trail).

Taxon	Citation	General locality	Age of rocks (per describer)	General taxonomic group
Pecten halli	Swallow 1860	Willow Springs	Pennsylvanian	Bivalve
Allorisma cuneata	Swallow in Shumard and Swallow 1858	Near Lexington	Pennsylvanian	Bivalve
Allorisma lata	Swallow in Shumard and Swallow 1858	Near Lexington	Pennsylvanian	Bivalve
Arca cuspidata	Swallow in Shumard and Swallow 1858	Near Burlingame	Pennsylvanian	Bivalve
Cardium? lexingtonensis	Swallow in Shumard and Swallow 1858	Lexington	Pennsylvanian	Bivalve
Orthis carbonaria	Swallow in Shumard and Swallow 1858	Locations including near Lexington	Pennsylvanian	Brachiopod
**Capulus triplicatus*	Swallow in Shumard and Swallow 1858	Near Bull Creek, Santa Fe Road	Pennsylvanian	Gastropod
Bellerophon meekianus	Swallow in Shumard and Swallow 1858	Lexington	Pennsylvanian	Gastropod
Macrocheilus kansasensis	Swallow in Shumard and Swallow 1858	Possibly Willow Springs	Pennsylvanian	Gastropod
Murchisonia minima	Swallow in Shumard and Swallow 1858	Lexington	Pennsylvanian	Gastropod
Allorisma curta	Swallow in Swallow and Hawn 1858	Near Council Grove	early Permian	Bivalve
Allorisma lanceolata	Swallow in Swallow and Hawn 1858	Near Council Grove	early Permian	Bivalve
Allorisma? minnahaha	Swallow in Swallow and Hawn 1858	Near Council Grove and Lexington	Pennsylvanian and early Permian	Bivalve
Cardinia cordata	Swallow in Swallow and Hawn 1858	Cottonwood valley	early Permian	Bivalve
Cardinia subangulata	Swallow in Swallow and Hawn 1858	Cottonwood valley	early Permian	Bivalve
Cardiomorpha kansasensis	Swallow in Swallow and Hawn 1858	Cottonwood valley	early Permian	Bivalve
Cardiomorpha? rhomboidea	Swallow in Swallow and Hawn 1858	Near Council Grove	early Permian	Bivalve
Edmondia gibbosa	Swallow in Swallow and Hawn 1858	Cottonwood valley	early Permian	Bivalve

SAFE Table 2 (continued). Fossil taxa named from localities in the vicinity of the trail (*=trail mentioned in original description, or otherwise known to be from near the trail).

Taxon	Citation	General locality	Age of rocks (per describer)	General taxonomic group
Edmondia otoensis	Swallow in Swallow and Hawn 1858	Cottonwood valley	early Permian	Bivalve
Edmondia semiorbiculata	Swallow in Swallow and Hawn 1858	Council Grove	early Permian	Bivalve
Monotis halli	Swallow in Swallow and Hawn 1858	Cottonwood valley	Permian	Bivalve
Monotis variabilis	Swallow in Swallow and Hawn 1858	Cottonwood valley	late Permian	Bivalve
Pecten cleavelandicus	Swallow in Swallow and Hawn 1858	Cottonwood valley	early Permian	Bivalve
Pecten ringens	Swallow in Swallow and Hawn 1858	Cottonwood valley	early Permian	Bivalve
Schizodus triangularis	Swallow in Swallow and Hawn 1858	Cottonwood valley	early Permian	Bivalve
Productus calhounianus	Swallow in Swallow and Hawn 1858	Cottonwood valley	early Permian	Brachiopod
Productus norwoodii	Swallow in Swallow and Hawn 1858	Cottonwood valley	early Permian	Brachiopod
Nautilus occidentalis	Swallow in Swallow and Hawn 1858	Cottonwood valley	early Permian?	Nautiloid
Murchisonia? kansasensis	Swallow in Swallow and Hawn 1858	Cottonwood valley	early Permian	Gastropod
Murchisonia? perversa	Swallow in Swallow and Hawn 1858	Cottonwood valley	early Permian	Gastropod
Spirobis orbiculostoma	Swallow in Swallow and Hawn 1858	Cottonwood valley	early Permian	Microconchid (described as annelid)
**Abietites cretacea*	Newberry 1898	Whetstone Creek on the Santa Fe Trail	Cretaceous	Conifer
**Myrica*(?) *trifoliate*	Newberry 1898	Whetstone Creek	Cretaceous	Angiosperm
**Salix foliosa*	Newberry 1898	Whetstone Creek	Cretaceous	Angiosperm

References Cited

Burden, D., H. L. Miller, P. Sadin, and D. Vogel. 2011. Historic resources study, Nicodemus National Historic Site. Report prepared for the Midwest Regional Office, National Park Service, United States Department of the Interior. Available at

http://www.nps.gov/nico/parkmgmt/upload/nicodemus_final_singlesided.pdf (accessed February 2015).

Byrne, F. E., H. V. Beck, and M. S. Houston. 1949. Construction materials in Rooks County, Kansas. U.S. Geological Survey, Washington, D.C. Circular 27. Available at http://pubs.er.usgs.gov/publication/cir27 (accessed February 2015).

Byrne, F. E., V. B. Coombs, and C. W. Matthews. 1951. Construction materials in Graham County, Kansas. U.S. Geological Survey, Washington, D.C. Circular 51. Available at http://pubs.er.usgs.gov/publication/cir51 (accessed February 2015).

Conrad, T. A. 1857. Descriptions of Cretaceous and Tertiary fossils. Pages 141–174 *in* W. H. Emory. Report on the United States and Mexican boundary survey, made under the direction of the Secretary of the Interior. Volume I, Part II. A.O.P. Nicholson, printer, Washington, D.C. Available at https://archive.org/details/reportonunitedst11unit (accessed November 2014).

Da Gama, R. O. B. P., B. Lutz, P. Desjardins, M. Thompson, I. Prince, and I. Espejo. 2014. Integrated paleoenvironmental analysis of the Niobrara Formation: Cretaceous Western Interior Seaway, northern Colorado. Palaeogeography, Palaeoclimatology, Palaeoecology 413:66–80.

Diffendal, R. F., Jr., and M. R. Voorhies. 1994. Geologic framework of the Niobrara River drainage basin and adjacent areas in South Dakota generally east of the 100th meridian west longitude and west of the Missouri River. Nebraska Geological Survey, Lincoln, NE. Report of Investigations 9. Available at http://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1093&context=geosciencefacpub (accessed January 2015).

Everhart, M. J. 2005a. Oceans of Kansas: a natural history of the Western Interior Sea. Indiana University Press, Bloomington and Indianapolis, Indiana.

Everhart, M. J. 2005b. Earliest record of the genus *Tylosaurus* (Squamata; Mosasauridae) from the Fort Hays Limestone (Lower Coniacian) of western Kansas. Transactions of the Kansas Academy of Science 108(3–4):149–155.

Fairchild, K. October 8, 2007. 2 stone posts places in Saline County to mark Santa Fe Trail. The Marshall Democrat-News, Marshall, Missouri. Available at http://www.marshallnews.com/story/1282878.html (accessed November 2014).

Frerichs, W. E. and C. Gaskill. 1988. Planktic foraminifera and age of the Niobrara Formation in its type area. Contributions to Geology 26(1):5–13.

Geinitz, H. B. 1866. Carbonformation und Dyas in Nebraska. Dresden, Germany. Available at https://archive.org/details/carbonformationu00gein (accessed November 2014).

Hall, J. 1856. Descriptions and notices of the fossils collected upon the route. Pages 99–105 *in* Chapter IX, No. 1, in Route near the Thirty-Fifth Parallel, explored by Lieut. A. W. Whipple,

Topographical Engineer, in 1853 and 1854. Part IV. Report on the geology of the route. Reports of explorations and surveys, to ascertain the most practicable and economical route for a railroad from the Mississippi River to the Pacific Ocean. Volume III. A. O. P. Nicholson, printer, Washington, D.C. Available at https://archive.org/details/reportsofexplora03unit_0 (accessed November 2014).

Hattin, D. E., and W. A. Cobban. 1977. Upper Cretaceous stratigraphy, paleontology and paleoecology of western Kansas. Mountain Geologist 14(3–4):175–217.

Hattin, D. E., C. T. Siemers, and G. F. Stewart. 1978. Upper Cretaceous stratigraphy and depositional environments of western Kansas. Kansas Geological Survey, Lawrence, Kansas. Guidebook Series 3. Available at http://www.kgs.ku.edu/Publications/Bulletins/GB3/ (accessed January 2015).

Hook, S. C., and W. A. Cobban. 1980. Some guide fossils in Upper Cretaceous Juana Lopez Member of Mancos and Carlile shales, New Mexico. Pages 38-49 *in* F. E. Kottlowski and staff. New Mexico Bureau of Mines and Mineral Resources Annual Report, July 1, 1978 to June 30, 1979. New Mexico Bureau of Geology and Mineral Resources, Socorro, NM. Available at http://geoinfo.nmt.edu/publications/annual_reports/78-79/AR1978_1979.pdf (accessed November 2014).

Laferriere, A. P. 1987. Cyclic sedimentation in the Fort Hays Limestone Member, Niobrara Formation (Upper Cretaceous) in northeastern New Mexico and southeastern Colorado. Pages 249–254 *in* S. G. Lucas and A. P. Hunt, editors. Northeastern New Mexico. New Mexico Geological Society, Socorro, New Mexico. Guidebook 38. Available at https://nmgs.nmt.edu/publications/guidebooks/downloads/38/38_p0249_p0254.pdf (accessed January 2015).

Loetterle, G. J. 1937. The micropaleontology of the Niobrara Formation in Kansas, Nebraska, and South Dakota. Nebraska Geological Survey, Lincoln, Nebraska. Bulletin 12.

Longman, M. W., B. A. Luneau, and S. M. Landon. 1998. Nature and distribution of Niobrara lithologies in the Cretaceous Western Interior Seaway of the Rocky Mountain region. The Mountain Geologist 35(4):137–170.

Lucas, S. G., A. P. Hunt, and K. Martini. 1987. Newberry's locality for Cretaceous plant fossils at Whetstone Creek, New Mexico. New Mexico Journal of Science 27(2):95–98.

Madsen, S. K. 2010. Exploring desert stone: John N. Macomb's 1859 expedition to the Canyonlands of the Colorado. Utah State University Press, Logan, Utah. Available at https://archive.org/details/ExploringDesertStone (accessed April 2015).

Marcou, J. 1858. Geology of North America. Zurcher and Furrer, Zurich, Switzerland. Available at https://archive.org/details/geologynorthame00marcgoog (accessed November 2014).

Meek, F. B. 1876. Descriptions of Cretaceous fossils collected on the San Juan exploring expedition under Capt. J. N. Macomb, U.S. Engineers. Pages 119–133 *in* J. N. Macomb. Report of the exploring expedition from Santa Fe, New Mexico, to the junction of the Grand and Green rivers of the Great Colorado of the West in 1859. Government Printing Office, Washington, D.C. U.S. Army Engineer Department. Available at https://archive.org/details/reportexploring00newbgoog (accessed November 2014).

Meek, F. B., and F. V. Hayden. 1858. Remarks on the lower Cretaceous beds of Kansas and Nebraska, together with descriptions of some new species of Carboniferous fossils from the valley of Kansas river. Proceedings of the Academy of Natural Sciences of Philadelphia 10:256–266. Available at http://biodiversitylibrary.org/page/26289851 (accessed November 2014).

Meek, F. B., and F. V. Hayden. 1859. Geological explorations in Kansas Territory. Proceedings of the Academy of Natural Sciences of Philadelphia 11:8–30. Available at http://biodiversitylibrary.org/page/26310398 (accessed November 2014).

Meek, F. B., and F. V. Hayden. 1860. Descriptions of new organic remains from the Tertiary, Cretaceous, and Jurassic rocks of Nebraska. Proceedings of the Academy of Natural Sciences of Philadelphia 12:175–185. Available at http://biodiversitylibrary.org/page/26297322 (accessed November 2014).

Meek, F. B., and F. V. Hayden. [1864.] 1865. Palaeontology of the Upper Missouri. Smithsonian Contributions to Knowledge 14(172). Available at http://www.biodiversitylibrary.org/bibliography/33149#/summary (accessed November 2014).

Merewether, E. A., W. A. Cobban, and J. D. Obradovich. 2007. Regional disconformities in Turonian and Coniacian (Upper Cretaceous) strata in Colorado, Wyoming, and adjoining states: biochronological evidence. Rocky Mountain Geology 42(2):95–122.

Muilenburg, G., and A. Swineford. 1975. Land of the post rock: its origins, history, and people. The University Press of Kansas, Lawrence, Kansas.

Newberry, J. S. 1861. Geological report. *In* J. C. Ives. Report upon the Colorado River of the West. U.S. 36th Congress, 1st Session, Senate Executive Document and House Executive Document 90(3). Available at https://archive.org/details/reportuponcolor00engigoog (accessed November 2014).

Newberry, J. S. 1876. Geological report. Pages 9–118 *in* J. N. Macomb. Report of the exploring expedition from Santa Fe, New Mexico, to the junction of the Grand and Green rivers of the Great Colorado of the West in 1859. Government Printing Office, Washington, D.C. U.S. Army Engineer Department. Available at https://archive.org/details/reportexploring00newbgoog (accessed November 2014).

Newberry, J. S. 1898. The later extinct floras of North America. U.S. Geological Survey, Washington, DC. Monograph 35. Available at https://archive.org/details/laterextinctflor00newb (accessed January 2015).

Prescott, G. C., Jr. 1955. Geology and ground-water resources of Graham County, Kansas. Kansas Geological Survey, Lawrence, Kansas. Bulletin 110. Available at http://www.kgs.ku.edu/General/Geology/Graham/ (accessed February 2015).

Scott, G. R., and W. A. Cobban. 1964. Stratigraphy of the Niobrara Formation at Pueblo, Colorado. U.S. Geological Survey, Washington, D.C. Professional Paper 454-L. Available at http://pubs.er.usgs.gov/publication/pp454L (accessed January 2015).

Shamrock, J. L. and D. K. Watkins. 2009. Evolution of the Cretaceous calcareous nannofossil genus Eiffellithus and its biostratigraphic significance. Cretaceous Research 30(5):1083–1102.

Shimada, K. 1996. Selachians from the Fort Hays Limestone Member of the Niobrara Chalk (Upper Cretaceous), Elias County, Kansas. Transactions of the Kansas Academy of Science 99(1–2):1–15.

Shimada, K., and C. Fielitz. 2006. Annotated checklist of fossil fished from the Smoky Hill Chalk of the Niobrara Chalk (Upper Cretaceous) in Kansas. New Mexico Museum of Natural History and Science Bulletin 35:193–213.

Shimada, K., M. J. Everhart, and K. Ewell. 2007. A unique reptilian (large dolichosaurid lizard?) tooth from the Upper Cretaceous Niobrara Chalk of western Kansas. Transactions of the Kansas Academy of Science 110(3–4):213–219.

Shumard, B. F., and G. C. Swallow. 1858. Descriptions of new fossils from the Coal Measures of Missouri and Kansas. Transactions of the Academy of Science of St. Louis Academy 1(2):198–227. Available at http://biodiversitylibrary.org/page/30339495 (accessed November 2014).

Simpson, H. E. 1960. Geology of the Yankton area, South Dakota and Nebraska. U.S. Geological Survey, Washington, D.C. Professional Paper 328. Available at http://pubs.er.usgs.gov/usgspubs/pp/pp328 (accessed February 2015).

Sutherland, P. K., and F. H. Harlow. 1973. Pennsylvanian brachiopods and biostratigraphy in southern Sangre de Cristo Mountains, New Mexico. New Mexico, Bureau of Mines and Mineral Resources Memoir 27.

Swallow, G. C. 1860. Descriptions of new fossils from the Carboniferous and Devonian rocks of Missouri. Transactions of the Academy of Science of St. Louis 1:635–660. Available at http://biodiversitylibrary.org/page/30339960 (accessed November 2014).

Swallow, G. C., and F. Hawn. 1858. The rocks of Kansas, with descriptions of new Permian fossils by G. C. Swallow. Transactions of the Academy of Science of St. Louis Academy 1(2):173–197. Available at http://biodiversitylibrary.org/page/30339470 (accessed November 2014).

Watkins, D. K., T. J. Bralower, J. M. Covington, and C. G. Fisher. 1993. Biostratigraphy and paleoecology of the Upper Cretaceous calcareous nannofossils in the Western Interior Basin, North America. Pages 521–537 *in* W. G. E. Caldwell and E. G. Kauffman, editors. Evolution of the Western Interior Basin. Geological Association of Canada, Toronto, Canada. Special Paper 39.

Additional References

Charlton, J., and D. Merriam. 2008. Geologic guideposts along the overland trails in Kansas. Kansas Geological Survey, Lawrence, Kansas. Open-File Report 2008-14. Available at http://www.kgs.ku.edu/Publications/OFR/2008/OFR08_14/ (accessed February 2015).

Darton, N. H., and others. 1915. Guidebook of the western United States: Part C, The Santa Fe Route, with a side trip to the Grand Canyon of the Colorado. U.S. Geological Survey Bulletin 613. Available at http://pubs.er.usgs.gov/publication/b613 (accessed February 2015).

Grisafe, D. A. 1983. Geology and characteristics of building limestone of Kansas. Pages 91–112 *in* C. H. Ault and G. S. Woodard, editors. Proceedings of 18th forum on geology of industrial minerals: Theme: Construction materials. Indiana Geological Survey, Bloomington, Indiana. Occasional Paper 37.

Hibbard, C. W., and A. A. Graffham. 1941. A new pycnodont fish from the Upper Cretaceous of Rooks County, Kansas. University of Kansas Science Bulletin 27(5):71-77. Available at http://biodiversitylibrary.org/page/4393656 (accessed February 2015).

Kues, B. S. 1987. A brief history of the Santa Fe Trail and early geological studies along the Cimarron cutoff in New Mexico. Pages 7–12 *in* S. G. Lucas and A. P. Hunt, editors. Northeastern New Mexico. New Mexico Geological Society, Socorro, New Mexico. Guidebook 38.

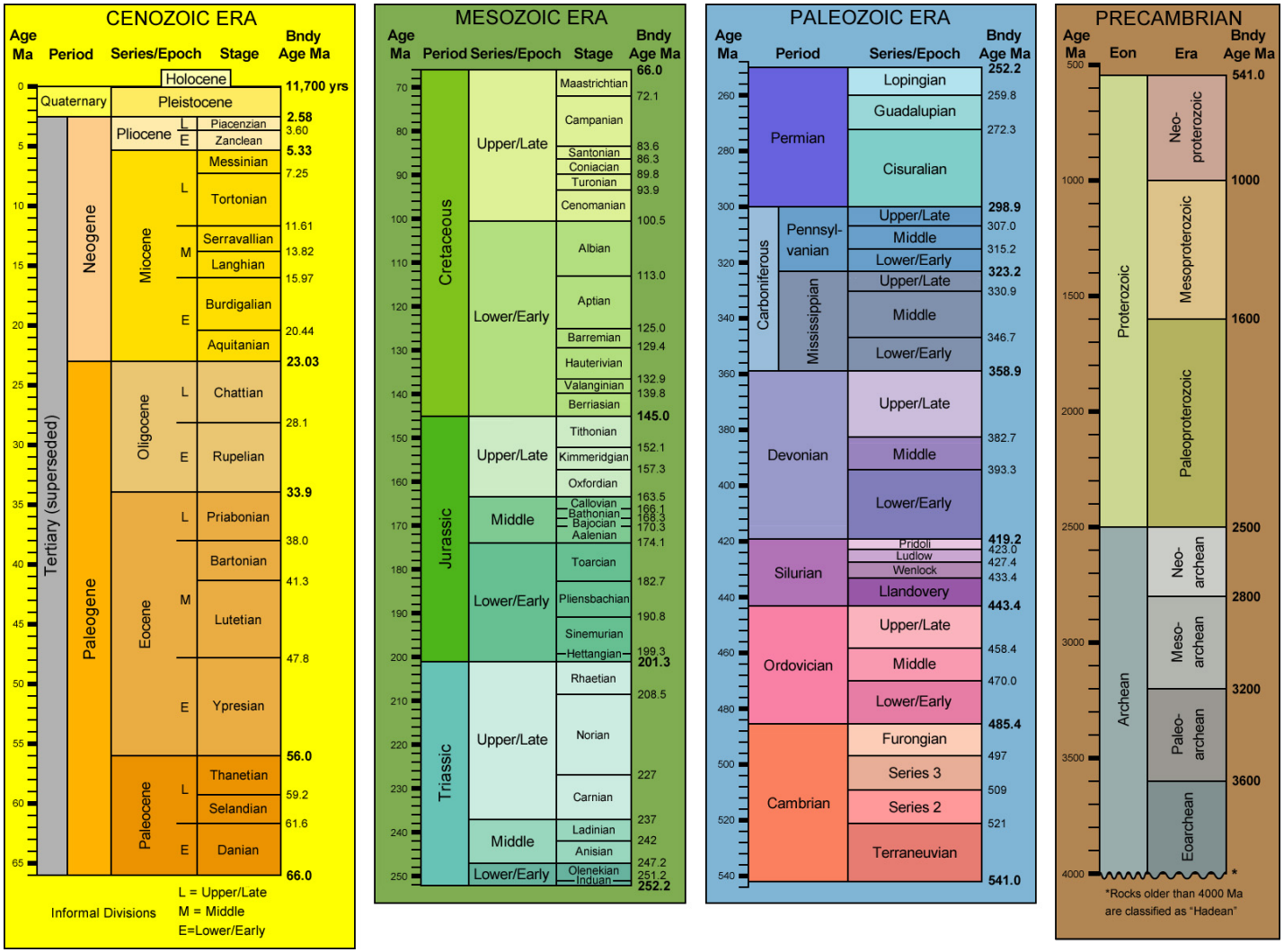
Meek, F. B. 1867. Remarks on Prof. Geinitz's views respecting the Upper Paleozoic rocks and fossils of southeastern Nebraska. American Journal of Science and Arts 44:170–187. Available at http://books.google.com/books?id=vO8qAAAAYAAJ (accessed November 2014).

Data Sets

Nicodemus National Historic Site Paleontological Archives
11/2014–present. (hard copy data; reports; electronic data; photographs; maps; publications).
Originated by Santucci, Vincent; status: Active.

Santa Fe National Historic Trail Paleontological Archives
11/2014–present. (hard copy data; reports; electronic data; photographs; maps; publications).
Originated by Santucci, Vincent; status: Active.

Appendix: Geologic Time Scale



Ma=Millions of year old. **Bndy Age**=Boundary Age. Colors are standard USGS colors for geologic maps. Modified from 1999 Geological Society of America Timescale (www.geosociety.org/science/timescale/timescl.pdf). Dates and additional information from International Commission on Stratigraphy update 2014/02 (http://www.stratigraphy.org/index.php/ics-chart-timescale) and USGS Fact Sheet 2007-3015 (http://pubs.usgs.gov/fs/2007/3015/).

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NPS 960/128686, May 2015

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