National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

National Park Service Geologic Type Section Inventory

Northern Great Plains Inventory & Monitoring Network

Natural Resource Report NPS/NGPN/NRR—2022/2439

ON THE COVER

The north face of Scotts Bluff, consisting of the Oligocene-Miocene Arikaree Group (Gering Formation, Monroe Creek Formation, Harrison Formation) overlying the Oligocene Brule Formation. A reference section of the Mitchell Pass Member of the Gering Formation is located on the west and north sides of Scotts Bluff in Scotts Bluff National Monument, consisting of thinly bedded sandstone and thin, resistant calcareous ledges measuring 15 m (48 ft) thick. Photograph provided by Ryan W. Barker with permission.

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The National Park Service, Natural Resource Stewardship and Science office in Fort Collins, Colorado, publishes a range of reports that address natural resource topics. These reports are of interest and applicability to a broad audience in the National Park Service and others in natural resource management, including scientists, conservation and environmental constituencies, and the public.

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Contents

Contents (continued)

Contents (continued)

Contents (continued)

Figures

Page

Figures (continued)

Page

Figures (continued)

Page

Tables

Photographs

Appendices

Executive Summary

Type sections are one of several kinds of stratotype. A stratotype is the standard (original or subsequently designated), accessible, and specific sequence of rock for a named geologic unit that forms the basis for the definition, recognition, and comparison of that unit elsewhere. Geologists designate stratotypes for rock exposures that are illustrative and representative of the map unit being defined. Stratotypes ideally should remain accessible for examination and study by others. In this sense, geologic stratotypes are similar in concept to biological type specimens, however, they remain in situ as rock exposures rather than curated in a repository. Therefore, managing stratotypes requires inventory and monitoring like other geologic heritage resources in parks. In addition to type sections, stratotypes also include type localities, type areas, reference sections, and lithodemes, all of which are defined in this report.

The goal of this project is to consolidate information pertaining to stratotypes that occur within NPS-administered areas, in order that this information is available throughout the NPS to inform park managers and to promote the preservation and protection of these important geologic heritage resources.

This effort identified 13 stratotypes designated within five park units of the Northern Great Plains Inventory & Monitoring Network (NGPN): Agate Fossil Beds National Monument (AGFO) contains one type locality; Badlands National Park (BADL) contains five type sections and one type area; Missouri National Recreational River (MNRR) contains one type area; Niobrara National Scenic River (NIOB) contains one type section, one type locality, and two reference sections; and Scotts Bluff National Monument (SCBL) contains one reference section. Table 1 provides information regarding the 13 stratotypes currently identified within the NGPN.

There are currently no designated stratotypes within Devils Tower National Monument (DETO), Fort Laramie National Historic Site (FOLA), Fort Union Trading Post National Historic Site (FOUS), Jewel Cave National Monument (JECA), Knife River Indian Villages National Historic Site (KNRI), Mount Rushmore National Memorial (MORU), Theodore Roosevelt National Park (THRO), and Wind Cave National Park (WICA). However, DETO, FOUS, JECA, and WICA contain important rock exposures that could be considered for formal stratotype designation, as discussed in "Recommendations".

The inventory of geologic stratotypes across the NPS is an important effort in documenting these locations in order that NPS staff recognize and protect these areas for future studies. The focus adopted for completing the baseline inventories throughout the NPS has centered on the 32 inventory and monitoring (I&M) networks established during the late 1990s. Adopting a network-based approach to inventories worked well when the NPS undertook paleontological resource inventories for the 32 I&M networks and was therefore adopted for the stratotype inventory. The Greater Yellowstone I&M Network (GRYN) was the pilot network for initiating this project (Henderson et al. 2020). Methodologies and reporting strategies adopted for the GRYN have been used in the development of this report for the NGPN.

This report includes a recommendation section that addresses outstanding issues and future steps regarding park unit stratotypes. These recommendations will hopefully guide decision-making and help ensure that these geoheritage resources are properly protected and that proposed park activities or development will not adversely impact the stability and condition of these geologic exposures.

Table 1. List of NGPN stratotype units sorted by park unit and geologic age, with associated reference publications and locations.

Park	Unit Name (GRI map symbol)	Reference	Stratotype Location	Age
AGFO	Agate Ash Bed, Harrison Formation	Skinner et al. 1977	Type locality: an easily accessible deposit from 2.1–2.4 m (7–8 ft) thick on the north side of the Niobrara River, about 3.2 km (2 mi) east of the former Agate post office, in the SE/4 SW/4 sec. 4, T. 28 N., R. 55 W., in Sioux County, NE.	early Miocene
BADL	Sharps Formation (Ts)	Harksen et al. 1961	Type section (composite): 1. Lower interval: measured on the north face of "wall" in SW/4 NW/4 sec. 31, T. 41 N., R. 42 W., in Shannon County, SD. 2. Upper interval: measured along drainage from NW/4 sec. 30, T. 39 N., R. 43 W. northeast into NE/4 sec. 20, T. 39 N., R. 43 W., in Shannon County, SD. ***NOTE: Only the lower composite type section interval is in BADL.	Oligocene
BADL	Wolff Camp Member, Sharps Formation	McConnell and DiBenedetto 2012	Type section: in the SW/4 NW/4 sec. 31, T. 41 N., R. 42 W., Evergreen NE 7.5′ Quadrangle, in Shannon County, SD.	Oligocene(?)
BADL	Rockyford Ash Member, Sharps Formation	Harksen et al. 1961; Nicknish and Macdonald 1962	Type section: south end of Sheep Mountain Table, in SE/4 NE/4 NE/4 sec. 32, T. 43 N., R. 44 W., in Shannon County, SD.	Oligocene
BADL	Brule Formation, White River Group (Tb)	Bump 1956; Harksen and Macdonald 1969	Type section (composite): 1. Lower interval: in the SW/4 sec. 27, T. 3 S., R. 13 E., in Pennington County, SD. 2. Upper interval: NE/4 sec. 33 and SW/4 sec. 28, T. 43 N., R. 44 W., Sheep Mountain Table 7.5′ Quadrangle, in Shannon County, SD. ***NOTE: Only the upper composite type section interval is in BADL.	Oligocene
BADL	Poleslide Member, Brule Formation, White River Group	Bump 1956; Harksen and Macdonald 1969	Type section: NE/4 sec. 33 and SW/4 sec. 28, T. 43 N., R. 44 W., Sheep Mountain Table 7.5′ Quadrangle, in Shannon County, SD.	Oligocene
BADL	White River Group (Tb, Tc, Twr)	Meek and Hayden 1857, 1861; Harksen et al. 1979; LaGarry 1998	Type area: the Big Badlands of southwestern SD.	Eocene–Oligocene
MNRR	Niobrara Formation (Knsh)	Meek and Hayden 1861; Frerichs and Gaskill 1988	Type area: exposures along the Niobrara River, where formation forms 27–30 m (90–100 ft) cliffs near mouth along Missouri River, in Knox County, NE.	Cretaceous

Table 1 (continued). List of NGPN stratotype units sorted by park unit and geologic age, with associated reference publications and locations.

Park	Unit Name (GRI map symbol)	Reference	Stratotype Location	Age
NIOB	Fort Niobrara Formation	Osborn 1918	Type locality: on the Niobrara River near Fort Niobrara, in Cherry County, NE. ***NOTE: Unit superseded by the Valentine Formation	Pliocene
NIOB	Cornell Dam Member, Valentine Formation	Skinner and Johnson 1984	Type section: roadcut a few miles northeast of the town of Valentine on the west side of Nebraska State Highway 12, west of the original mouth of Minnechaduza Creek and its junction with the Niobrara River, in SE/4 sec. 22, T. 34 N., R. 27 W., Cornell Dam 7.5′ Quadrangle, in Cherry County, NE. Reference sections: 1. On the north side of the Niobrara River at Rock Rapids [Rocky Ford], in secs. 9 and 16, T. 33 N., R. 24 W., Muleshoe Creek 7.5′ Quadrangle, in Keya Paha County, NE; 2. On the south side of the Niobrara River at Norden Bridge, in SW/4 NE/4 SW/4 sec. 33, T. 33 N., R. 23 W., Norden 7.5′ Quadrangle, in Brown County, NE.	Miocene
SCBL	Mitchell Pass Member, Gering Formation	Vondra et al. 1969	Reference section: at Mitchell Pass and the west to north sides of Scotts Bluff, approximately 3.5 km (2.2 mi) west and 1.3 km (0.8 mi) north of Gering, in the SW/4 and NE/4 sec. 33, T. 22 N., R. 55 W. (Scottsbluff South and Scotts Bluff National Monument Quadrangles), in Scotts Bluff County, NE.	late Oligocene–early Miocene

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Many individuals were consulted in the preparation of this report on the geologic type sections for the national parks of the Northern Great Plains Inventory & Monitoring Network (NGPN). We first want to extend our sincere appreciation to Randy Orndorff, David Soller, and Nancy Stamm (U.S. Geological Survey) for their assistance with this geologic type section inventory and other important NPS projects. Randy, Dave, and Nancy manage the National Geologic Map Database and GEOLEX (the U.S. Geologic Names Lexicon, a national compilation of names and descriptions of geologic units), respectively, for the United States, critical sources of geologic map information for science, industry and the American public. We also extend our appreciation to Tim Cowman (State Geologist, South Dakota Geological Survey) and R. M. Joeckel (State Geologist/Professor, University of Nebraska-Lincoln) for reviewing the report manuscript and contributing professional feedback. Special thanks to Ryan W. Barker (Union Pacific Railroad) for providing geologic exposure photographs and Mai Reitmeyer (American Museum of Natural History) for permission to reuse the photo in Figure 40.

We thank our colleagues and partners in the Geological Society of America (GSA) and Stewards Individual Placement Program for their continued support to the NPS with the placement of geologic interns and other ventures. Additionally, we are grateful to Rory O’Connor-Walston and Alvin Sellmer from the NPS Technical Information Center in Denver for their assistance with locating hard-to-find publications.

Thanks to our NPS colleagues in the Northern Great Plains Inventory & Monitoring Network and various network parks, including: Kara Paintner-Green (NGPN), Dan Morford and Arthur Stiles (AGFO and SCBL), Ellen Starck and Ed Welsh (BADL), Carolyn Campbell (MNRR), and Susan Cook (NIOB). Kara served as the peer review coordinator for this report. Additional thanks to Carmen Thomson and Nancy Finley for continued support for this and other important geology projects in the Midwest Region of the NPS.

This project is possible through the support from research associates and staff in the National Park Service Geologic Resources Division and we extend our thanks to Stephanie Gaswirth, Hal Pranger, Julia Brunner, Jim Wood, Jason Kenworthy, and Rebecca Port. Finally, we want to thank the past and current members of the NPS Geologic Resource Inventory Team for more than 20 years of work to expand our understanding of the geologic features, issues, and processes in our national parks!

Dedication

We are pleased to dedicate the Northern Great Plains Inventory and Monitoring Network Geologic Type Section Inventory to Julia Brunner, Energy and Minerals Branch Lead, NPS Geologic Resources Division. Julia joined the NPS in June 1995 as a regulatory specialist initially involved with mining and minerals policy. During her career, Julia has expanded her work to include a broad portfolio supporting policy and planning involving paleontology, coastal resources, geologic hazards, and Abandoned Mineral Lands. We extend our appreciation to Julia for her support to make this geologic type section inventory possible. Thank you, Julia!

Julia Brunner; Energy & Minerals Branch Lead, National Park Service, Geologic Resources Division.

Introduction

Geologic maps show the distribution and classification of rocks, sedimentary deposits, and geologic features for a given area. The geologic classification of rocks and deposits is hierarchical with several different categories of geologic or stratigraphic units including, from regional scale to local exposure scale: supergroup, group, formation, member, and bed. The mapping of stratigraphic units involves the evaluation of lithologies, bedding properties, thickness, geographic distribution, and other factors. Mappable geologic units may be described and named through a rigorously defined process that is standardized and codified by the professional geologic community (North American Commission on Stratigraphic Nomenclature 2021). In most instances, when a new geologic unit (such as a formation) is described and named in the scientific literature, a specific and well-exposed section or exposure area of the unit is designated as the stratotype (see "Definitions" below). The type section is an important reference exposure for a named geologic unit which presents a relatively complete and representative example for this unit. Geologic stratotypes are important geoheritage resources with historic and scientific significance, and should be available for other researchers to evaluate in the future.

The importance of stratotypes lies in the fact that they represent important comparative sites where past investigations can be built upon or re-examined and can serve as teaching sites for the next generation of geoscientists (Brocx et al. 2019). The geoheritage significance of stratotypes is analogous to libraries and museums in that they are natural repositories of Earth history and record the physical and biologic evolution of our planet. In addition, geologic formations are named after topographic or geologic features and landmarks that are recognizable to park staff and visitors. Therefore, geologic stratotypes are part of our national geologic heritage and are a cornerstone of the scientific value used to define the societal significance of geoheritage sites (refer to https://www.nps.gov/articles/scientific-value.htm for more about geologic heritage).

The goals of this project are to: (1) systematically report the assigned stratotypes that occur within national parks of the Northern Great Plains Inventory and Monitoring (I&M) Network (NGPN); (2) provide detailed descriptions of the stratotype exposures and their locations; and (3) reference the stratotype assignments from published literature. It is important to note that this project cannot verify a stratotype for a geologic unit if one has not been formally assigned and/or published. This effort identified 13 stratotypes with five NGPN parks: Agate Fossil Beds National Monument (AGFO) contains one type locality; Badlands National Park (BADL) contains five type sections and one type area; Missouri National Recreational River (MNRR) contains one type area; Niobrara National Scenic River (NIOB) contains one type section, one type locality, and two reference sections; and Scotts Bluff National Monument (SCBL) contains one reference section. Table 1 provides information regarding the 13 stratotypes currently identified within the NGPN. Additionally, numerous stratotypes are located geographically outside of national park boundaries; those within 48 km (30 mi) of park boundaries are mentioned in this report.

The NGPN Geologic Type Section Inventory report is part of a larger effort to document stratotypes in all 32 I&M networks and selected non-I&M parks with significant rock exposures. This report follows the standard practices, methodologies, and organization of information introduced in the Greater Yellowstone I&M Network type section inventory (Henderson et al. 2020), which was the pilot for this effort; Refer to the Methods section below for detailed information. As discussed in the Methods section, the NPS Geologic Type Section Inventory Project utilizes NPS Geologic Resources Inventory (GRI) data and information, which is considered the "official" baseline geologic map and report for each park in the Inventory and Monitoring (I&M) program.

Geologic stratotypes within NPS areas have not been previously inventoried, so this report fills a void in basic geologic information compiled by the NPS at most parks. NPS staff may not be aware of the concept of geologic stratotypes nor the significance or occurrence of them in parks. Without proper documentation and awareness, the NPS cannot proactively monitor the stability, condition, or potential impacts to these locations from activities such as ground disturbance or construction. Instances where geologic stratotypes occurred within NPS areas were determined through research of published geologic literature and maps as described in the Methods section. Sometimes the lack of specific locality or other data limited determination of whether a particular stratotype was located within NPS administered boundaries.

Given the importance of geologic stratotypes as geologic references and geologic heritage resources, these NGPN locations should be afforded some level of documentation, preservation, or protection as appropriate. This inventory can inform important conversations on whether geologic stratotypes rise to the level of national register documentation. The NPS should consider if any other legal authorities (e.g., National Historic Preservation Act), policy, or other safeguards currently in place can help protect geologic stratotypes that are established on NPS administered lands.

Through this inventory, the associated report, and close communication with park and I&M Network staff, we hope there will be an increased awareness about these important geologic landmarks in parks. In turn, the awareness of these resources and their significance may be recognized in park planning and operations, to ensure that geologic stratotypes are preserved and available for future study.

Definitions

In order to clarify, standardize, and consistently reference stratigraphic concepts, principles, and definitions, the North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature 2021) is recognized and adopted for this inventory. This code describes explicit practices for classifying and naming all formally defined geologic units. An important designation for a geologic unit is known as a ***stratotype***—the standard exposure (original or subsequently designated) for a named geologic unit or boundary, constituting the basis for definition or recognition of that unit or boundary (North American Commission on Stratigraphic Nomenclature 2021). There are several variations of stratotype referred to in the literature and this report, and they are defined as follows:

1. **Unit stratotype**: the **type section** for a stratified deposit or the **type area** for a non-stratified body that serves as the standard for recognition and definition of a geologic unit (North American Commission on Stratigraphic Nomenclature 2021). Once a unit stratotype is

assigned, it is never changed, but it may be supplemented if it proves inadequate. The term "unit stratotype" is commonly referred to as "type section" and "type area" in this report.

2. **Type locality**: the specific geographic locality encompassing the unit stratotype of a formally recognized and defined unit. On a broader scale, a type area is the geographic territory encompassing the type locality. Before development of the stratotype concept, only type localities and type areas were designated for many geologic units that are now long- and well-established (North American Commission on Stratigraphic Nomenclature 2021).
3. **Reference sections**: for well-established geologic units for which a type section was never assigned, a reference section may serve as an invaluable standard in definitions or revisions. A principal reference section may also be designated for units whose stratotypes have been destroyed, covered, or are otherwise inaccessible (North American Commission on Stratigraphic Nomenclature 2021). Multiple reference sections can be designated for a single unit to help illustrate heterogeneity or some critical feature not found in the stratotype. Reference sections can help supplement unit stratotypes in the case where the stratotype proves inadequate (North American Commission on Stratigraphic Nomenclature 2021).
4. **Lithodeme**: the term "lithodeme" is defined as a mappable unit of plutonic (igneous rock that solidified at great depth) or highly metamorphosed and pervasively deformed rock that is equivalent in rank to "formation" among stratified rocks (North American Commission on Stratigraphic Nomenclature 2021). The formal name of a lithodeme consists of a geographic name followed by a descriptive term that denotes the average modal composition of the rock (example: Cathedral Peak Granodiorite). Lithodemes are commonly assigned type localities, type areas, and reference localities.

Methods

Methodology

The process of determining whether a specific stratotype occurs within an NPS area involves multiple steps. The process begins with an evaluation of a park-specific Geologic Resources Inventory (GRI) map to prepare a full list of recognized map units (Figure 1). More information about the GRI data can be found later in this section.

Each geologic map unit name is queried in the USGS Geologic Names Lexicon online database ("GEOLEX", a national compilation of names and descriptions of geologic units) at https://ngmdb.usgs.gov/Geolex/search. Information provided by GEOLEX includes the geologic unit name, stratigraphic nomenclature usage, geologic age, published stratotype location descriptions, and the database provides a link to significant publications as well as the USGS Geologic Names Committee Archives (Wilmarth 1938; Keroher et al. 1966). Figure 2 is taken from a search on the Oligocene Rockyford Ash Member, which is mapped within Badlands National Park.

Published GEOLEX stratotype spatial information is provided in three formats: (1) descriptive, using distance from nearby points of interest; (2) latitude and longitude coordinates; or (3) Township/Range/Section (TRS) coordinates. TRS coordinates are based upon subdivisions of a single 93.2 km^2 (36 mi^2) township into 36 individual 2.59 km^2 (1 mi^2) sections, and were converted into Google Earth (.kmz file) locations using Earth Point (https://www.earthpoint.us/TownshipsSearchByDescription.aspx). They are typically presented in an abbreviated format such as "sec. [#], T. [#] [N. or S.], R. [#] [E. or W.]". The most accurate GEOLEX descriptions using TRS coordinates can help locate features within 0.1618 km^2 (0.0625 mi^2). Once stratotype locality information provided for a given unit is geolocated using Google Earth, a GRI digital geologic map of the national park is draped over it. This step serves two functions: to improve accuracy in locating the stratotype, and validating the geologic polygon for agreement with GEOLEX nomenclature. Geolocations in Google Earth are then converted into an ArcGIS format using a "KML to Layer" conversion tool in ArcMap.

Upon accurately identifying the stratotypes using GEOLEX or peer-reviewed literature, a Microsoft Excel spreadsheet is populated with information pertinent to the geologic unit and its stratotype attributes. Attribute data recorded in this way include: (1) whether a stratotype is officially designated; (2) whether the stratotype is on NPS land; (3) whether the stratotype location has undergone a quality control check in Google Earth; (4) reference of the publication citing the stratotype; (5) description of geospatial information; (6) coordinates of geospatial information; (7) geologic age (era, period, epoch, etc.); (8) hierarchy of nomenclature (supergroup, group, formation, member, bed, etc.); (9) whether the geologic unit was listed in GEOLEX; and (10) a generic notes field (Figure 3).

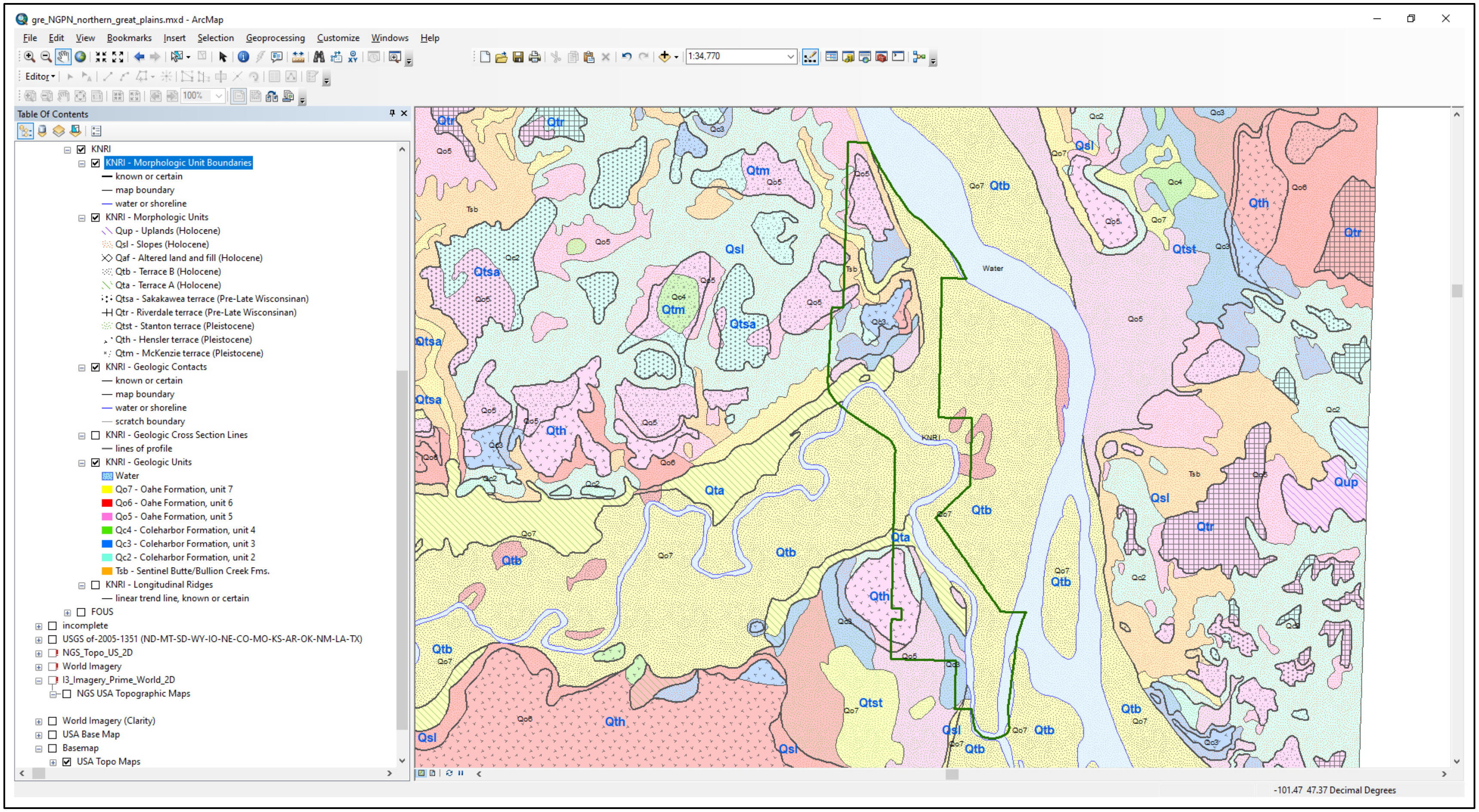
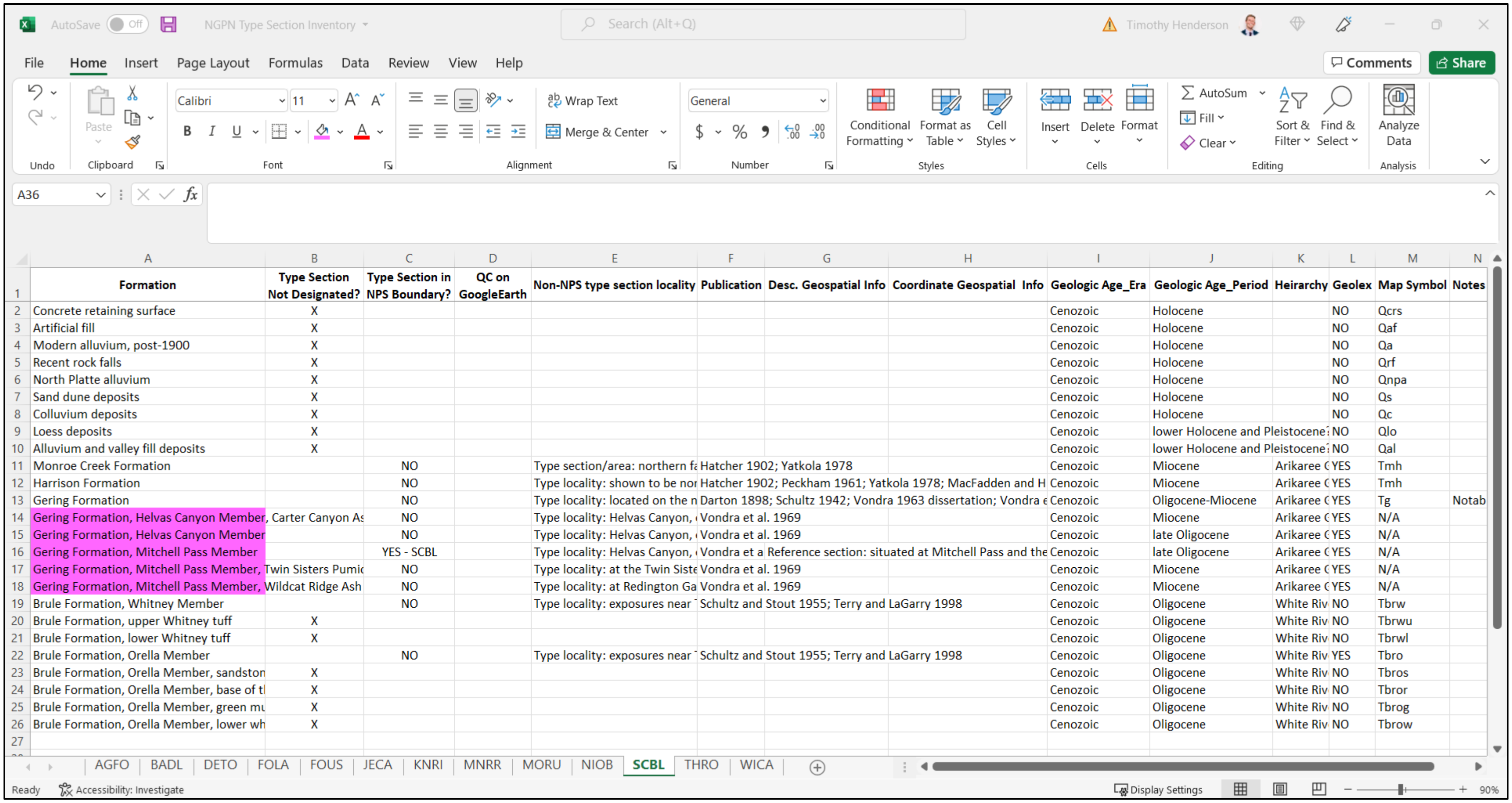


Figure 1. Screenshot of the GRI-compiled digital geologic map of Knife River Indian Villages National Historic Site showing mapped geologic units. The NPS boundary layer has been added (green lines). Access the GIS version of the NPS boundary online: https://irma.nps.gov/DataStore/Reference/Profile/2224545?lnv=True and the KNRI geology at https://irma.nps.gov/DataStore/Reference/Profile/2176225.

Figure 2. GEOLEX search result for the Rockyford Ash Member of the Sharps Formation of the Arikaree Group. Note that the age of the Rockyford Ash Member is now more accurately assigned to the Oligocene Epoch.



	Formation	Type Section Not Designated?	Type Section in NPS Boundary?	QC on GoogleEarth	Non-NPS type section locality	Publication	Desc. Geospatial Info	Coordinate Geospatial Info	Geologic Age_Era	Geologic Age_Period	Heirarchy	Geolex	Map Symbol	Notes
2	Concrete retaining surface	X							Cenozoic	Holocene		NO	Qcrs	
3	Artificial fill	X							Cenozoic	Holocene		NO	Qaf	
4	Modern alluvium, post-1900	X							Cenozoic	Holocene		NO	Qa	
5	Recent rock falls	X							Cenozoic	Holocene		NO	Qrf	
6	North Platte alluvium	X							Cenozoic	Holocene		NO	Qnpa	
7	Sand dune deposits	X							Cenozoic	Holocene		NO	Qs	
8	Colluvium deposits	X							Cenozoic	Holocene		NO	Qc	
9	Loess deposits	X							Cenozoic	lower Holocene and Pleistocene?		NO	Qlo	
10	Alluvium and valley fill deposits	X							Cenozoic	lower Holocene and Pleistocene?		NO	Qal	
11	Monroe Creek Formation		NO		Type section/area: northern fa	Hatcher 1902; Yatkola 1978			Cenozoic	Miocene	Arikaree (	YES	Tmh	
12	Harrison Formation		NO		Type locality: shown to be nor	Hatcher 1902; Peckham 1961; Yatkola 1978; MacFadden and H			Cenozoic	Miocene	Arikaree (	YES	Tmh	
13	Gering Formation		NO		Type locality: located on the n	Darton 1898; Schultz 1942; Vondra 1963 dissertation; Vondra e			Cenozoic	Oligocene-Miocene	Arikaree (	YES	Tg	Notab
14	Gering Formation, Helvas Canyon Member, Carter Canyon As		NO		Type locality: Helvas Canyon, (	Vondra et al. 1969			Cenozoic	Miocene	Arikaree (	YES	N/A	
15	Gering Formation, Helvas Canyon Member		NO		Type locality: Helvas Canyon, (	Vondra et al. 1969			Cenozoic	late Oligocene	Arikaree (	YES	N/A	
16	Gering Formation, Mitchell Pass Member		YES - SCBL		Type locality: Helvas Canyon, (	Vondra et a	Reference section: situated at Mitchell Pass and the		Cenozoic	late Oligocene	Arikaree (	YES	N/A	
17	Gering Formation, Mitchell Pass Member, Twin Sisters Pumic		NO		Type locality: at the Twin Siste	Vondra et al. 1969			Cenozoic	Miocene	Arikaree (	YES	N/A	
18	Gering Formation, Mitchell Pass Member, Wildcat Ridge Ash		NO		Type locality: at Redington Ga	Vondra et al. 1969			Cenozoic	Miocene	Arikaree (	YES	N/A	
19	Brule Formation, Whitney Member		NO		Type locality: exposures near '	Schultz and Stout 1955; Terry and LaGarry 1998			Cenozoic	Oligocene	White Riv	NO	Tbrw	
20	Brule Formation, upper Whitney tuff	X							Cenozoic	Oligocene	White Riv	NO	Tbrwu	
21	Brule Formation, lower Whitney tuff	X							Cenozoic	Oligocene	White Riv	NO	Tbrwl	
22	Brule Formation, Orella Member		NO		Type locality: exposures near '	Schultz and Stout 1955; Terry and LaGarry 1998			Cenozoic	Oligocene	White Riv	YES	Tbro	
23	Brule Formation, Orella Member, sandston	X							Cenozoic	Oligocene	White Riv	NO	Tbros	
24	Brule Formation, Orella Member, base of tl	X							Cenozoic	Oligocene	White Riv	NO	Tbror	
25	Brule Formation, Orella Member, green mu	X							Cenozoic	Oligocene	White Riv	NO	Tbrog	
26	Brule Formation, Orella Member, lower wh	X							Cenozoic	Oligocene	White Riv	NO	Tbrow	

Figure 3. Stratotype inventory spreadsheet of the NGPN displaying attributes appropriate for geolocation assessment. Pink highlighted cells represent geologic units that are supplementary to the GRI stratigraphy listing for SCBL.

Geologic Resources Inventory (GRI) Data

The Geologic Resources Inventory (GRI) provides digital geologic map data and pertinent geologic information on park-specific features, issues, and processes to support resource management and science-informed decision-making to the 270 parks in the I&M program. The GRI team provides three products to each park that can be useful in the determination of stratotypes: (1) a summary document from an initial scoping meeting, (2) digital geologic map data in a geographic information system (GIS) format, and (3) a GRI report.

Scoping meetings bring together park staff and geologic experts to review and assess available geologic maps, develop a geologic mapping plan, and discuss geologic features, processes, and resource management issues that should be addressed in the GRI report. Scoping meeting summaries serve as an interim report until the final report is delivered.

Following the scoping meeting, the GRI map team converts the geologic source maps identified in the mapping plan to GIS data in accordance with the GRI data model (https://www.nps.gov/articles/gri-geodatabase-model.htm). The GRI uses a unique "GMAP ID" value for each geologic source map, and all sources used to produce the GRI GIS data sets for the NGPN parks can be found in Appendix A. The GRI map data is the basis for this stratotype inventory as it is considered the "official" geologic dataset for the park. The list of units present in the GRI GIS data was used to search GEOLEX.

After the digital geologic map is completed, the GRI report team uses the map data, as well as the scoping summary and additional research, to prepare the GRI report. The GRI reports were utilized for additional information about geologic resources in a given park and connections to park landscape, history, or other resources. Posters that display the GRI GIS data over imagery of the park are also created as part of the report process. They are available with the reports or separately from the GRI publications page (https://www.nps.gov/subjects/geology/geologic-resources-inventory-products.htm).

Additional Considerations

There are several additional considerations for this inventory. The most up-to-date information available is necessary, and is either found online or in published articles and maps. Occasionally, there is a lack of specific information which limits the information contained within the final report. This inventory does not include any field work and is dependent on the existing information related to individual park geology and stratigraphy. Additionally, this inventory does not attempt to resolve any unresolved or controversial stratigraphic interpretations, which is beyond the scope of the project.

Stratigraphic nomenclature may change over time with refined stratigraphic field assessments and discovery of information through the expansion of stratigraphic mapping and measured sections. One important observation regarding stratigraphic nomenclature relates to differences in use of geologic names for units that cross state boundaries. Geologic formations and other geologic units that cross state boundaries may have different names or ranks in each of the states the units are mapped. An example is the Paleocene Fort Union Formation (as used by the Montana Bureau of Mines and

Geology and the U.S. Geological Survey), which is equivalent to the Fort Union Group of the North Dakota Geological Survey.

The lack of a designated and formal type section, or inadequate and vague geospatial information associated with a type section, limits the ability to capture precise information for this inventory. The available information related to the geologic type sections is included in this report.

This inventory report is intended for a wide audience, including NPS staff who may not have a background in geology. Therefore, this document is developed as a reference document that supports science, resource management, and a historic framework for geologic information associated with NGPN parks.

All network-specific reports are peer-reviewed and submitted to the Natural Resources Stewardship and Science Publications Office for finalization.

Geology and Stratigraphy of the NGPN I&M Network Parks

The Northern Great Plains Inventory and Monitoring Network (NGPN) consists of 13 national park units in portions of Montana, Nebraska, North Dakota, South Dakota, and Wyoming (Figure 4). The park units of the NGPN include Agate Fossil Beds National Monument (AGFO), Badlands National Park (BADL), Devils Tower National Monument (DETO), Fort Laramie National Historic Site (FOLA), Fort Union Trading Post National Historic Site (FOUS), Jewel Cave National Monument (JECA), Knife River Indian Villages National Historic Site (KNRI), Missouri National Recreational River (MNRR), Mount Rushmore National Memorial (MORU), Niobrara National Scenic River (NIOB), Scotts Bluff National Monument (SCBL), Theodore Roosevelt National Park (THRO), and Wind Cave National Park (WICA). Together, the parks that comprise the Northern Great Plains Network protect a combined 177,100 hectares (437,700 acres) of land and vary in size from 178 hectares (440 acres) in FOUS to 98,239 hectares (242,756 acres) in BADL.

The rich geologic history of the Northern Great Plains Network dates back more than a billion years, recording the growth of ancestral North America, the rise of the Rocky Mountains, shallow continental seaways, and Pleistocene glaciations. Some of the oldest rocks underlying the park units of the NGPN are Paleoproterozoic crystalline rocks in MORU and WICA that form the core of the Black Hills of South Dakota and Wyoming (see Appendix B for a geologic time scale). These metamorphic and igneous rocks include the Harney Peak Granite, used as the in situ medium for the colossal sculpted busts of U.S. Presidents Washington, Jefferson, Roosevelt, and Lincoln at Mount Rushmore. The Harney Peak Granite was emplaced as a series of sills and dikes during an ancient tectonic collisional event known as the Trans-Hudson Orogeny that occurred approximately 1.7 billion years ago (Nabelek et al. 1999; Sirbescu and Nabelek 2003).

Following the Trans-Hudson Orogeny, the geologic record in the NGPN only provides episodic glimpses into the past until the late Cambrian Period, approximately 495 million years ago. The diverse Paleozoic and Mesozoic bedrock underlying the park units of the NGPN spans from the late Cambrian through the Cretaceous, providing a richer but still incomplete view of the evolution of North America. These bedrock strata were deposited during a series of marine transgressions (sea-level rise) and regressions (sea-level fall) associated with shallow, tropical continental seaways such as the Sundance Sea and Western Interior Seaway. The Mississippian Pahasapa Limestone was deposited in this kind of marine setting and is the predominant bedrock hosting the vast cave resources of JECA and WICA. During the Late Cretaceous and Paleogene, approximately 80 to 50 million years ago, the Laramide Orogeny would elevate the Northern Great Plains and uplift the Rocky Mountains and the Black Hills region (Lisenbee 1988; Lisenbee and DeWitt 1993; Sirbescu and Nabelek 2003). The Black Hills contain several NGPN park units (BADL, DETO, JECA, WICA) and represents an exposed basement uplift or arch that displays a central core of Precambrian crystalline rocks flanked by concentric ridges and valleys underlain by much younger Paleozoic and Mesozoic sedimentary strata (Keefer 1974; Lisenbee 1988).

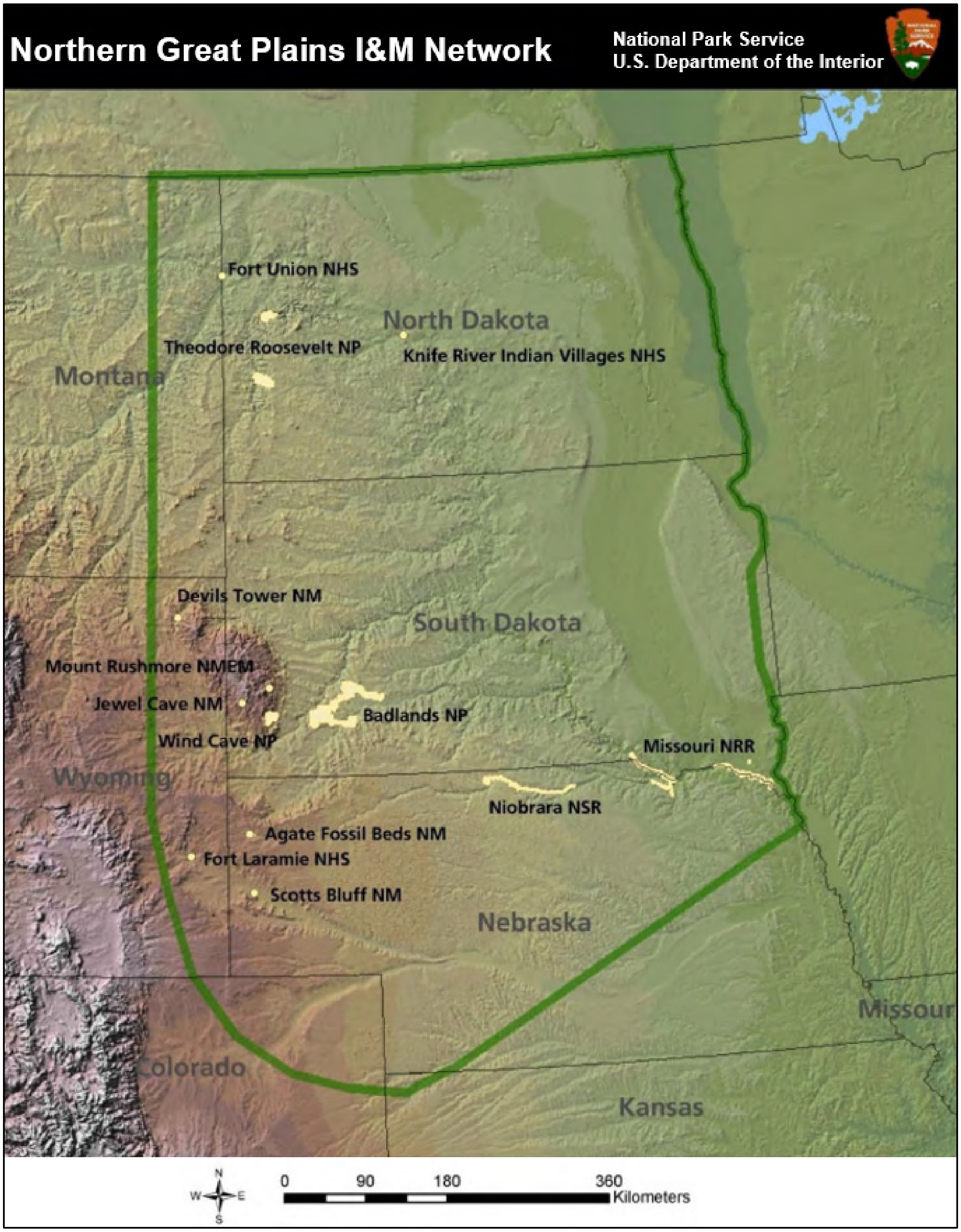


Figure 4. Map of Northern Great Plains I&M Network parks: Agate Fossil Beds National Monument (AGFO), Badlands National Park (BADL), Devils Tower National Monument (DETO), Fort Laramie National Historic Site (FOLA), Fort Union Trading Post National Historic Site (FOUS), Jewel Cave National Monument (JECA), Knife River Indian Villages National Historic Site (KNRI), Missouri National Recreational River (MNRR), Mount Rushmore National Memorial (MORU), Niobrara National Scenic River (NIOB), Scotts Bluff National Monument (SCBL), Theodore Roosevelt National Park (THRO), and Wind Cave National Park (WICA) (NPS).

At the beginning of the Cenozoic Era, the last remnants of the Western Interior Seaway retreated from the Northern Great Plains as highlands to the west continued to rise. Igneous activity associated with the continuation of the Laramide Orogeny produced several igneous intrusions including what is now Devils Tower at DETO. Vast amounts of sediment were shed from the young Rocky Mountains and distributed as large wedges and sheets of clastic material across the central Great Plains region; many of these sediments contain the renowned fossiliferous strata of the Eocene–Oligocene White River Group (BADL, SCBL, WICA), Arikaree Group (AGFO, BADL, FOLA, NIOB, SCBL), and Ogallala Group (AGFO, NIOB). Volcanism in the Western Cordilleran region (Great Basin and Rocky Mountain areas) occurred from the Oligocene through Miocene and introduced thick blankets of pyroclastic material that are associated with the White River Group and overlying Sharps Formation. Rivers draining the high plains east of the Black Hills dissected the region of BADL, exposing the iconic layer-cake stratigraphy of the park and sculpting the namesake badlands topographic landscape (Stoffer 2003). The Quaternary history of the NGPN includes a period of glacial advances and retreats that are recorded by only a few park units (FOUS, KNRI, MNRR, and THRO). A diverse assemblage of Quaternary deposits mapped throughout the NGPN are associated with fluvial landscapes associated with the Missouri River (FOUN, KNRI, MNRR), Niobrara River (AGFO, MNRR, NIOB), North Platte River (FOLA, SCBL), Belle Fourche River (DETO), Knife River (KNRI), and Little Missouri River (THRO).

Precambrian (4.6 billion to 539 million years ago)

As mentioned above, the oldest rocks underlying the park units of the NGPN are Paleoproterozoic igneous and metamorphic rocks in MORU and WICA that form the exposed core of the Black Hills and include the Harney Peak Granite, metagraywacke, metamorphosed black shale, quartzite, and metapelite.

Paleozoic (539 to 252 million years ago)

Geologic units of the Paleozoic Era are mapped in only three park units of the NGPN. The oldest and most diverse assemblage of Paleozoic rocks is found at WICA and includes sedimentary strata spanning from the Cambrian–Ordovician through the Permian. Several units are distributed across multiple park units, such as: the Mississippian Pahasapa Limestone (JECA, WICA), an important carbonate formation hosting the Jewel Cave and Wind Cave networks; Pennsylvanian–Permian Minnelusa Formation (JECA, WICA); and the Permian–Triassic Spearfish Formation (DETO, WICA). Additional Paleozoic units are only found at WICA and consist of the Cambrian–Ordovician Deadwood Formation, Devonian–Mississippian Englewood Formation, and the Permian Opeche Shale and Minnekahta Limestone.

Mesozoic (252 to 66 million years ago)

Rocks of the Mesozoic Era occur in five park units of the NGPN, with some of the oldest units occurring in both DETO and WICA. Strata of the Jurassic Gypsum Spring Formation and Sundance Formation are mapped in both parks, in addition to the Morrison Formation that exclusively underlies WICA. The Cretaceous Pierre Shale is widely distributed across BADL, MNRR, and NIOB. Other Cretaceous sedimentary strata include the Dakota Formation, Graneros Shale, Greenhorn Limestone, Carlile Shale, and Niobrara Formation in MNRR, as well as the Lakota Formation and Fall River Formation in WICA.

Cenozoic (66 million years ago to the present)

The park units of the NGPN contain a diverse suite of Cenozoic deposits that include world-renowned fossil beds, igneous intrusions, glacial deposits, and modern fluvial sediments. Several sedimentary formations are distributed across multiple park units such as the Paleocene Sentinel Butte Formation and Bullion Creek Formation (KNRI, THRO); Eocene–Oligocene White River Group (BADL, WICA, SCBL, and possibly NIOB); Oligocene–Miocene Arikaree Group (AGFO, BADL, FOLA, NIOB, SCBL); and Miocene–Pliocene Ogallala Group (AGFO, NIOB). Other formally named Cenozoic deposits include the Paleocene Fort Union Formation in FOUS; Miocene Anderson Ranch Formation in AGFO; Pleistocene Coleharbor Formation in KNRI and Peoria Loess in MNRR; and the Quaternary Oahe Formation in KNRI. Igneous rocks that comprise Devils Tower in DETO consist of an unnamed Paleogene phonolite porphyry (Bassett 1961).

A wide variety of young, Quaternary surficial deposits has been mapped across the parks of the NGPN and includes glacial outwash and till (FOUS, KNRI, MNRR, THRO), terrace deposits (AGFO, DETO, MNRR, WICA), aeolian sand and loess (BADL, FOLA, MNRR, SCBL), alluvial deposits (MORU, THRO, WICA), landslide deposits (BADL, THRO, WICA), rockfall deposits (DETO, MORU, SCBL), alluvium (AGFO, BADL, DETO, FOLA, FOUS, JECA, MNRR, NIOB, SCBL, THRO), and colluvium (AGFO, FOUS, MNRR, SCBL).

Agate Fossil Beds National Monument (AGFO)

Park Establishment

Agate Fossil Beds National Monument (AGFO) is located along the Niobrara River Valley in Sioux County, Nebraska, approximately 65 km (40 mi) north of the city of Scottsbluff and neighboring SCBL (Figure 5). Although AGFO was authorized on June 5, 1965, the park unit was not established for many years due to shifting NPS priorities and funding (Cockrell 1986), with establishment coming June 14, 1997 (National Park Service 2016a). AGFO contains approximately 1,237 hectares (3,058 acres) and protects an internationally renowned fossil site featuring exceptionally preserved mammal specimens from the Miocene Epoch (National Park Service 2012). Fossil collections from the monument provide valuable insight into the evolution, climate, and biological diversity of the Miocene, and include early cousins of modern-day birds, beavers, horse, rhinos, and camels (Tweet et al. 2011). The monument's name is derived from a thin band of agate deposits that occur just above the fossil beds. Paleontological resources of considerable interest include: (1) multiple historic fossil quarries including the Carnegie Hill, University Hill, and *Stenomylus* quarries; (2) the Great Bone Bed, a rich fossil deposit containing thousands of densely packed bones; (3) bear dog (*Daphoenodon*) burrows that record the earliest known denning behavior of terrestrial carnivores; and (4) "Devils Corkscrews" (*Daemonelix*), giant sandstone spirals up to 3 m (10 ft) tall that are sedimentary casts of ancient rodent burrows (Graham 2009a; Tweet et al. 2011).

Geologic Summary

AGFO is situated in the High Plains physiographic province in a dissected tableland of the Niobrara Valley. The bedrock underlying AGFO dates to the late Oligocene and early Miocene, consisting of sedimentary and volcanic rocks of the Sharps Formation, Harrison Formation (including the Agate Ash Bed), informal Anderson Ranch formation (former upper Harrison beds), and Runningwater Formation. The bone beds at AGFO are concentrated in sedimentary strata of the Arikaree Group, primarily the Harrison Formation and Anderson Ranch formation. These two formations underlie most of the monument and are exposed along the Niobrara River and its tributary valleys. Overlying the bedrock of the monument are Quaternary paleosols (ancient soils), alluvium, colluvium, and terrace deposits mapped along the Niobrara River and its tributaries (Figure 6). Because the region of AGFO was unglaciated, the national monument features a complex array of Pleistocene and Holocene geomorphology and stratigraphy that record significant climate variations over the past 15,000–12,000 years (Graham 2009a).

Stratotypes

AGFO contains one identified stratotype that is assigned to the early Miocene Agate Ash Bed of the Harrison Formation (Table 2; Figure 7). In addition to the designated stratotype located within AGFO, there are 26 stratotypes located within 48 km (30 mi) of AGFO boundaries; they are listed in Appendix C for reference in case of future boundary expansion.

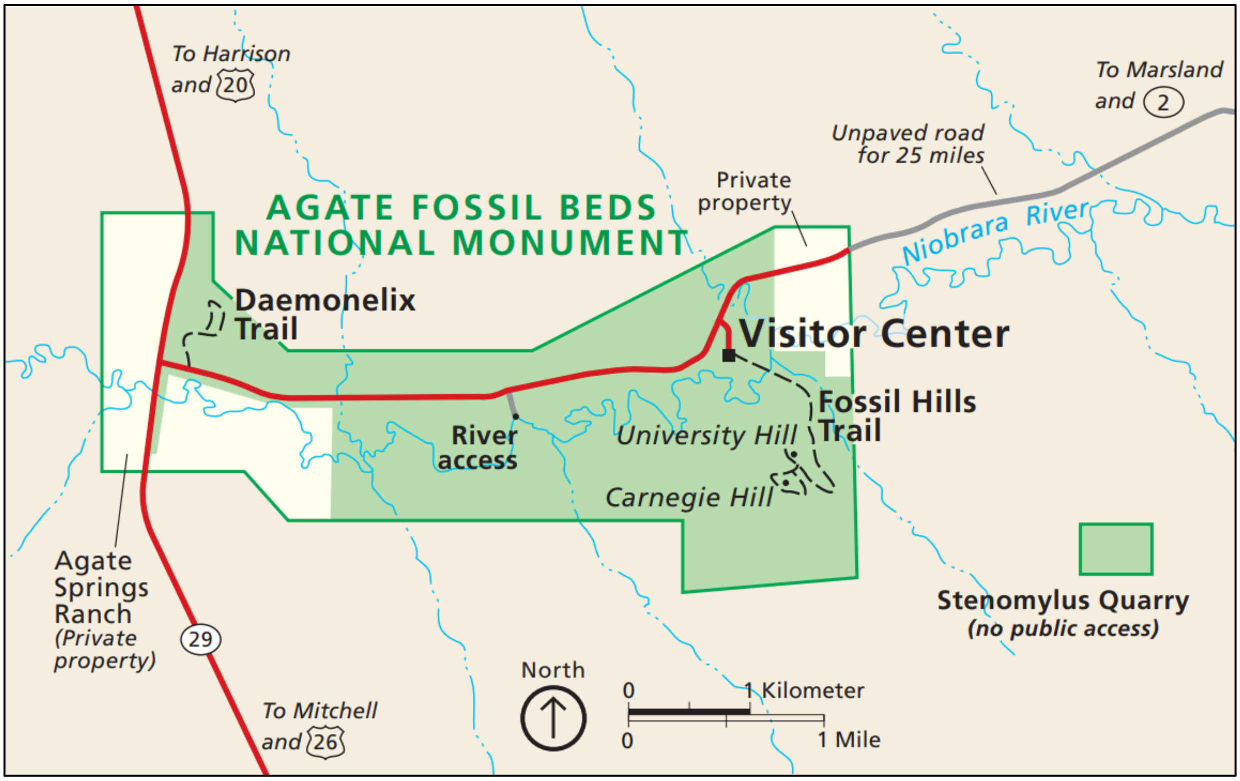


Figure 5. Park map of AGFO, Nebraska (NPS).

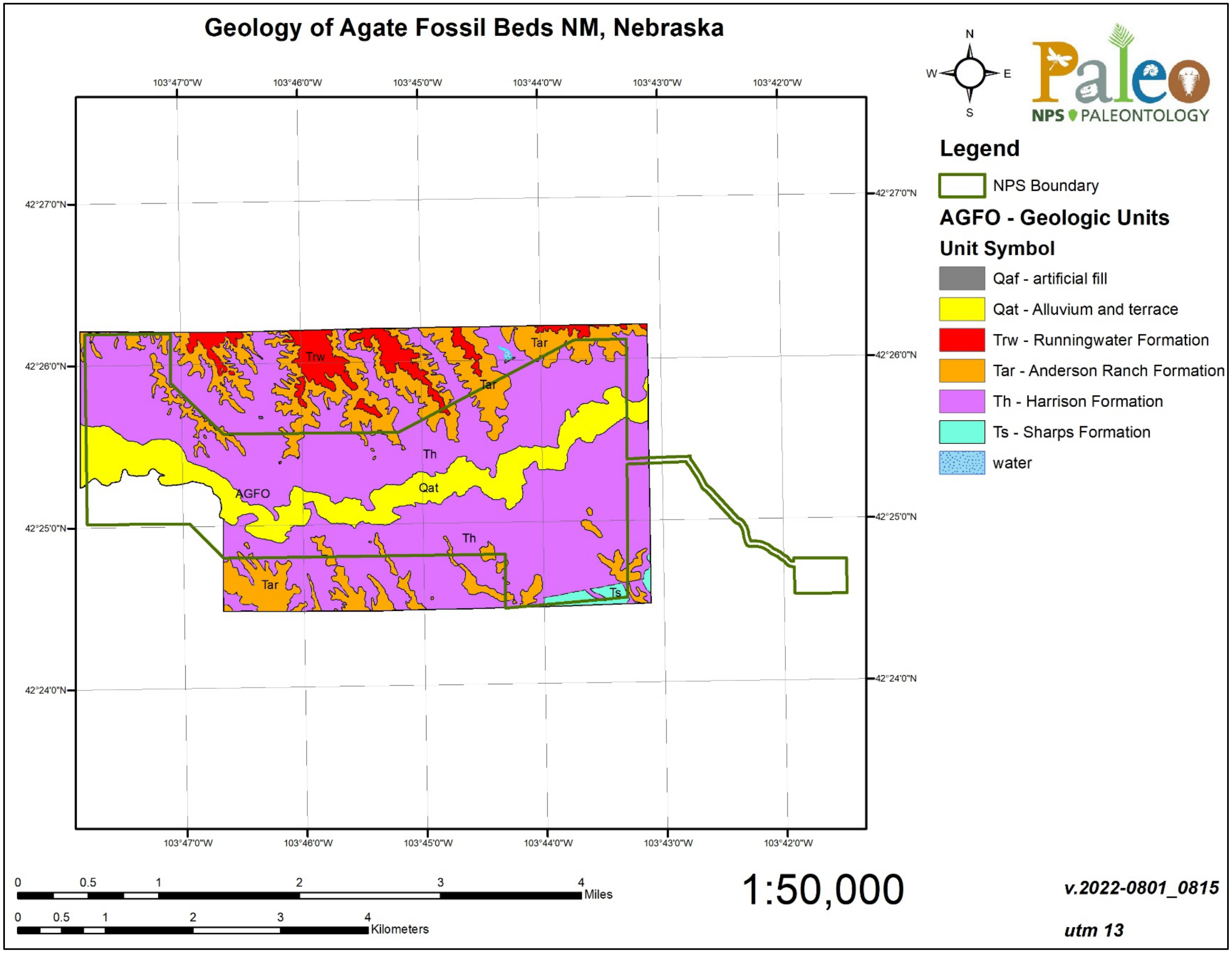


Figure 6. Geologic map of AGFO, Nebraska. Data modified from AGFO digital geologic map data at https://irma.nps.gov/DataStore/Reference/Profile/1047294.

Table 2. List of AGFO stratotype units sorted by age with associated reference publications and locations.

Unit Name (GRI map symbol)	Reference	Stratotype Location	Age
Agate Ash Bed, Harrison Formation	Skinner et al. 1977	Type locality: an easily accessible deposit from 2.1–2.4 m (7–8 ft) thick on the north side of the Niobrara River, about 3.2 km (2 mi) east of the former Agate post office, in the SE/4 SW/4 sec. 4, T. 28 N., R. 55 W., in Sioux County, NE.	early Miocene

Agate Ash Bed, Harrison Formation

The early Miocene Agate Ash Bed of the Harrison Formation was introduced by Skinner et al. (1977) to describe a white volcanic ash bed that was previously referred to as "tuff" by Evernden et al. (1964). The Agate Ash represents an important marker bed that underlies the Great Bone Bed of AGFO and constrains the oldest age of the overlying fossils to the Miocene Epoch. Early radiometric dating (K-Ar) by Evernden et al. (1964) resulted in an age of 21.3 Ma, but more recent methods (Ar-Ar) by Izett and Obradovich (2001) and Lander and Lindsay (2011) have yielded an age of 23.23 ± 0.13 Ma. Although the unit is considered informal, a type locality was assigned by Skinner et al. (1977) as an easily accessible deposit from 2.1–2.4 m (7–8 ft) thick on the north side of the Niobrara River, about 3.2 km (2 mi) east of the former Agate post office in Sioux County, Nebraska (Figure 7; Table 2). At the type locality, the unit consists of a white, friable, compact ash with highly variable local thickness (Skinner et al. 1977). The base of the Agate Ash occurs at an elevation of 1,361 m (4,465 ft) within the Harrison Formation, approximately 14 m (45 ft) above the Niobrara River and 9 m (30 ft) below the Agate Spring quarries (Skinner et al. 1977).

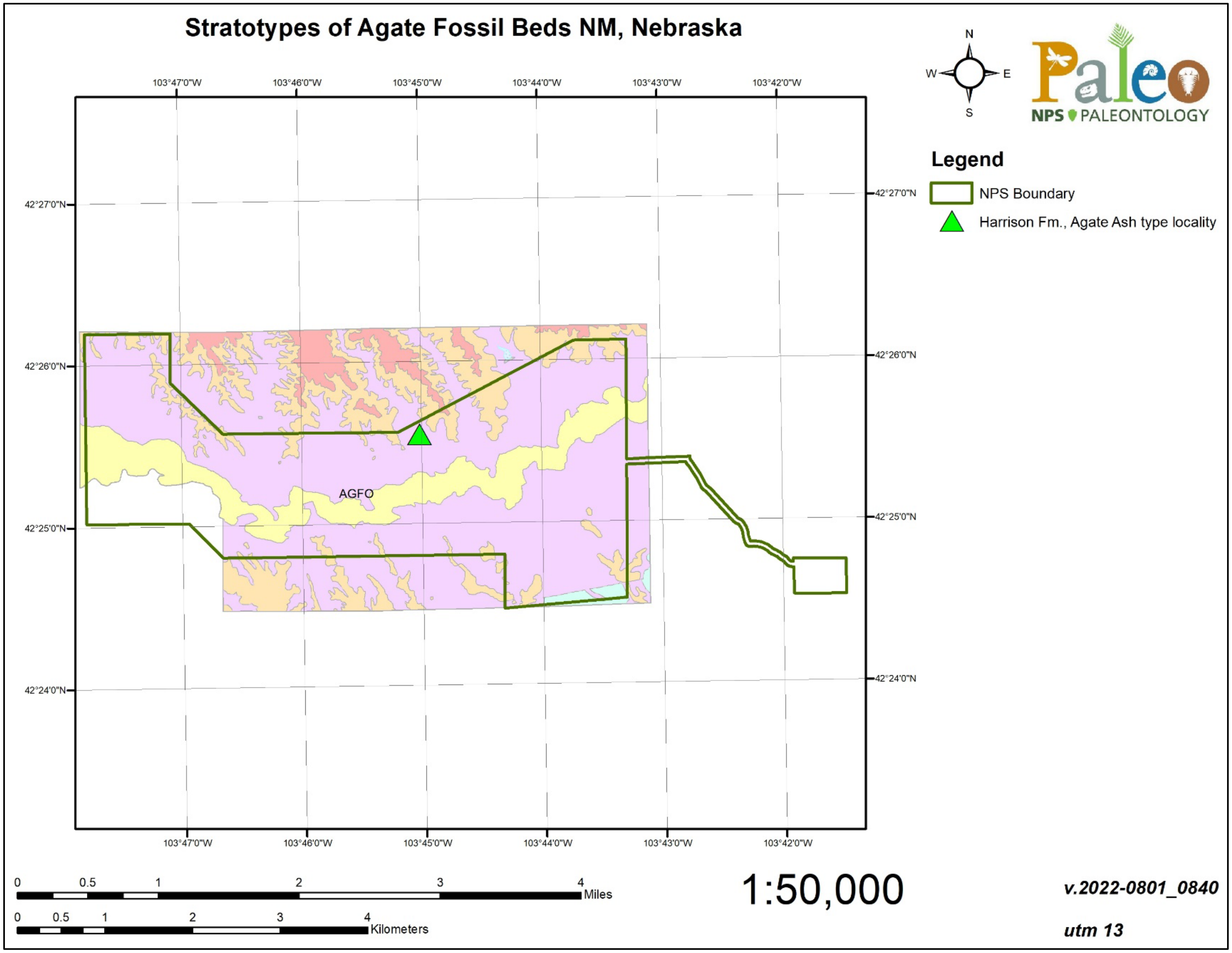


Figure 7. Modified geologic map of AGFO showing stratotype locations. The transparency of the geologic units layer has been increased.

Badlands National Park (BADL)

Park Establishment

Badlands National Park (BADL) is located about 110 km (70 mi) east of Rapid City in the White River Badlands of Pennington, Oglala Lakota, and Jackson Counties, southwestern South Dakota (Figure 8). Originally established as a national monument on January 24, 1939, the park unit was redesignated as a national park on November 10, 1978 (National Park Service 2016a). Encompassing approximately 98,239 hectares (242,756 acres), BADL preserves a scenic landscape featuring colorful geologic formations that have eroded into buttes, pinnacles, and spires. BADL contains a rich collection of paleontological resources that include ancient mammalian fauna of the Eocene and Oligocene Epochs (37–26 million years ago) such as rhinos, horses, and nimravids (false saber-toothed cats) (Tweet et al. 2011). Fossil specimens at BADL have provided valuable insight into the evolution, climate, and biological diversity of the Eocene and Oligocene, and significantly contributed to the study of vertebrate paleontology in North America (National Park Service 2017a). The national park consists of three park units—the North, Stronghold (or South), and Palmer Creek Unit—that also protect remnants of native prairie and the largest mixed-grass prairie within the NPS.

Geologic Summary

BADL is situated in the Great Plains physiographic province east of the Black Hills and features an iconic, dissected "badlands"-style topography (named after the landscape of BADL) that reflects millions of years of dynamic erosional processes. Rivers draining the high plains east of the Black Hills dissected the region of BADL, exposing the iconic layer-cake stratigraphy of the park and sculpting its many geologic features (Stoffer 2003). The bedrock underlying BADL can be subdivided into three groups based on age and lithology: (1) Cretaceous rocks of the Pierre Shale; (2) strata of the Eocene–Oligocene White River Group (Chadron Formation and Brule Formation) and Oligocene Sharps Formation; and (3) young, Quaternary surficial units (Figure 9). Rocks of the Pierre Shale are restricted to areas along the northern park boundary near the Cheyenne River and its tributaries. Sedimentary deposits of the White River Group underlie a significant portion of BADL and preserve the renowned fossil resources that are intimately associated with the establishment of the park. Surficial Quaternary deposits are mapped throughout BADL and include unconsolidated alluvium, aeolian sand, and landslide deposits.

Stratotypes

BADL contains six identified stratotypes that include five type sections and one type area (Table 3; Figure 10). In addition to the designated stratotypes located within BADL, there are 20 stratotypes located within 48 km (30 mi) of BADL boundaries; they are listed in Appendix C for reference in case of future boundary expansion.

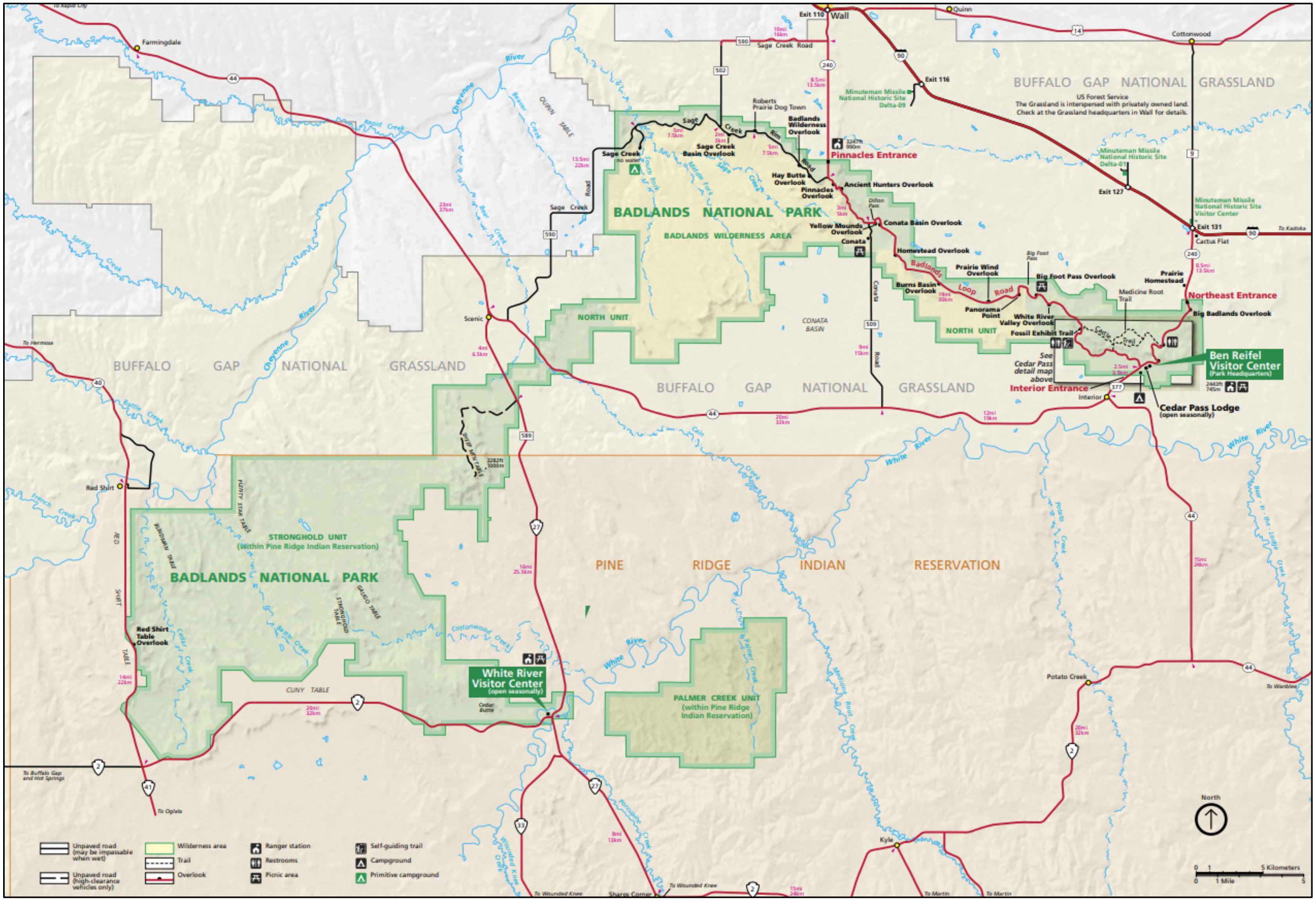


Figure 8. Park map of BADL, South Dakota (NPS).

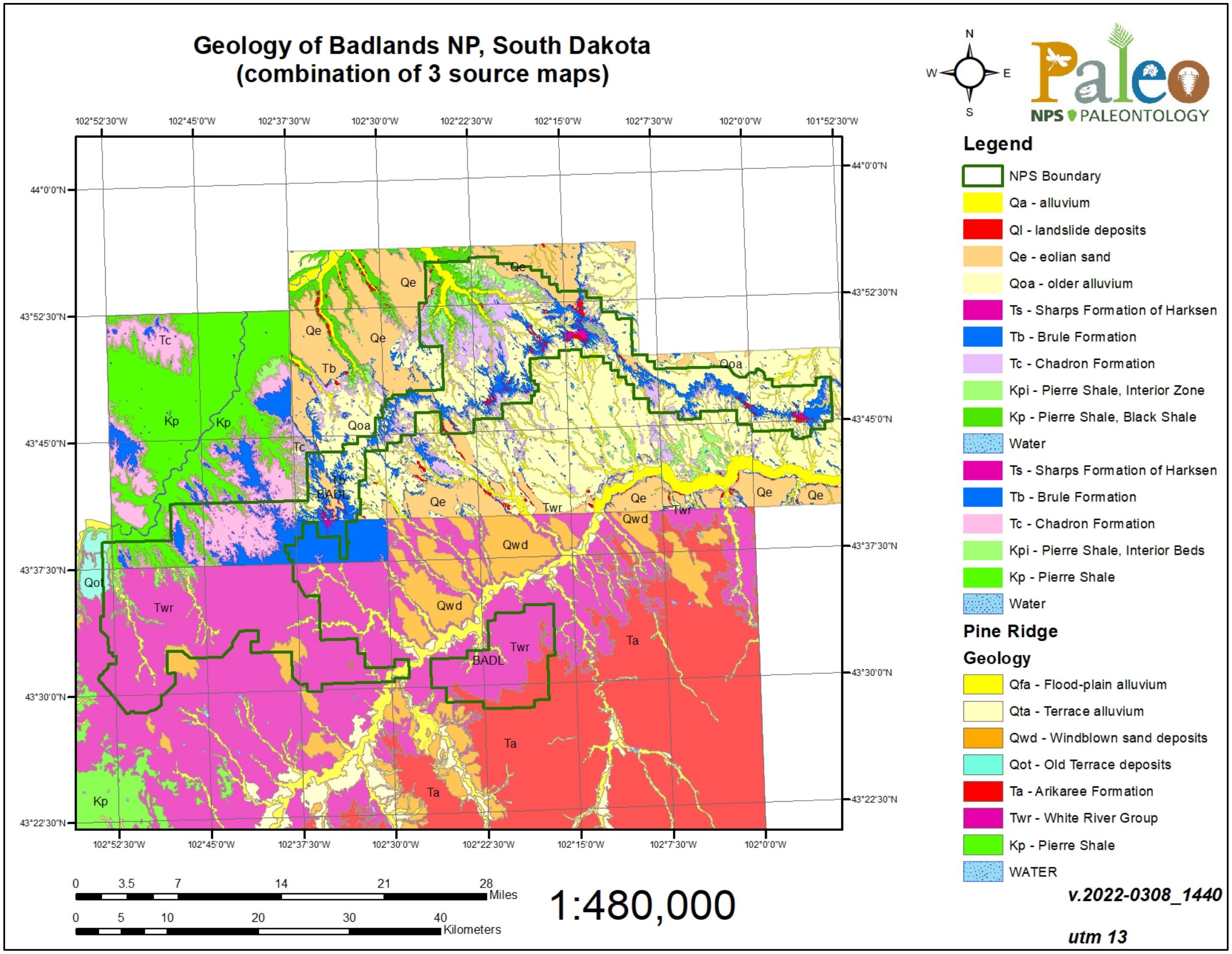


Figure 9. Geologic map of BADL, South Dakota. Data modified from BADL GRI digital geologic map data at https://irma.nps.gov/DataStore/Reference/Profile/1045901, https://irma.nps.gov/DataStore/Reference/Profile/1045899, and https://irma.nps.gov/DataStore/Reference/Profile/1045900 (the three source maps do not agree in nomenclature and polygon boundaries).

Table 3. List of BADL stratotype units sorted by age with associated reference publications and locations.

Unit Name (GRI map symbol)	Reference	Stratotype Location	Age
Sharps Formation (Ts)	Harksen et al. 1961	Type section (composite): 1. Lower interval: measured on the north face of "wall" in SW/4 NW/4 sec. 31, T. 41 N., R. 42 W., in Shannon County, SD. 2. Upper interval: measured along drainage from NW/4 sec. 30, T. 39 N., R. 43 W. northeast into NE/4 sec. 20, T. 39 N., R. 43 W., in Shannon County, SD. ***NOTE: Only the lower composite type section interval is in BADL.	Oligocene
Wolff Camp Member, Sharps Formation	McConnell and DiBenedetto 2012	Type section: in the SW/4 NW/4 sec. 31, T. 41 N., R. 42 W., Evergreen NE 7.5′ Quadrangle, in Shannon County, SD.	Oligocene
Rockyford Ash Member, Sharps Formation	Harksen et al. 1961; Nicknish and Macdonald 1962	Type section: south end of Sheep Mountain Table, in SE/4 NE/4 NE/4 sec. 32, T. 43 N., R. 44 W., in Shannon County, SD.	Oligocene
Brule Formation, White River Group (Tb)	Bump 1956; Harksen and Macdonald 1969	Type section (composite): 1. Lower interval: in the SW/4 sec. 27, T. 3 S., R. 13 E., in Pennington County, SD. 2. Upper interval: NE/4 sec. 33 and SW/4 sec. 28, T. 43 N., R. 44 W., Sheep Mountain Table 7.5′ Quadrangle, in Shannon County, SD. ***NOTE: Only the upper composite type section interval is in BADL.	Oligocene
Poleslide Member, Brule Formation, White River Group	Bump 1956; Harksen and Macdonald 1969	Type section (corrected from Bump 1956): NE/4 sec. 33 and SW/4 sec. 28, T. 43 N., R. 44 W., Sheep Mountain Table 7.5′ Quadrangle, in Shannon County, SD.	Oligocene
White River Group (Tb, Tc, Twr)	Meek and Hayden 1857, 1861; Harksen et al. 1979; LaGarry 1998	Type area: the Big Badlands of southwestern SD.	Eocene–Oligocene

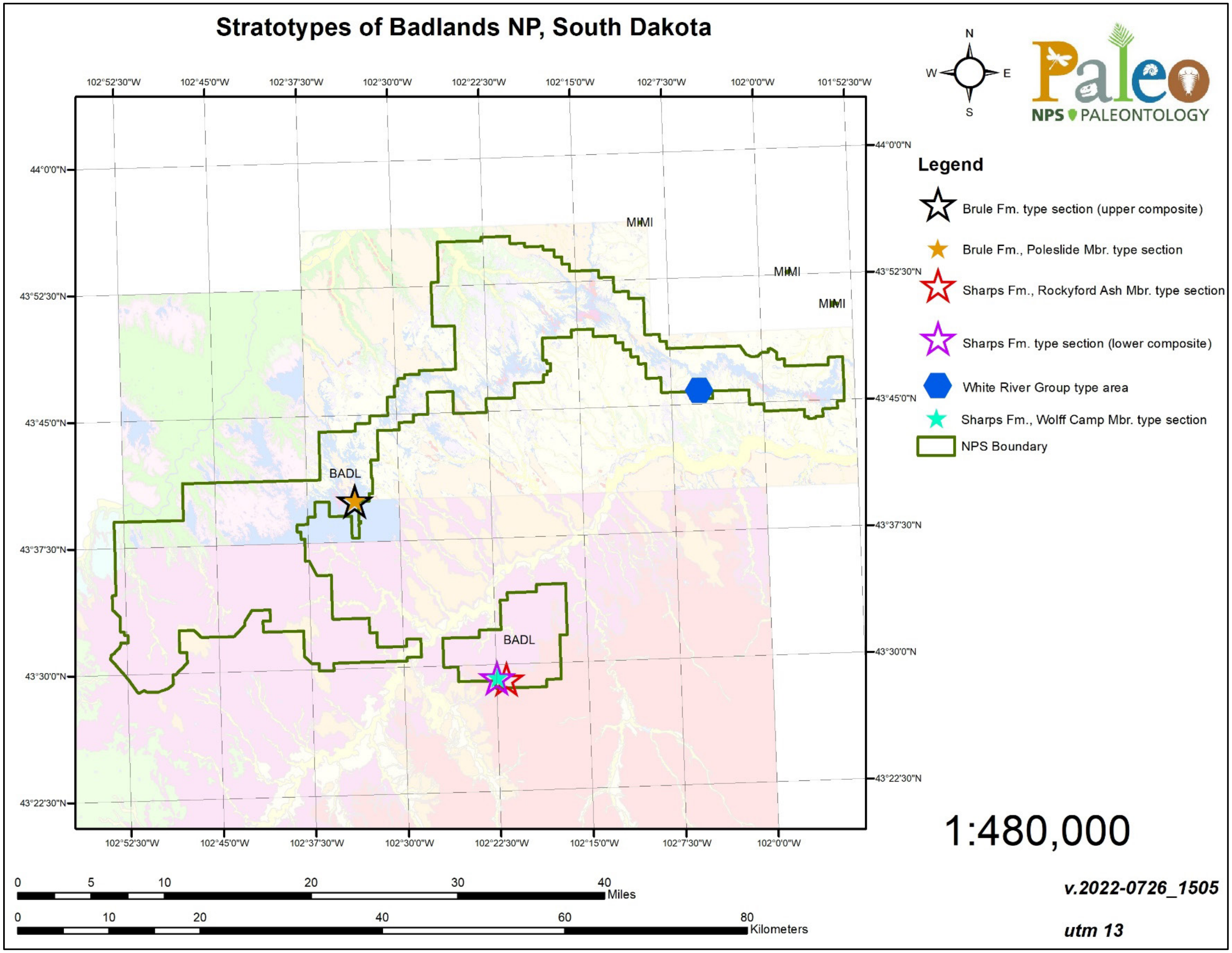


Figure 10. Modified geologic map of BADL showing stratotype locations. The transparency of the geologic units layer has been increased.

Sharps Formation

The Oligocene Sharps Formation was proposed by Harksen et al. (1961) and named after Sharps Corner, South Dakota, just south of the Palmer Creek Unit of BADL. Harksen et al. (1961) described the Sharps Formation as the lowest unit of the Arikaree Group and designated a composite type section that includes: (1) a lower interval measured on the north face of the "wall" in SW/4 NW/4 sec. 31, T. 41 N., R. 42 W., Shannon County, South Dakota; and (2) an upper interval measured along drainage from NW/4 sec. 30, T. 39 N., R. 43 W. northeast into NE/4 sec. 20, T. 39 N., R. 43 W, Shannon County, South Dakota (Table 3; Figures 10–12). Although the upper type section interval is not within BADL, the lower interval is excellently displayed in the Palmer Creek Unit. The lower part of the Sharps Formation type section measures approximately 82 m (270 ft) thick and predominantly consists of pinkish-tan, calcareous siltstone that weathers to form smooth slopes punctuated by randomly scattered nodular calcareous concretions (Harksen et al. 1961). The bottom 30–60 cm (1–2 ft) of section consists of white volcanic ash of the Rockyford Ash Member. The Sharps Formation conformably overlies the Brule Formation (White River Group) and underlies the Monroe Creek Formation (Arikaree Group).

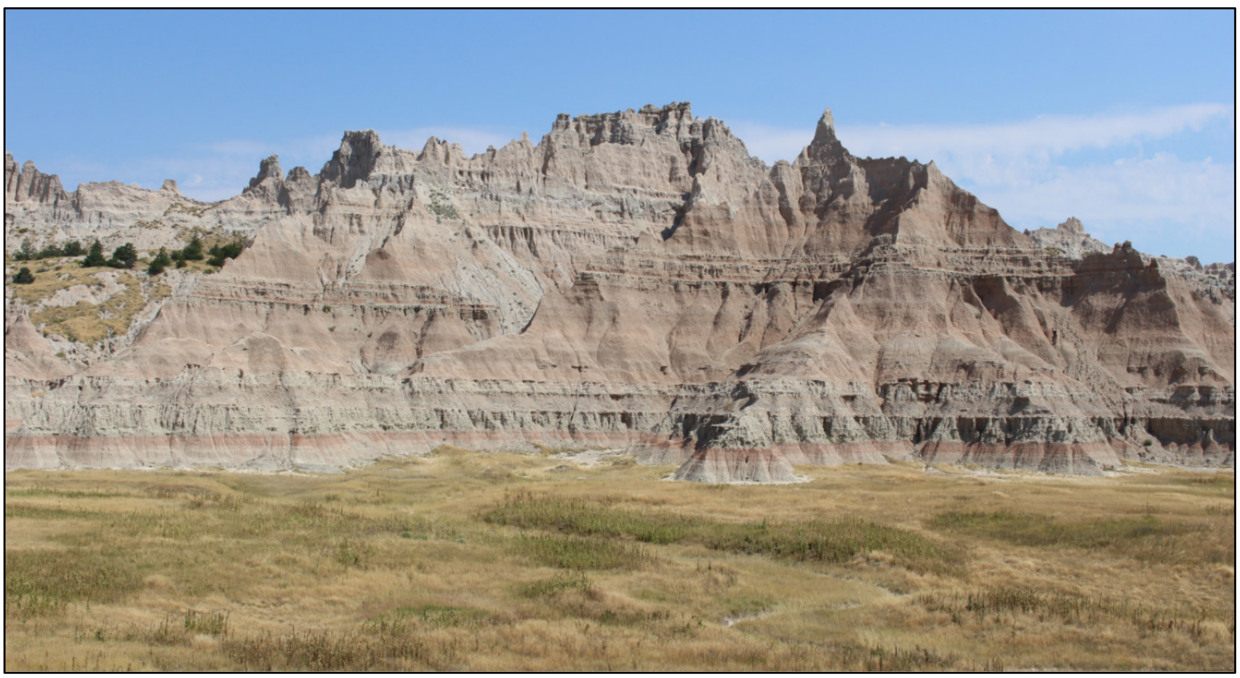


Figure 11. The Badlands "wall", one of the most recognizable features at BADL and the location of the lower composite type section interval of the Sharps Formation (NPS).

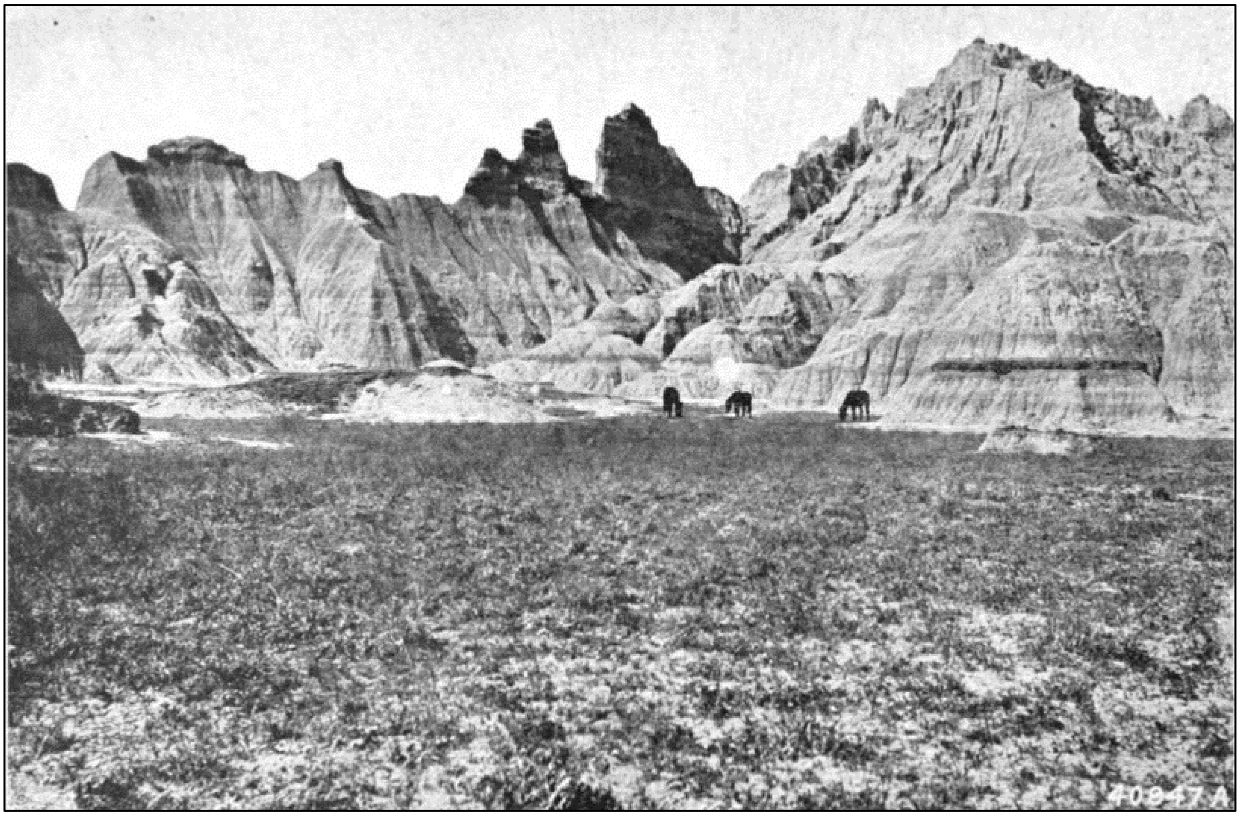


Figure 12. The south side of the "wall". Plate V from Ward (1922). Photograph taken by the U.S. Forest Service.

Rockyford Ash Member, Sharps Formation

The Oligocene Rockyford Ash Member represents a basal volcanic ash bed of the Sharps Formation that was introduced by Nicknish (1957) and named after the town of Rockyford, South Dakota, just south of the Stronghold Unit of BADL. The type section of the unit is located at the south end of Sheep Mountain Table in Shannon County, South Dakota (Table 3; Figure 10; Harksen et al. 1961; Nicknish and Macdonald 1962). At the type section, the Rockyford Ash Member caps Sheep Mountain Table and consists of white, buff, tan, and reddish-brown ash layers with varying amounts of silt, measuring approximately 9 m (30 ft) thick overall (Harksen et al. 1961; Nicknish and Macdonald 1962). The member is widely but discontinuously exposed throughout the White River Badlands, where it forms a prominent capping unit on many of the higher buttes and tables throughout BADL (Figures 13 and 14; Nicknish and Macdonald 1962). The Rockyford Ash Member conformably overlies the Brule Formation (White River Group) and underlies calcareous siltstone of the Sharps Formation.

Figure 13. View from Cedar Butte in the Stronghold Unit of BADL looking west at rugged pinnacles and canyons consisting of the Brule Formation overlain by the Rockyford Ash Member of the Sharps Formation. The Rockyford Ash Member caps the pinnacles in the foreground and is outlined by the yellow dashed line (annotated NPS photo).

Figure 14. White and buff ash exposures of the Rockyford Ash Member in BADL (NPS).

Wolff Camp Member, Sharps Formation

The Oligocene Wolff Camp Member of the Sharps Formation was named by McConnell and DiBenedetto (2012) after the area near Sharps Corner, South Dakota, known as Wolff Camp. The type section of the member is designated in the Palmer Creek Unit of BADL, in the SW/4 NW/4 sec. 31, T. 41 N., R. 42 W., Evergreen NE 7.5′ Quadrangle, in Shannon County, South Dakota (Table 3; Figure 10; McConnell and DiBenedetto 2012). At the type section the Wolff Camp Member measures 49 m (161 ft) thick and predominantly consists of tan- to pinkish-gray siltstone with minor beds of ash, claystone, sandstone, and limestone (McConnell and DiBenedetto 2012). Siltstone intervals of the Wolff Camp Member contain reworked, elongate nodular concretions that are interpreted as overbank/floodplain deposits (McConnell and DiBenedetto 2012). The Wolff Camp Member stratigraphically occurs between the underlying Rockyford Ash Member and overlying Gooseneck Road Member of the Sharps Formation.

Brule Formation

The Oligocene Brule Formation of the White River Group was originally referred to as the “Brule clay” by Darton (1899), who named the unit after the Brulé, one of several branches of the Lakota tribe that settled in the lands of the Pine Ridge Indian Reservation in southwestern South Dakota.

Darton (1899) provides detailed sections in several locales, with the thickest section west of the former Adelia railroad station in T. 33 N., R. 53 W., Sioux County, Nebraska (Darton's "Round Top to Adelia" section). Located approximately 100 km (60 mi) southwest of BADL in Toadstool Geologic Park, the "Round Top to Adelia" section is 200 m (655 ft) thick and consists of (in ascending order) greenish sands and sandy clays, sandstone, light buff-gray clays, volcanic ash, pink clays, and pure volcanic ash (Darton 1899). However, because Darton (1899) did not assign a stratotype to the Brule Formation, there is disagreement surrounding the type section of the formation. Schultz and Stout (1955) and LaGarry (1998) agree that Darton's "Round Top to Adelia" section is the formal type section of the Brule Formation. However, Harksen and Macdonald (1969) disagree with Schultz and Stout (1955), stating it was not Darton's intent to have the type section in Nebraska. A composite type section for the Brule Formation was assigned by Harksen and Macdonald (1969) using corrected measured sections of the lower Scenic Member and upper Poleslide Member from Bump (1956) at the following locations: 1) lower interval (= type section of the Scenic Member) measured in the SW/4 sec. 27, T. 3 S., R. 13 E., Pennington County, South Dakota; and 2) upper interval (= type section of the Poleslide Member) measured in the NE/4 sec. 33 and SW/4 sec. 28, T. 43 N., R. 44 W., Sheep Mountain Table 7.5′ Quadrangle, in Shannon County, South Dakota (Table 3; Figure 10). Although the lower composite type section of the Brule Formation (Scenic Member type section) is located just outside BADL, the upper composite section (Poleslide Member type section) is located within the national park near Sheep Mountain Table. The upper composite type section measures approximately 91 m (300 ft) thick and is subdivided into three zones: 1) a basal zone consisting of grayish-brown clay; 2) middle zone comprised of fossiliferous, buff- to gray-colored clay and highly fossiliferous sandstone; and 3) an upper zone of vertically weathered, gray, silty ash (Bump 1956). The Brule Formation overlies the Chadron Formation and conformably underlies the Rockyford Ash Member of the Sharps Formation.

Poleslide Member, Brule Formation

The Oligocene Poleslide Member is the upper member assigned to the Brule Formation of South Dakota by Bump (1956); the derivation of the name "Poleslide" remains ambiguous and was not provided. A standard section of the member measured and described by Bump (1956) was later corrected and redescribed as the type section by Harksen and Macdonald (1969). The type section of the Poleslide Member doubles as the upper composite type section of the Brule Formation and is located just south of Sheep Mountain Table in BADL, in NE/4 sec. 33 and SW/4 sec. 28, T. 43 N., R. 44 W., Sheep Mountain Table 7.5′ Quadrangle, Shannon County, South Dakota (Table 3; Figures 10 and 15). The type section of the Poleslide Member measures about 91 m (300 ft) thick and is subdivided into three zones: (1) a basal zone consisting of grayish-brown clay; (2) middle zone comprised of fossiliferous, buff- to gray-colored clay and highly fossiliferous sandstone; and (3) an upper zone of vertically weathered, gray, silty ash (Bump 1956). The Poleslide Member overlies the Scenic Member of the Brule Formation and underlies the Rockyford Ash Member of the Sharps Formation.

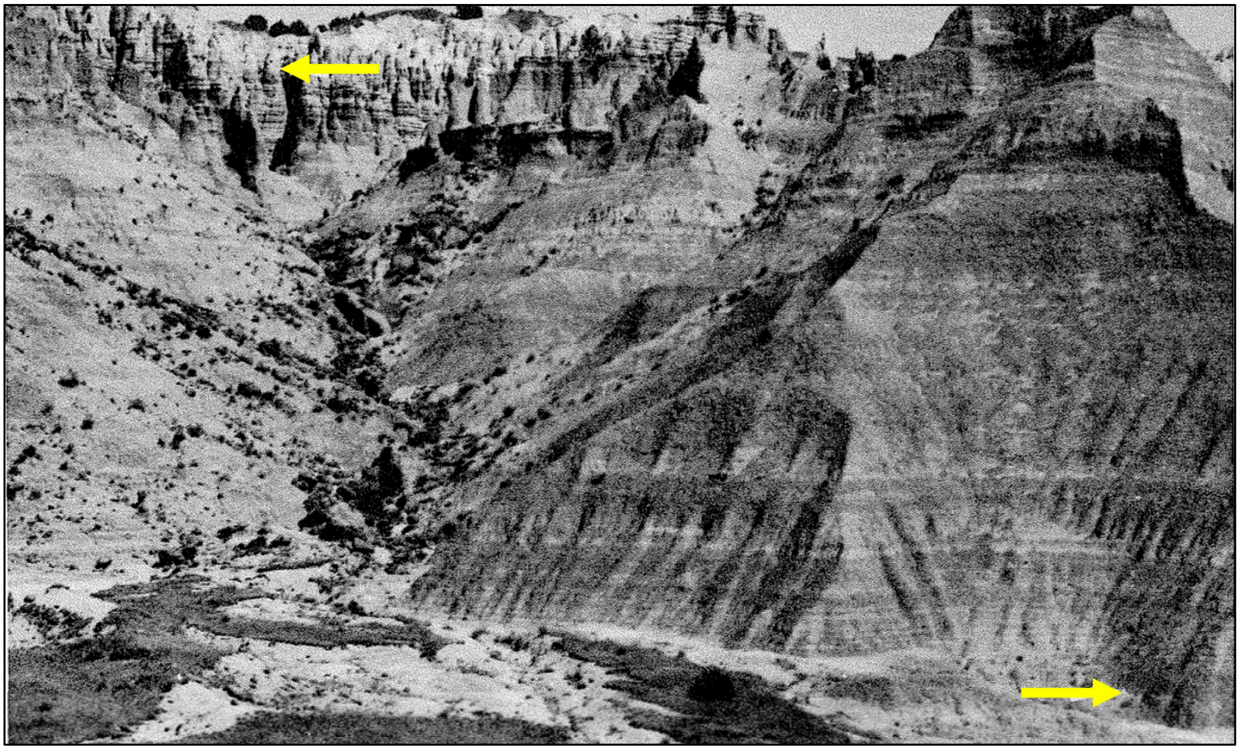


Figure 15. Type section of the Poleslide Member of the Brule Formation and the type section for the upper part of the Brule Formation. Arrows indicate the upper and lower contact. Annotated Figure 9 from Harksen and Macdonald (1969) (courtesy South Dakota Geological Survey).

White River Group

The Eocene–Oligocene White River Group was first introduced by Meek and Hayden (1857, 1861) and named from exposures near the mouth of the White River in South Dakota. Although Meek and Hayden (1857, 1861) never assigned a formal stratotype, several papers have described the type area of the White River Group in the Big Badlands of southwestern South Dakota—an area that certainly encompasses BADL (Table 3; Figure 10; Bump 1956; Harksen et al. 1979; LaGarry 1998). In the South Dakota region of BADL, the White River Group is comprised of the lower Chamberlain Pass Formation (Eocene), middle Chadron Formation (Eocene) and upper Brule Formation (Oligocene), three fossiliferous units that were deposited in dominantly fluvial (river) and aeolian (wind-driven) environments (Retallack 1983; Stoffer 2003; Tweet et al. 2011). Strata of the White River Group consist of conglomerates, sandstones, tuffaceous sandstones, siltstones, claystones, bone beds, and volcanic ash beds that preserve world-renowned fossil specimens that have made significant contributions to the field of paleontology (Singler 1969; Harksen and Macdonald 1969; Larsen and Evanoff 1998; Stoffer 2003; National Park Service 2017a). The Chadron Formation and Brule Formation are very well exposed throughout BADL and have a combined thickness of close to 190 m (630 ft) in the type area (Figures 16 and 17; Harksen et al. 1979). In southwestern South Dakota, the White River Group underlies strata of the Oligocene–Miocene Arikaree Group and overlies the Cretaceous Pierre Shale.

The Chamberlain Pass Formation is a sandstone and mudstone-dominated unit that includes paleosols and often preserves a basal conglomerate (Clark 1967; Evans and Terry 1994). Fossils of the Chamberlain Pass Formation are sparse but similar to the overlying Chadron Formation and include root traces, wood, turtles, rhinos, and brontotheres (rhinoceros-like extinct mammals) (Clark 1967; Terry and Evans 1994; LaGarry et al. 1996; Tweet et al. 2011). The Chadron Formation principally consists of poorly consolidated mudrock made up of gray- to olive-gray sandy clay, with local lenses of coarse gravel conglomerate and white freshwater limestone preserved at or near its base (Stoffer 2003). In South Dakota, the Chadron Formation was subdivided by Clark (1954) into three members (oldest to youngest): (1) Ahearn Member; (2) Crazy Johnson Member; and (3) Peanut Peak Member. All three members are mapped in the vicinity of the Stronghold Unit of BADL, but only the Peanut Peak Member is recognized in the North Unit (Stoffer 2003). A rich variety of fossils have been reported from the Chadron Formation and include invertebrates, frogs, turtles, lizards, alligators, birds, creodont, nimravids, rhinos, brontotheres, horses, entelodonts, oreodonts (sheep-like animals), trace fossils, and more (see Tweet et al. 2011 for a more complete review). The Brule Formation is composed of paleosols, vari-colored claystones, sandstones, and silty ash beds (Darton 1899; Clark 1954; Stoffer 2003). Clark (1954) assigned two members to the Brule Formation in South Dakota (oldest to youngest): (1) Scenic Member; and (2) Poleslide Member. Paleontological resources reported from the Brule Formation include tree stumps, invertebrates, fishes, turtles, lizards, snakes, birds, trace fossils, and a diverse mammalian assemblage consisting of rodents, rabbits, rhinos, horses, entelodonts, oreodonts, camels, and more (see Tweet et al. 2011 for a more complete review).

Figure 16. View from Big Badlands Overlook looking east across the dissected badlands topography of the White River Group (NPS).

Figure 17. View from Yellow Mounds Overlook near Dillon Pass at sedimentary exposures of the Chadron Formation and Brule Formation of the White River Group overlying the Interior and Yellow Mounds paleosols (NPS/ED WELSH).

Devils Tower National Monument (DETO)

Park Establishment

Devils Tower National Monument (DETO) is located on the northwest edge of the Black Hills, about 72 km (45 mi) northeast of Gillette in Crook County, Wyoming (Figure 18). Proclaimed as the nation's first national monument on September 24, 1906, DETO contains approximately 545 hectares (1,347 acres) and preserves Devils Tower, a towering, isolated monolith that rises about 386 m (1,267 ft) above the Belle Fourche River Valley. Devils Towers consists of a rare igneous rock (phonolite porphyry) that has developed stunning, symmetrical, columnar joints, making it a premier area for rock climbing enthusiasts. The conspicuous geologic feature has a long cultural history and has inspired Native Americans, fur trappers, explorers, settlers, and modern-day visitors. Also known as Bear Lodge in numerous tribal traditions, Devils Tower has been considered a sacred site for Northern Plains tribes for thousands of years (National Park Service 2014a).

Geologic Summary

The scenic landscape of DETO is a product of millions of years of dynamic geologic processes, and its beauty and scientific merit inspired President Theodore Roosevelt to establish the area as the first national monument. The monument is situated in the Great Plains physiographic province in the Black Hills of Wyoming, an elongate domal uplift covering approximately 0.8 million hectares (2 million acres) along the South Dakota–Wyoming border. Development of the Black Hills uplift occurred throughout the Paleocene approximately 60 to 50 million years ago due to tectonic collisional forces associated with an ancient mountain-building event known as the Laramide Orogeny (Lisenbee 1988; Lisenbee and DeWitt 1993). The bedrock of DETO consists of Paleozoic and Mesozoic sedimentary rocks, Eocene igneous rocks that comprise Devils Tower, and Quaternary surficial deposits (Figure 19). Older Paleozoic and Mesozoic strata form the hills and slopes surrounding Devils Tower and consist of colorful red, green, yellow, and gray shale (mudstone), siltstone, and sandstone, and white gypsum of the Permian–Triassic Spearfish Formation, Jurassic Sundance Formation, and Jurassic Gypsum Spring Formation. Intruding these sedimentary rocks is the crystalline igneous mass of Devils Tower, a phonolite porphyry that was emplaced during the Eocene (Bassett 1961). No formal name or stratotype for the phonolite has been assigned (see "Recommendations"). Several hypotheses exist to explain the origin of Devils Tower, but most geologists agree the feature represents the exposed remains of an intrusive igneous body (Robinson 1956; Graham 2008). Young surficial deposits mapped within DETO include Quaternary stream terrace deposits and alluvium that occur in the southeastern area of the monument along the Belle Fourche River.

Stratotypes

There are no designated stratotypes identified within the boundaries of DETO. There are five identified stratotypes located within 48 km (30 mi) of DETO boundaries; they are listed in Appendix C for reference in case of future boundary expansion.

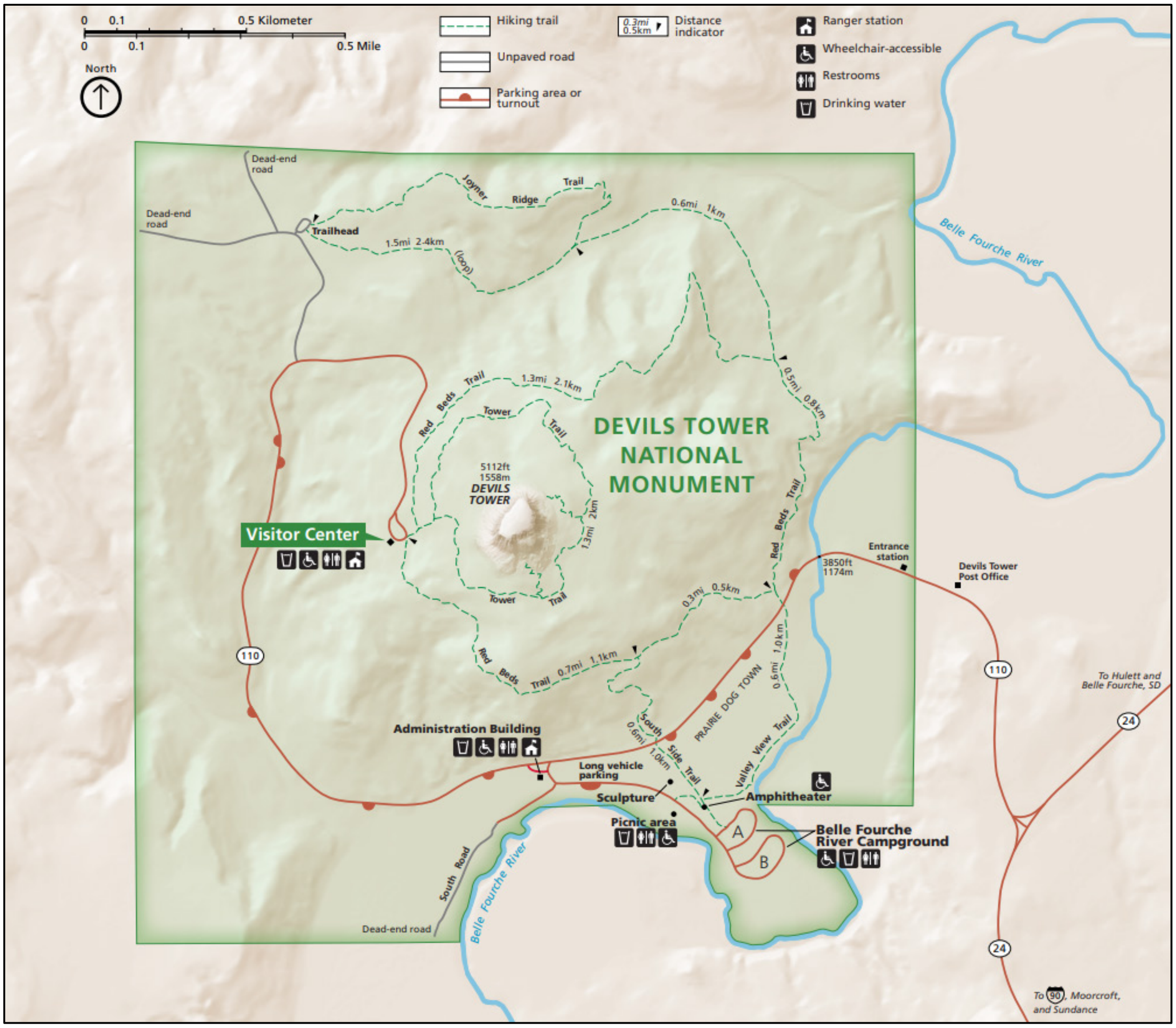


Figure 18. Park map of DETO, Wyoming (NPS).

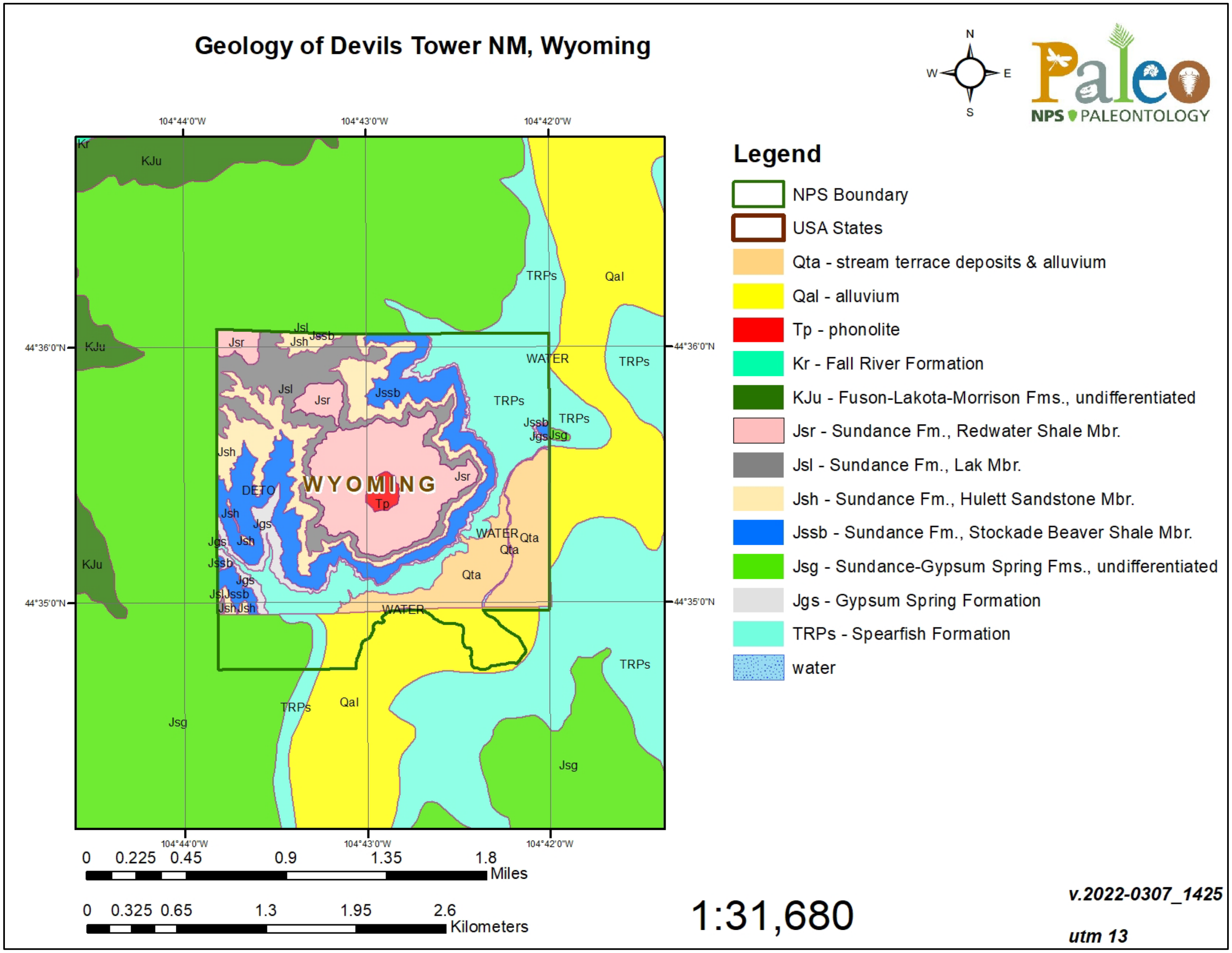


Figure 19. Geologic map of DETO, Wyoming. Data modified from DETO GRI digital geologic map data at https://irma.nps.gov/DataStore/Reference/Profile/1046190.

Fort Laramie National Historic Site (FOLA)

Park Establishment

Fort Laramie National Historic Site (FOLA) is situated at the confluence of the North Platte and Laramie Rivers in Goshen County, southeastern Wyoming (Figure 20). Originally proclaimed as a national monument on July 16, 1938, the park unit was redesignated as a national historic site on April 29, 1960 (National Park Service 2016a). Encompassing nearly 350 hectares (867 acres), FOLA preserves the historical and cultural resources of the 19th century fur trading post (1834–1849) and major U.S. military post that was operational until 1890. Fort Laramie's strategic location at the intersection of two rivers transformed the site into a popular crossroads for westward expansion and represented the largest military post on the Northern Great Plains. Representing one of the first fur trading posts in the central Rocky Mountains, Fort Laramie served as a commercial and social hub that greatly influenced the development of the West and was a major landmark and resupply point along the Oregon, California, Mormon Pioneer, Pony Express, Bozeman, and Cheyenne–Deadwood Trails. The establishment of Fort Laramie faced strong resistance from area tribes, who feared westward expansion and settlement would encroach upon their lands. Fort Laramie hosted several treaty negotiations between the U.S. government and the Northern Plains tribes, including the Treaty of 1868 that marked the beginning of the reservation system, displacing tribes from significant portions of their original homelands (National Park Service 2017b).

Geologic Summary

FOLA is situated in the Great Plains physiographic province near the Hartville Uplift, a structural divide separating the southern Powder River Basin from the northern Denver Basin. The Hartville Uplift developed in response to collisional forces associated with the Trans-Hudson Orogeny that occurred during the Paleoproterozoic Era approximately 2.1 to 1.76 billion years ago (Sims et al. 1996). Located in the incised fluvial valleys of the North Platte and Laramie Rivers, Fort Laramie was constructed upon young, unconsolidated, Quaternary floodplain deposits and tributary valley alluvium. The oldest rocks in FOLA consist of loosely cemented sandstone of the Oligocene–Miocene Arikaree Formation that form the hills and slopes bordering the historic site to the south (Figure 21). The fluvial landscape of FOLA has evolved since the Pleistocene about 2 million years ago and contains geomorphic features that record the evolution of the North Platte and Laramie Rivers before and after Fort Laramie was built (Graham 2009b).

Stratotypes

There are no designated stratotypes identified within the boundaries of FOLA. There are nine identified stratotypes located within 48 km (30 mi) of FOLA boundaries; they are listed in Appendix C for reference in case of future boundary expansion.

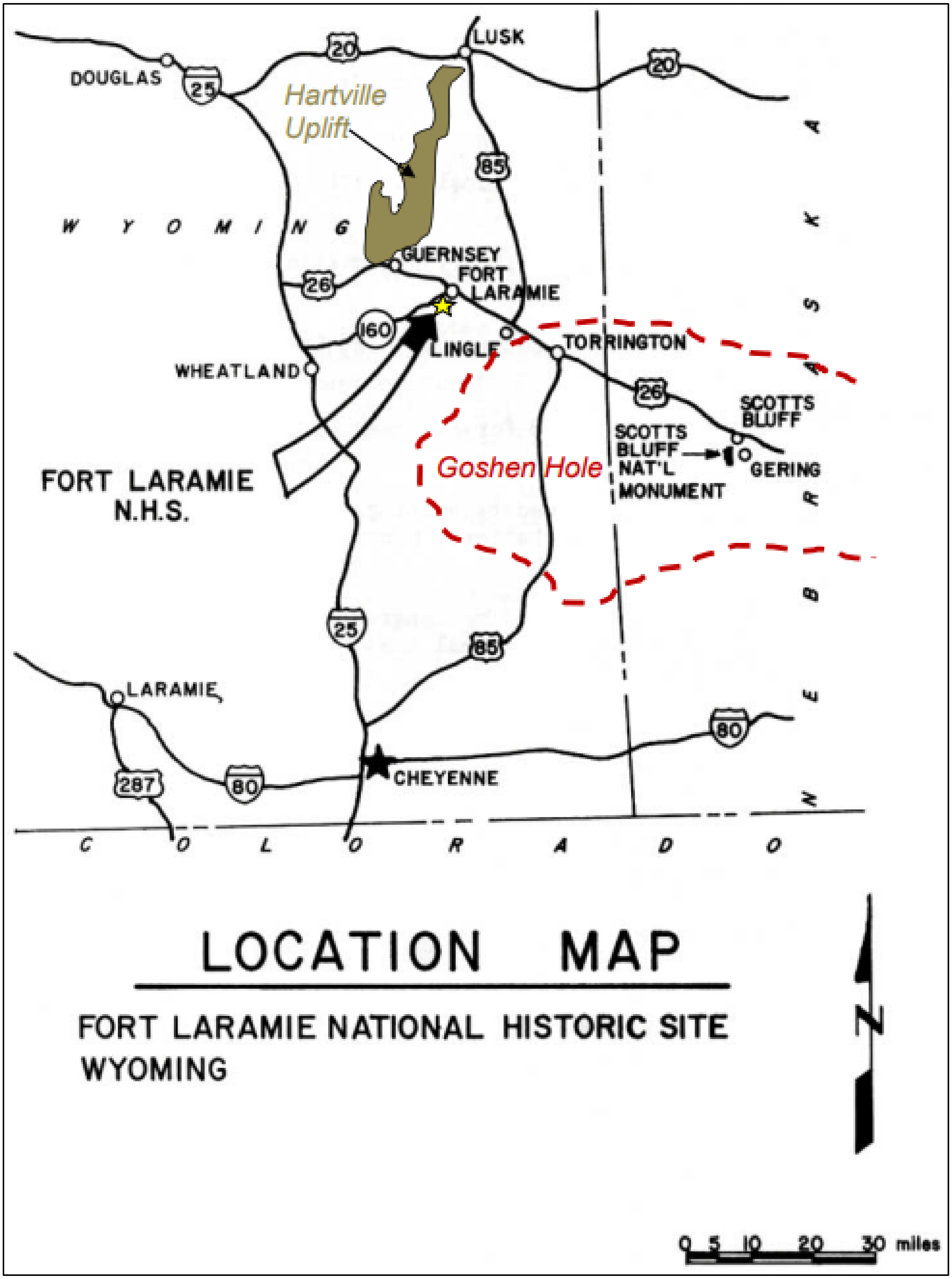


Figure 20. Regional map of FOLA, Wyoming (NPS).

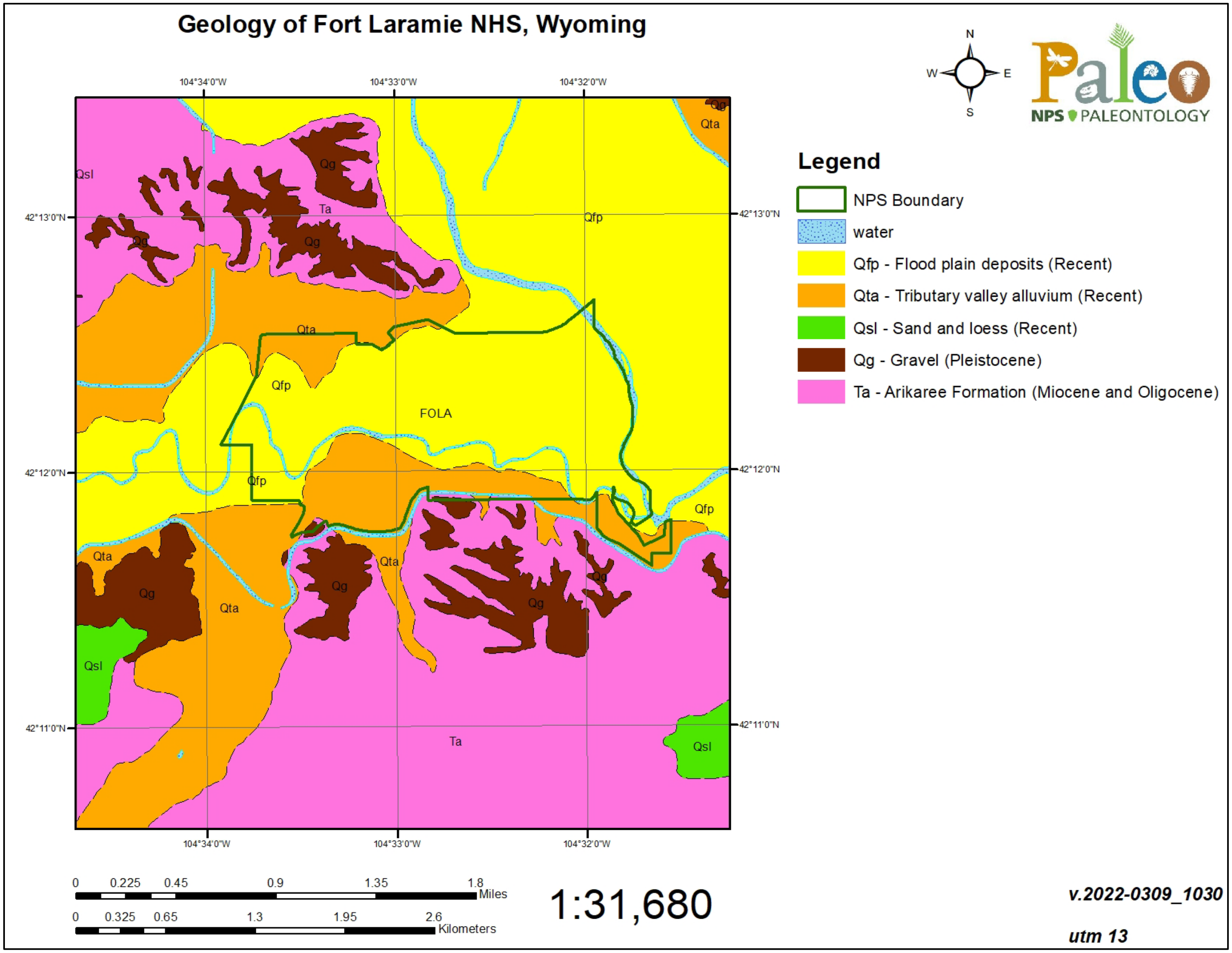


Figure 21. Geologic map of FOLA, Wyoming. Data modified from FOLA GRI digital geologic map data at https://irma.nps.gov/DataStore/Reference/Profile/1047424.

Fort Union Trading Post National Historic Site (FOUS)

Park Establishment

Fort Union Trading Post National Historic Site (FOUS) is located on the upper Missouri River along the Montana–North Dakota border at the intersection of McKenzie and Williams Counties, North Dakota and Richland and Roosevelt Counties, Montana (Figure 22). Authorized on June 20, 1966, FOUS encompasses about 178 hectares (440 acres) and commemorates the Fort Union fur trading post (1828–1867), the principal commerce hub of the American Fur Company and the longest-lasting fur trading post in the United States (National Park Service 2016a). Despite its name, Fort Union was never a military installation but represented a commercial enterprise where frontiersman and Northern Plains tribes (Assiniboine, Crow, Cree, Ojibwa, Blackfeet, Hidatsa, Mandan, Arikara, and others) traded buffalo skins and other furs for items such as beads, textiles, blankets, kettles, guns, and knives. Fort Union significantly influenced the exploration of the American frontier and epitomized the economically beneficial relationship between Northern Plains tribes and European Americans (National Park Service 2013a). Fort Union Trading Post features a full-scale reconstruction of the 1850s-era structures that include the fort's 5 m (17 ft)-tall palisade walls, a trade house, clerk's office, and the extravagant Bourgeois House.

Geologic Summary

FOUS is situated in the Great Plains physiographic province, a large plateau-like region featuring lowlands and isolated mountains that stretches from Mexico to Canada and extends east from the Rocky Mountains to the Missouri Escarpment in the central Dakotas (Keefer 1974). The fluvial landscape of FOUS features bluffs, terraces, and a floodplain that consist entirely of Cenozoic sedimentary rocks of the Paleocene Fort Union Formation and Holocene surficial units (Figure 23; Graham 2015a). Although the Fort Union Formation was named by Meek and Hayden (1862) after Old Fort Union near the mouth of the Yellowstone River, no formal stratotype for the unit has been assigned (see "Recommendations"). The Fort Union Formation consists of sandstone, siltstone, and mudstone that underlie the historic site north of the Missouri River. Mapped along the southern area of FOUS are young, unconsolidated deposits of alluvium and colluvium that occur along the floodplain of the Missouri River Valley.

Stratotypes

There are no designated stratotypes identified within the boundaries of FOUS.

Figure 22. Regional map of FOUS, Montana–North Dakota (NPS).

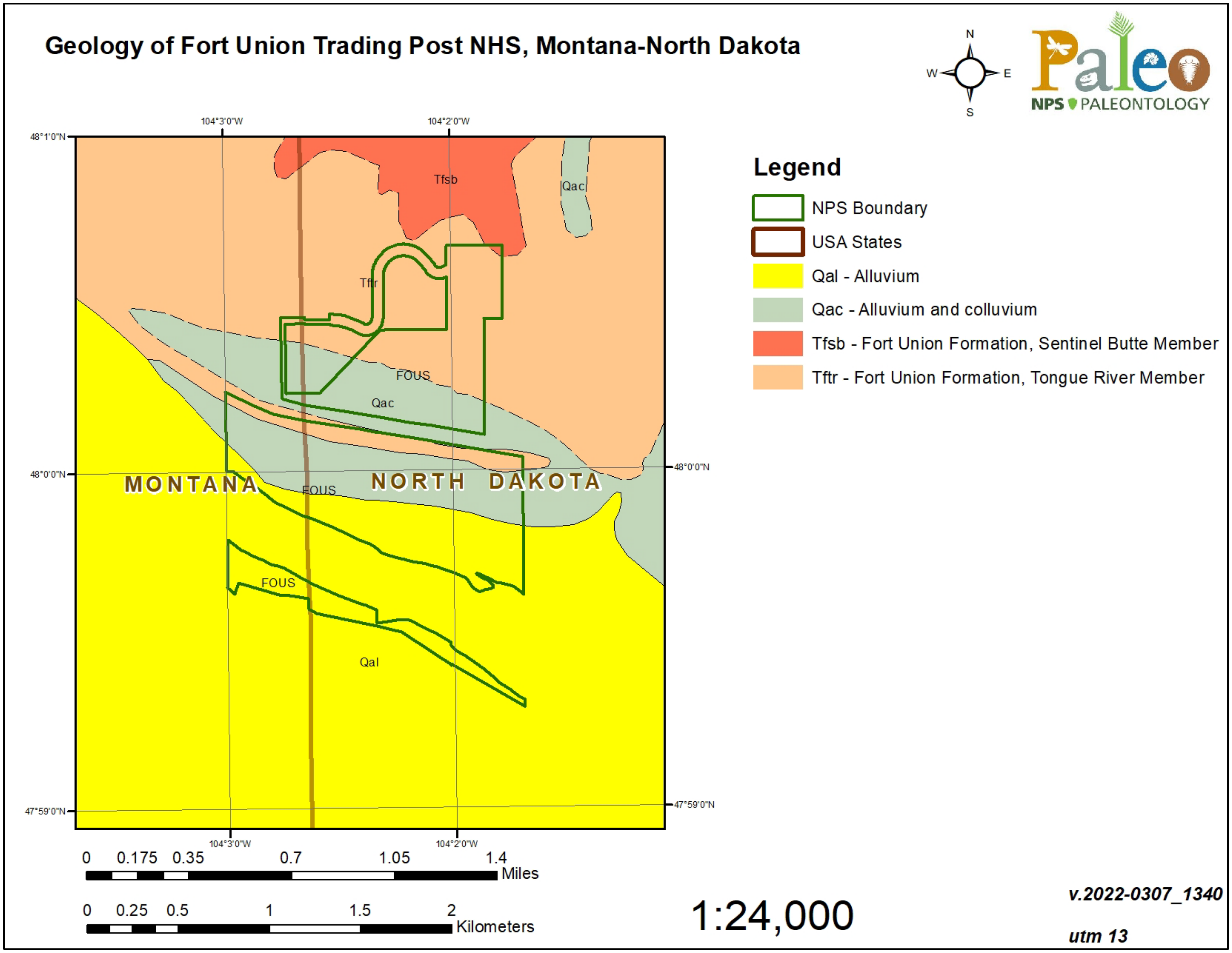


Figure 23. Geologic map of FOUS, Montana–North Dakota. Data modified from FOUS GRI digital geologic map data at https://irma.nps.gov/DataStore/Reference/Profile/2176227.

Jewel Cave National Monument (JECA)

Park Establishment

Jewel Cave National Monument (JECA) is located in the Black Hills of South Dakota, approximately 65 km (40 mi) southwest of Rapid City in Custer County (Figure 24). Proclaimed on February 7, 1908, JECA contains about 515 hectares (1,274 acres) and protects an expansive limestone cave network with more than 338 km (210 mi) of surveyed passages—the third longest cave on Earth (National Park Service 2016a). Land prospectors Frank and Albert Michaud discovered Jewel Cave in 1900 when they came across cold air blowing out of a small hole above Hell Canyon. Upon entering the cave, they explored crawlways and low-ceiling rooms covered with calcite crystals that sparkled like "jewels" by the light of their lanterns (National Park Service 2016b; KellerLynn 2009). Jewel Cave features a relatively unchanged underground environment that includes subterranean lakes, spectacular speleothems, and abundant calcite spar crystals coating most of the cave surfaces. Research has shown that the mapped passages of Jewel Cave represent only a fraction of the total cave system, creating scientific opportunities to discover and survey unexplored portions of the cave.

Geologic Summary

Situated in the Black Hills of the Great Plains physiographic province, the regional geology of JECA is similar to nearby DETO, MORU, and WICA. Development of the Black Hills region occurred during the Paleocene Epoch ~60 to 50 million years ago due to collisional forces associated with the Laramide Orogeny (Lisenbee 1988; Lisenbee and DeWitt 1993). Uplifted Paleozoic and Mesozoic strata were eroded away from the central Black Hills Uplift, exposing a core of ancient Precambrian metamorphic and igneous rocks. Sedimentary strata spanning the Cambrian through Cretaceous form the flanks of the Black Hills and dip away from the central uplift in all directions (Palmer et al. 2016). The bedrock underlying JECA consists of Paleozoic sedimentary rocks of the Mississippian Pahasapa Limestone and Pennsylvanian–Permian Minnelusa Formation. Carbonate rocks of the Pahasapa Limestone formed in an ancient shallow sea and were subsequently uplifted and slowly eroded via groundwater dissolution to form the expansive Jewel Cave network and its many cave features. Strata of the Minnelusa Formation overlie the Pahasapa Limestone and consist of sandstone, siltstone, shale, and limestone that were deposited in aeolian and marine settings (Fryberger 1984). The youngest rocks mapped within JECA include unconsolidated Quaternary alluvium deposits that occur along Hell Canyon and Lithograph Canyon (Figure 25).

Stratotypes

There are no designated stratotypes identified within the boundaries of JECA. Although Darton's (1901) Pahasapa Limestone is derived from the Dakota tribal term "Pahasapa" meaning the Black Hills, there is currently no stratotype designation (see "Recommendations"). There are 12 identified stratotypes located within 48 km (30 mi) of JECA boundaries; they are listed in Appendix C for reference in case of future boundary expansion.

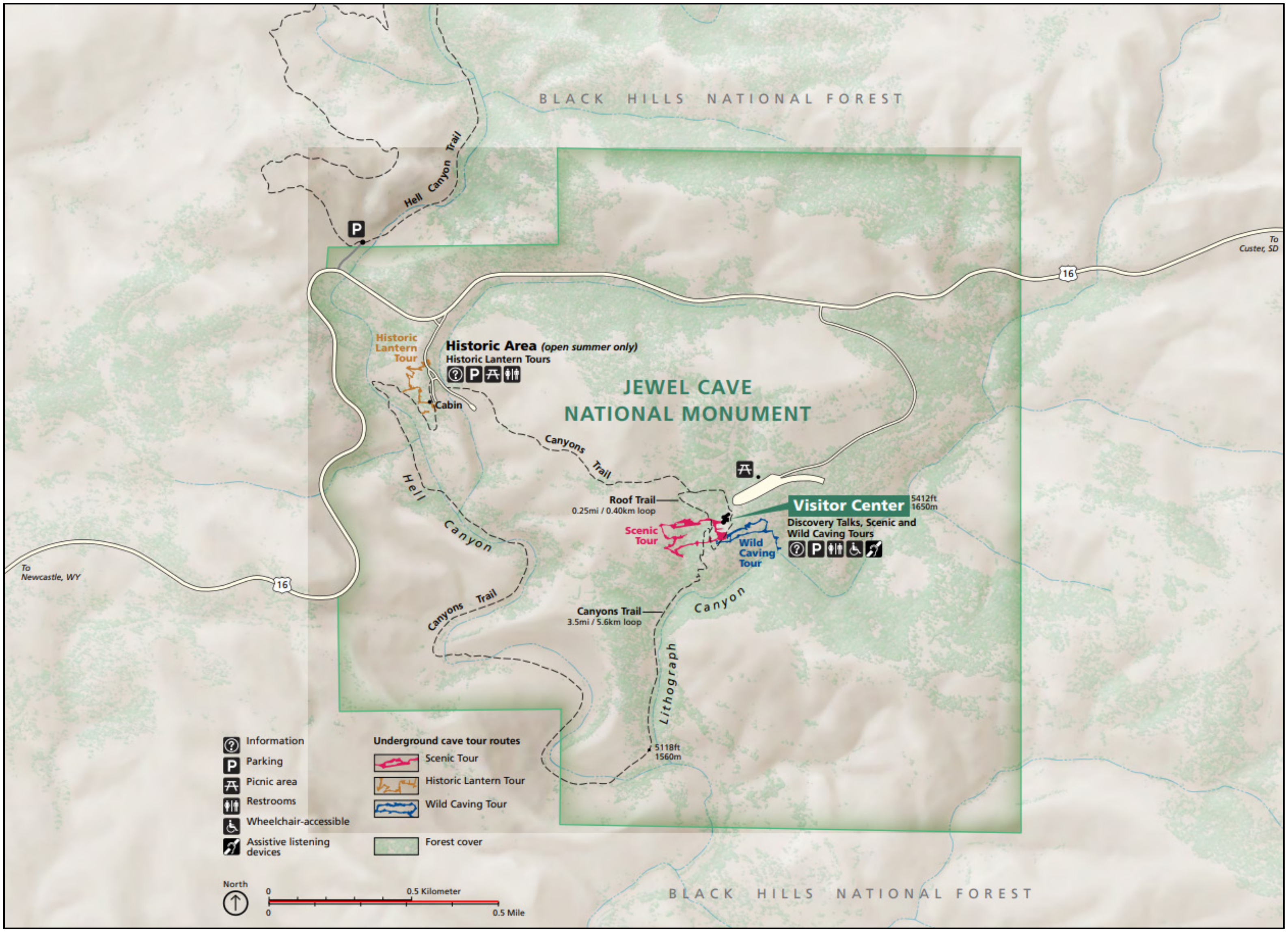


Figure 24. Park map of JECA, South Dakota (NPS).

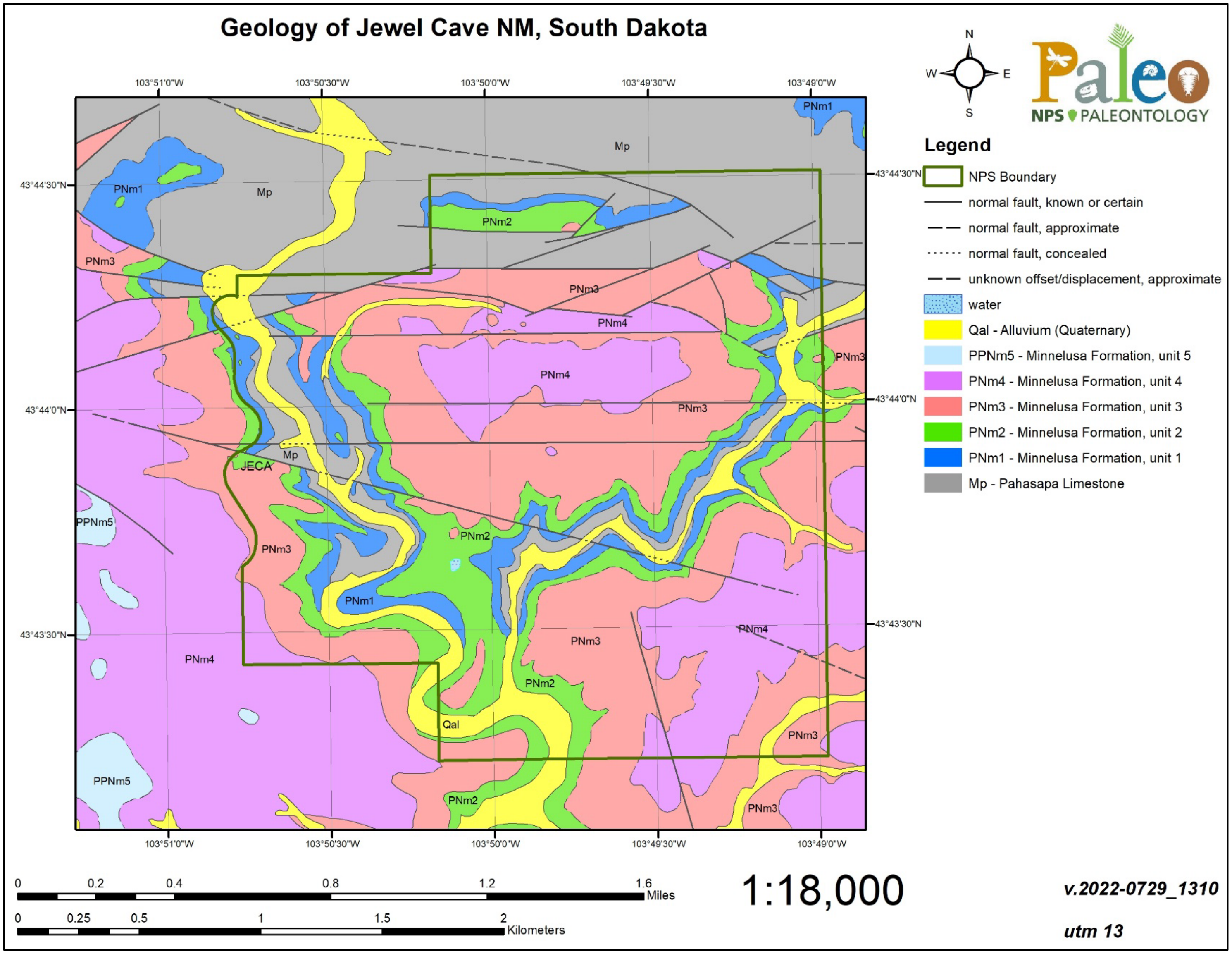


Figure 25. Geologic map of JECA, South Dakota. Data modified from JECA GRI digital geologic map data at https://irma.nps.gov/DataStore/Reference/Profile/2186009.

Knife River Indian Villages National Historic Site (KNRI)

Park Establishment

Knife River Indian Villages National Historic Site (KNRI) is located along the Knife and Missouri Rivers just north of the city of Stanton, about 80 km (50 mi) northwest of Bismarck in Mercer County, North Dakota (Figure 26). The national historic site was authorized on October 26, 1974, and contains approximately 707 hectares (1,749 acres) featuring some of the best-preserved examples of remnant earthlodge villages related to Hidatsa, Mandan, and Arikara tribes of the Northern Great Plains (National Park Service 2016a). The resources preserved at KNRI document the cultural lifestyles of Northern Great Plains communities along the Missouri River and represent a cornerstone in archeological, ethnographic, and historical research (National Park Service 2013b). Three main village sites within KNRI include (from north to south): Hidatsa Village (Big Hidatsa Site), Awatixa Village (Sakakawea Site), and the Awatixa Xi'e Village (Lower Hidatsa Site). The village communities at KNRI were part of a major trade center for Northern Great Plains tribes and served an important role in the exploration of the American West, hosting several notable travelers that include the Corps of Discovery, John James Audubon, George Catlin, and many others. The historic site is associated with the Lewis and Clark National Historic Trail as a notable stop along the Corps of Discovery route: Lewis and Clark first met Sacagawea when she was living at the Sakakawea Site (Graham 2015b).

Geologic Summary

KNRI is situated in the Great Plains physiographic province within the Williston Basin, a large, petroleum-rich sedimentary basin that stretches across parts of North Dakota, South Dakota, Montana, and southern Canada. The geologic history of the Williston Basin dates back at least 550 million years ago, to a time when ancient seas inundated the Great Plains region of ancestral North America (Gerhard et al. 1982). Geologic formations mapped within KNRI are entirely Cenozoic in age and include the Paleozoic Bullion Creek Formation and Sentinel Butte Formation; Pleistocene Coleharbor Formation; and Quaternary Oahe Formation (Figure 27). The Bullion Creek Formation and Sentinel Butte Formation are mapped as one undivided unit in the northern hills and river bluffs of KNRI, and consist of poorly lithified sedimentary deposits of yellow, brown, gray, and white sand, silt, clay, and some carbonaceous shale and lignite (Jacob 1973). The Coleharbor Formation forms the hills in southern and northern KNRI and is composed of an interlayered sequence of glacial till, lacustrine silt and clay, and fluvial sand and gravel that have been interpreted to record different episodes of Pleistocene glaciation (Benson 1952; Bluemle 1971). Deposits of the Oahe Formation contain loess, aeolian sand, alluvium, and colluvium that primarily occur in the floodplain of the Knife River and Missouri River.

Stratotypes

There are no designated stratotypes identified within the boundaries of KNRI. There are six identified stratotypes located within 48 km (30 mi) of KNRI boundaries; they are listed in Appendix C for reference in case of future boundary expansion.

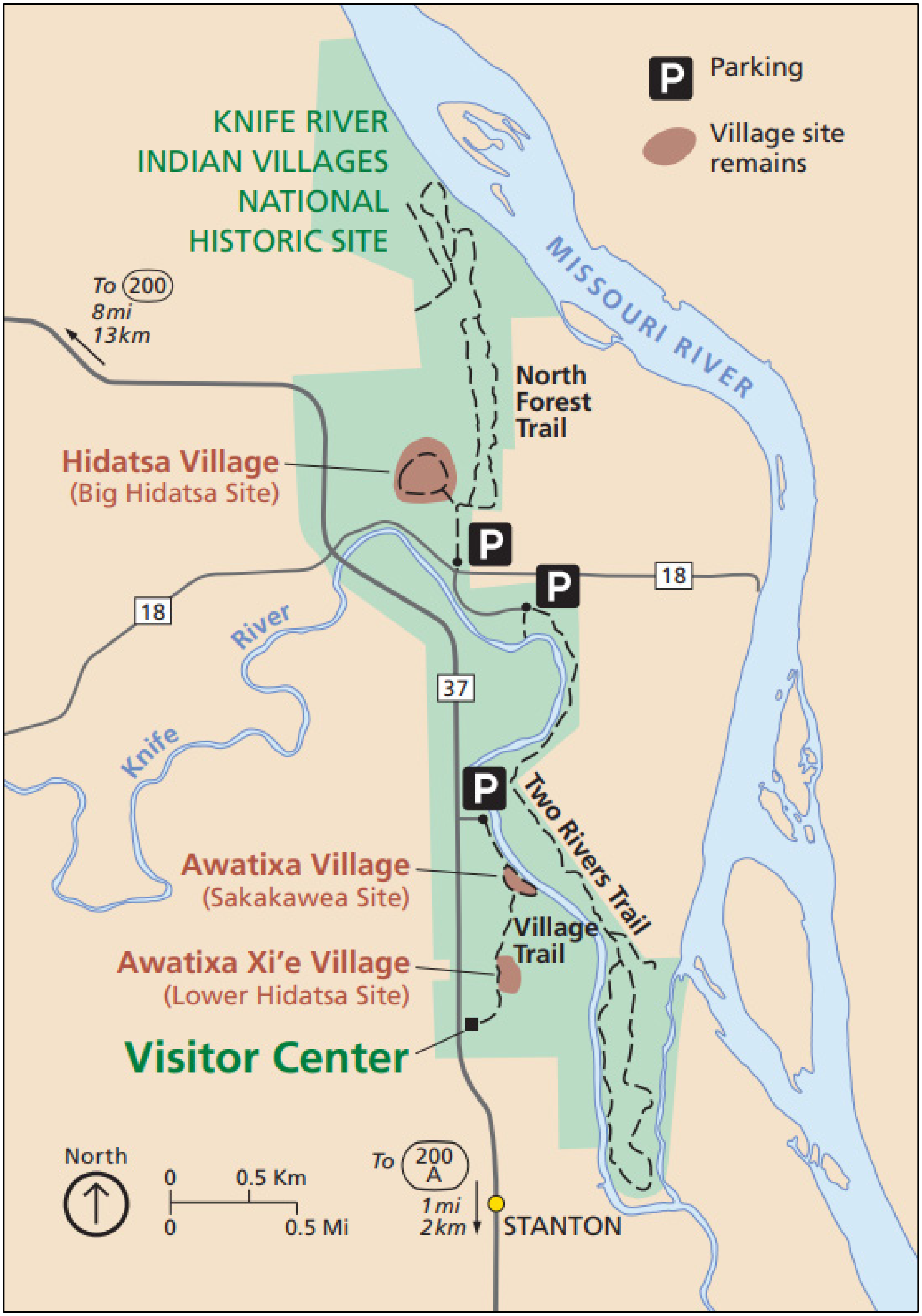


Figure 26. Park map of KNRI, North Dakota (NPS).

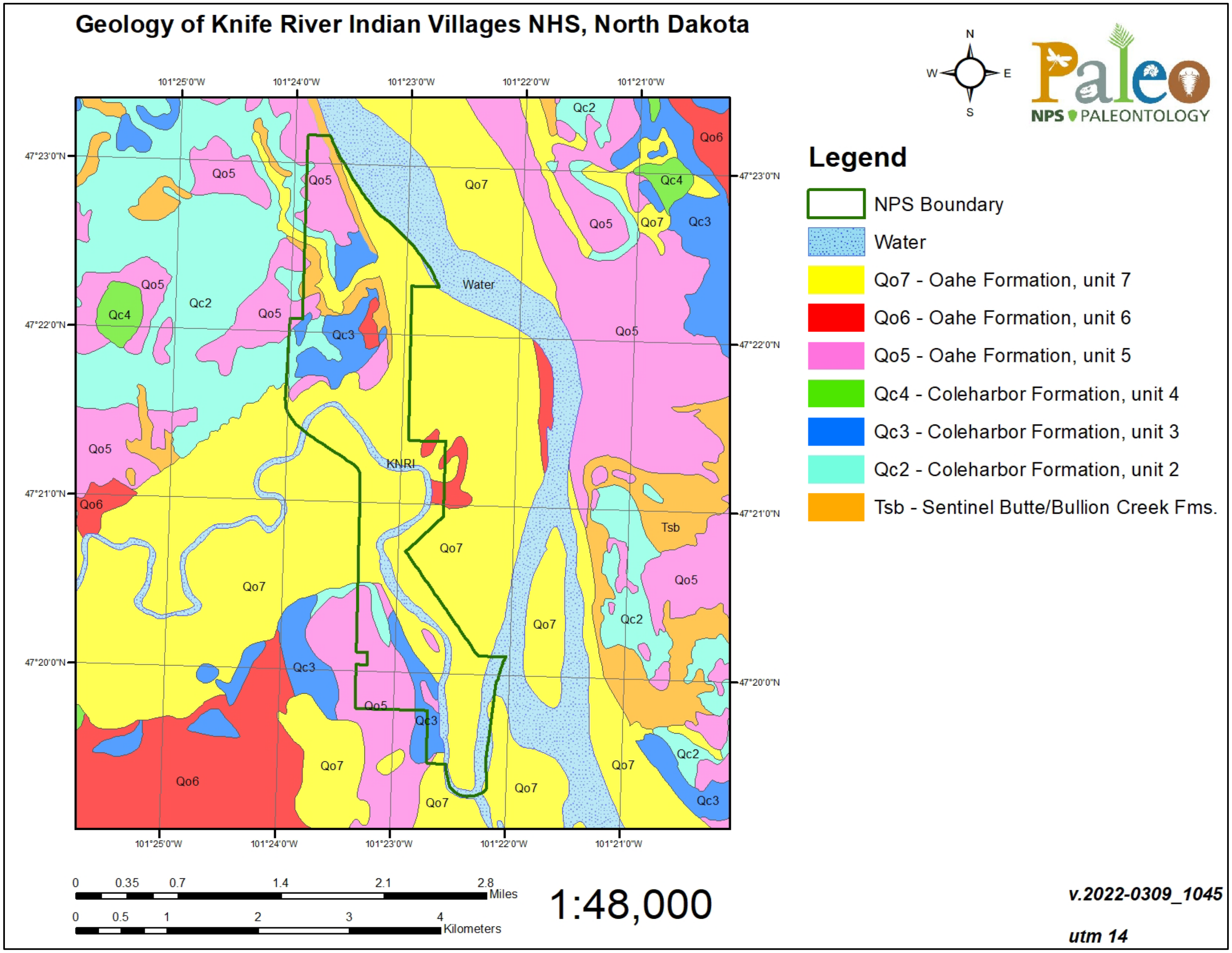


Figure 27. Geologic map of KNRI, North Dakota. Data modified from KNRI GRI digital geologic map data at https://irma.nps.gov/DataStore/Reference/Profile/2176225.

Missouri National Recreational River (MNRR)

Park Establishment

Missouri National Recreational River (MNRR) protects two stretches of the Missouri River separated by Lewis and Clark Lake in portions of Bon Homme, Charles Mix, Clay, Union, and Yankton Counties, South Dakota, and Boyd, Cedar, Dixon, and Knox Counties, Nebraska (Figure 28). Authorized on November 10, 1978, MNRR encompasses about 19,609 hectares (48,457 acres) and preserves the last unchannelized and unimpounded segments of the Missouri River along with its native floodplain forest, floodplain wetland, tallgrass, and mixed-grass prairie habitats (National Park Service 2016a). The 39-Mile District represents the western, upstream portion of MNRR and extends from Fort Randall Dam downstream to Running Water, South Dakota. Also included in the district are the last 13 km (8 mi) of Verdigre Creek and the lower 32 km (20 mi) of the Niobrara River at their confluence with the Missouri River. The 59-Mile District begins just below Gavins Point Dam and ends at Ponca State Park in Nebraska. The rich cultural history of MNRR dates back thousands of years and is recorded by prehistoric sites, old steamboat wrecks, Fort Randall, and numerous archeological and historical resources (National Park Service 2017c).

Geologic Summary

MNRR occupies the transition zone between the Great Plains and Central Lowland physiographic provinces in a region situated between the glaciated and unglaciated portions of the Missouri Plateau. The 39-Mile District of MNRR features a landscape characterized by steep, dissected chalkstone river bluffs, gently rolling hills, and flat agricultural land. Further downstream, the 59-Mile District occupies a wide, meandering river valley and features a mosaic of sandbars, snags, backwaters, islands, and tributary channels. Strata that underlie MNRR can be subdivided into two main groups based on age and lithology: (1) older Cretaceous rocks of the (in ascending order) Dakota Formation, Graneros Shale, Greenhorn Limestone, Carlile Shale, Niobrara Formation, and Pierre Shale; and (2) younger Quaternary units that include the Peoria Loess, glacial till, flood channel deposits, alluvial terraces, alluvium, and colluvium (Figures 29–31).

Stratotypes

MNRR contains one identified stratotype that represents the type area of the Cretaceous Niobrara Formation (Table 4; Figure 32). In addition to the designated stratotype located within MNRR, there are two stratotypes located within 48 km (30 mi) of MNRR boundaries; they are listed in Appendix C for reference in case of future boundary expansion.

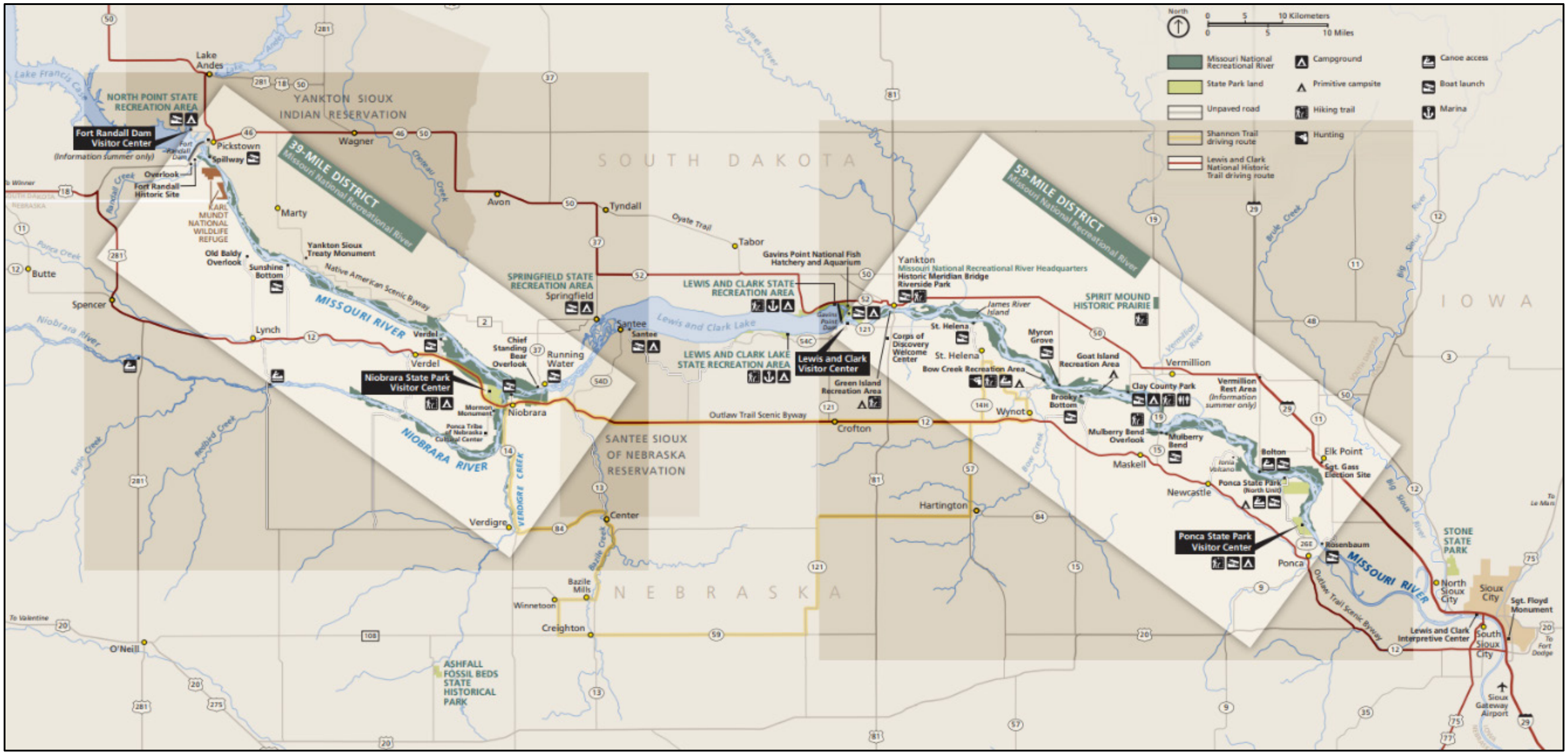


Figure 28. Park map of MNRR, South Dakota–Nebraska (NPS).

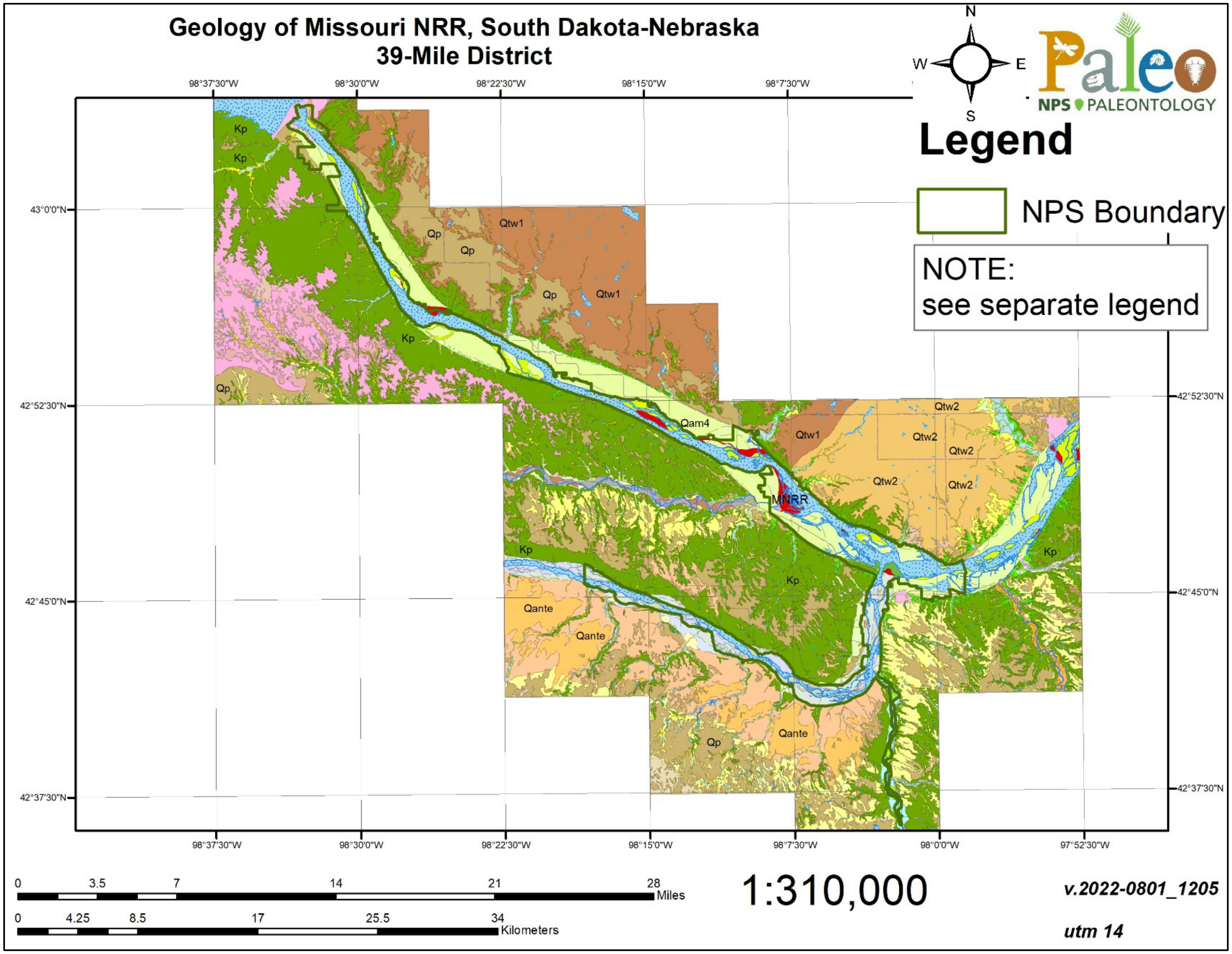


Figure 29. Geologic map of the 39-Mile District of MNRR, Nebraska–South Dakota; see Figure 30 for legend. Data modified from MNRR GRI digital geologic map data at https://irma.nps.gov/DataStore/Reference/Profile/2287253.

Figure 30. Geologic map legend of the 39-Mile District of MNRR, Nebraska–South Dakota.

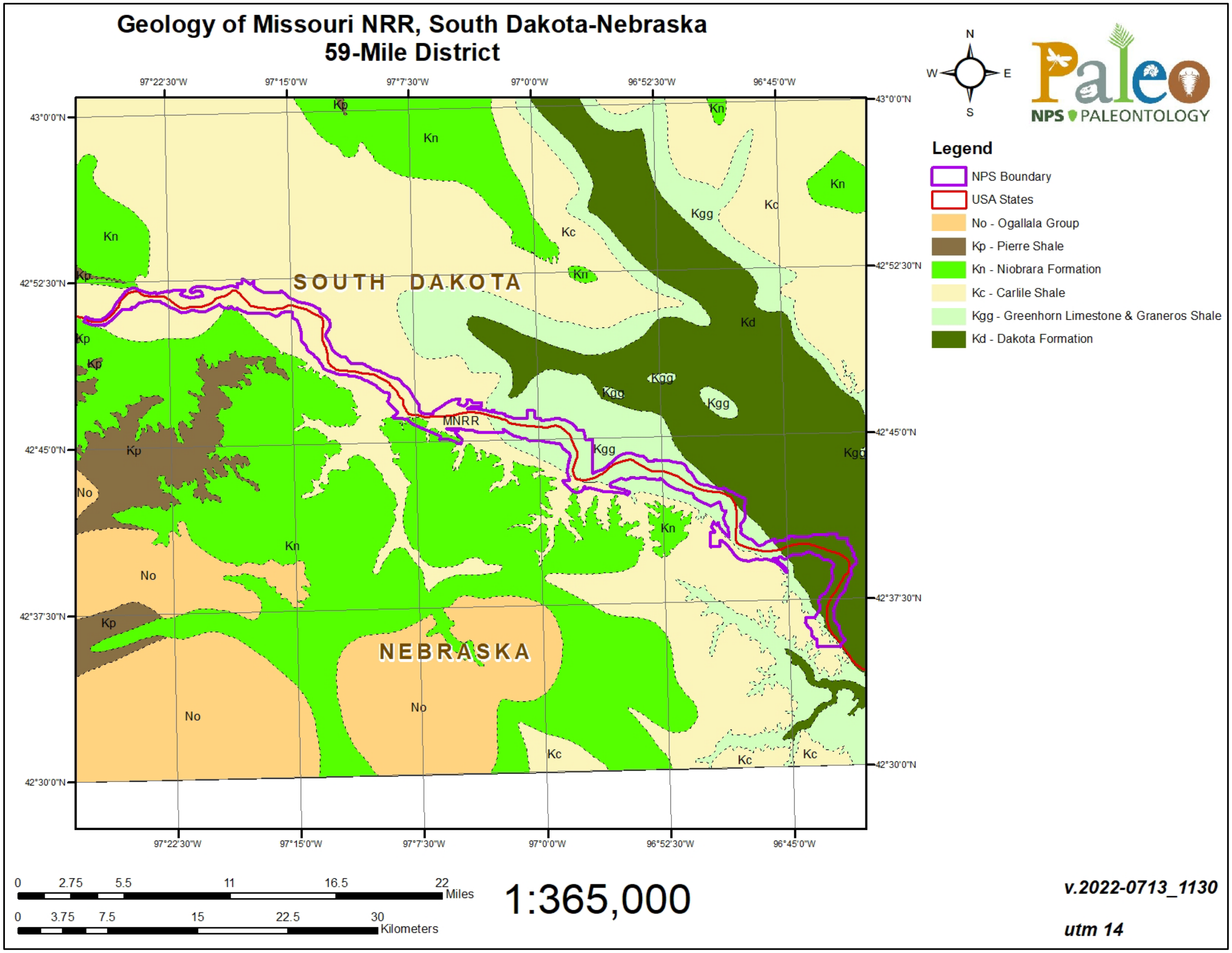


Figure 31. Geologic map of the 59-Mile District of MNRR, Nebraska–South Dakota. Data modified from MNRR GRI digital geologic map data at https://irma.nps.gov/DataStore/Reference/Profile/2293830.

Table 4. List of MNRR stratotype units sorted by age with associated reference publications and locations.

Unit Name (GRI map symbol)	Reference	Stratotype Location	Age
Niobrara Formation (Knsh)	Meek and Hayden 1861; Frerichs and Gaskill 1988	Type area: exposures along the Niobrara River, where formation forms 27–30 m (90–100 ft) cliffs near mouth along Missouri River, in Knox County, NE.	Cretaceous

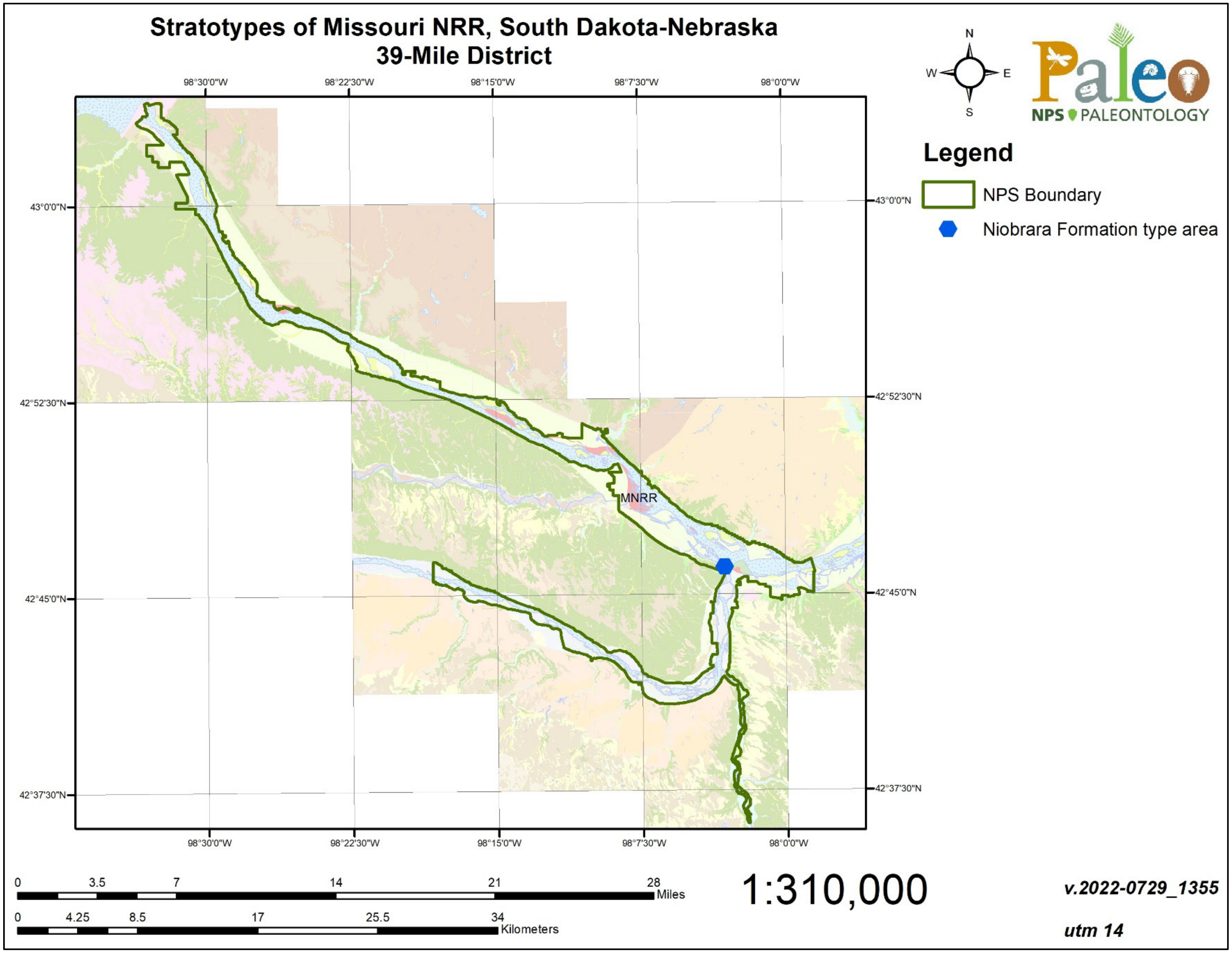


Figure 32. Modified geologic map of MNRR showing stratotype locations. The transparency of the geologic units layer has been increased.

Niobrara Formation

The Cretaceous Niobrara Formation was originally referred to as the "Niobrara division" by Meek and Hayden (1861), who derived the name from exposures along the Missouri River near its confluence with the Niobrara River in Knox County, Nebraska. Although Meek and Hayden (1861) never assigned a formal stratotype, the type area of the formation has been described as the same exposures along the confluence of the Niobrara and Missouri Rivers where the unit forms 27–30 m (90–100 ft) tall cliffs (Table 4; Figure 32 and 33; Frerichs and Gaskill 1988 citing Meek and Hayden 1861). Meek and Hayden (1861) described the Niobrara Formation as a gray, calcareous marl that grades downward into more compact beds of bluish-gray limestone that weather to a whitish color (Figure 34). In the type area the Niobrara Formation underlies either the Cretaceous Pierre Shale or Pleistocene Peoria Loess and its basal contact is not exposed.

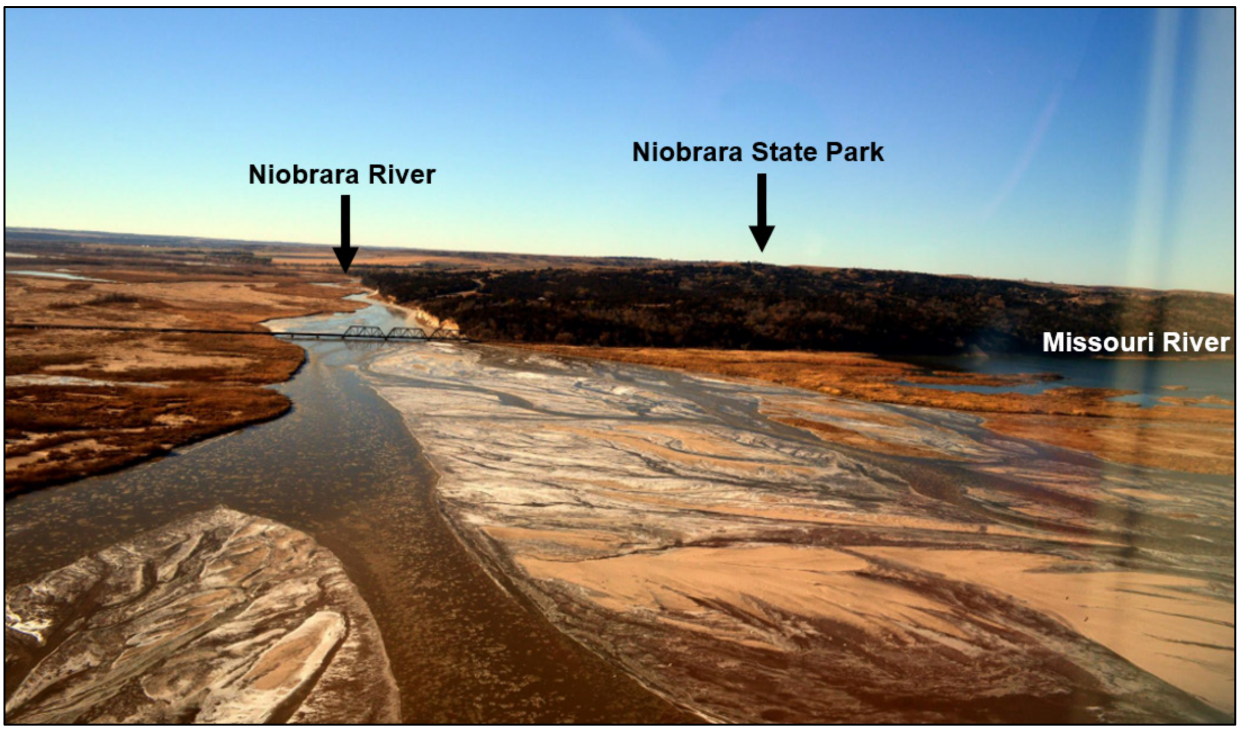


Figure 33. South-facing view of the confluence of the Niobrara River with the Missouri River in the 39-Mile District of MNRR. Type area exposures of the Niobrara Formation form 27–30 m (90–100 ft) tall cliffs of whitish-gray chalky limestone near the confluence of the two rivers and can be seen in the background just beyond the railroad bridge/Niobrara Trail (annotated NPS photo).

Figure 34. Chalky limestone river bluffs of the Niobrara Formation near Chief Standing Bear Overlook, located on the north bank of the Missouri River immediately west of South Dakota Highway 37, South Dakota (NPS).

Mount Rushmore National Memorial (MORU)

Park Establishment

Mount Rushmore National Memorial (MORU) is located in the central Black Hills of southwestern South Dakota, approximately 3.2 km (2 mi) southwest of Keystone in Pennington County (Figure 35). The 517-hectare (1,278 acre) national memorial was authorized on March 3, 1925 and preserves the famous granite mountain sculpture commemorating U.S. Presidents George Washington, Thomas Jefferson, Theodore Roosevelt, and Abraham Lincoln (National Park Service 2016a). The design and construction of Mount Rushmore was inspired by artist Gutzon Borglum and required a construction team of roughly 400 workers to complete from 1927 until 1941. The 18 m (60 ft)-tall busts of Washington, Jefferson, Roosevelt, and Lincoln represent an engineering marvel sculpted by dynamite, drilling, and manpower. Set against the ponderosa pine forest and granite walls of the Black Hills region, the iconic sculpture stands as an internationally recognized symbol and powerful representation of American democracy and freedom (National Park Service 2017d).

Geologic Summary

MORU is situated in the Great Plains physiographic province in the Black central Black Hills Uplift, an asymmetric domal uplift covering approximately 0.8 million hectares (2 million acres) along the South Dakota–Wyoming border. Development of the Black Hills Uplift largely occurred throughout the Paleocene approximately 60 to 50 million years ago due to tectonic collisional forces associated with the Laramide Orogeny (Lisenbee 1988; Lisenbee and DeWitt 1993). Uplifted Paleozoic and Mesozoic strata were eroded away from the central Black Hills Uplift, exposing a core of Precambrian metamorphic and igneous rocks that is found in MORU. These ancient Paleoproterozoic rocks include metamorphosed black shale, meta-graywacke, and the Harney Peak Granite. The Harney Peak Granite is especially important to MORU in that the granite was chosen as the artistic medium in which to sculpt Mount Rushmore. Young surficial deposits mapped in MORU include Quaternary alluvial and talus deposits (Figure 36).

Stratotypes

There are no designated stratotypes identified within the boundaries of MORU. There are seven identified stratotypes located within 48 km (30 mi) of MORU boundaries; they are listed in Appendix C for reference in case of future boundary expansion.

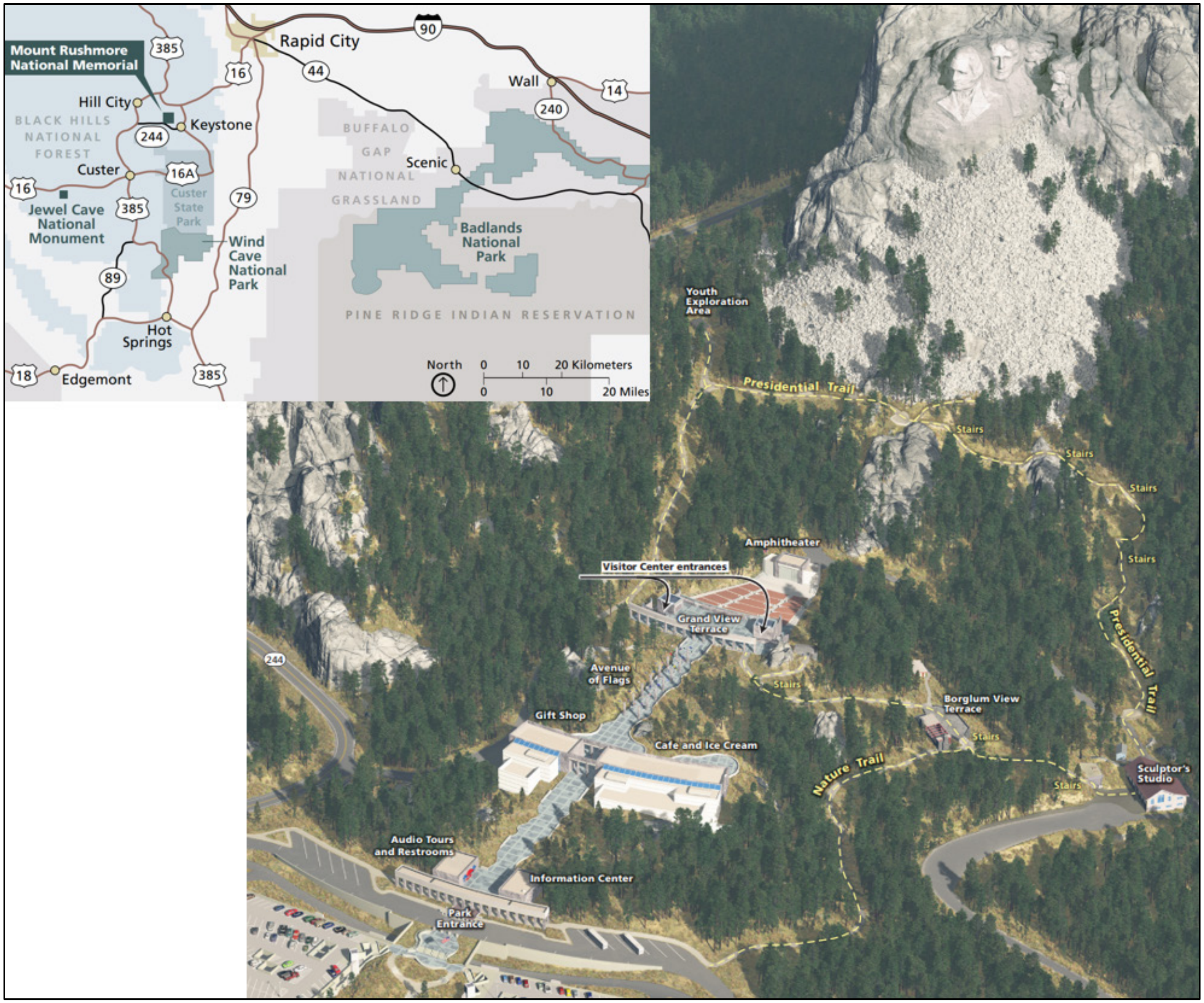


Figure 35. Park map of MORU with regional inset map, South Dakota (NPS).

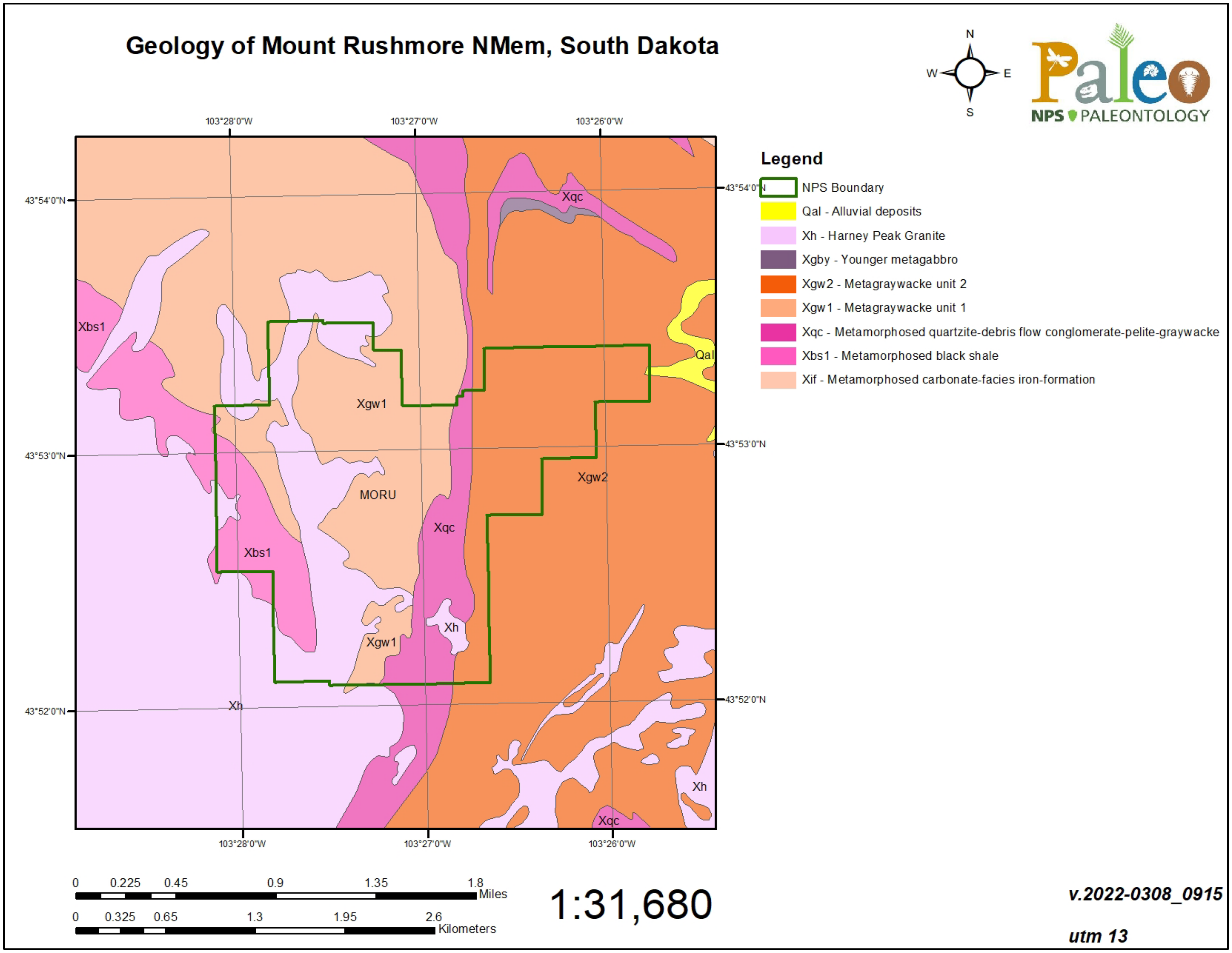


Figure 36. Geologic map of MORU, South Dakota. Data modified from MORU GRI digital geologic map data at https://irma.nps.gov/DataStore/Reference/Profile/2164831.

Niobrara National Scenic River (NIOB)

Park Establishment

Niobrara National Scenic River (NIOB) protects a 120 km (76 mi)-long stretch of the Niobrara River in Brown, Cherry, Keya Paha, and Rock Counties, northern Nebraska (Figures 37a & b). Authorized on May 24, 1991, NIOB contains approximately 11,776 hectares (29,101 acres) and features outstanding ecological, scenic, recreational, cultural, and scientific resources (National Park Service 2016a). Niobrara National Scenic River begins at Borman Bridge near the city of Valentine and encompasses the Niobrara River Valley downstream to Mariaville, Nebraska. The national scenic river supports a variety of biologically diverse ecosystems that include tallgrass, sandhills, and mixed-grass prairies in addition to northern boreal, eastern deciduous, and western coniferous forests (National Park Service 2016c). The landscape of western (upstream) NIOB features relatively narrow river canyons with steep, eroded bluffs that progressively widen and become more rounded in appearance downstream. The nature of the Niobrara River evolves downstream as well, becoming more braided and seasonally shallow east (downstream) of Norden Bridge.

Geologic Summary

NIOB lies within the Nebraska Sand Hills and Dakota–Nebraska Eroded Tableland of north-central Nebraska, a region featuring mixed-grass prairies and some of the largest sand dunes in the Western Hemisphere. The bedrock underlying NIOB is composed of Mesozoic and Cenozoic rocks that represent ancient marine, fluvial, and aeolian environments (Figure 38). The oldest rocks in NIOB are the marine shales, siltstones, and sandstones of the Cretaceous Pierre Shale. Exposures of the Pierre Shale form the dark gray river bluffs in the eastern area of NIOB. Younger Cenozoic strata underlie the western portion of NIOB and include Oligocene sedimentary rocks that have been correlated with the White River Group as well as Miocene units of the Ogallala Group (Ash Hollow Formation and Valentine Formation) and Rosebud Formation (Skinner and Johnson 1984). The youngest rocks mapped in NIOB are composed of unconsolidated, Quaternary terrace deposits, linear dunes, alluvium, and colluvium (Swinehart et al. 1994; Joeckel et al. 2015, 2016a, 2016b).

Stratotypes

NIOB contains four identified stratotypes that are subdivided into one type section, one type locality, and two reference sections (Table 5; Figure 39). In addition to the designated stratotypes located within NIOB, there are 10 stratotypes located within 48 km (30 mi) of NIOB boundaries; they are listed in Appendix C for reference in case of future boundary expansion.

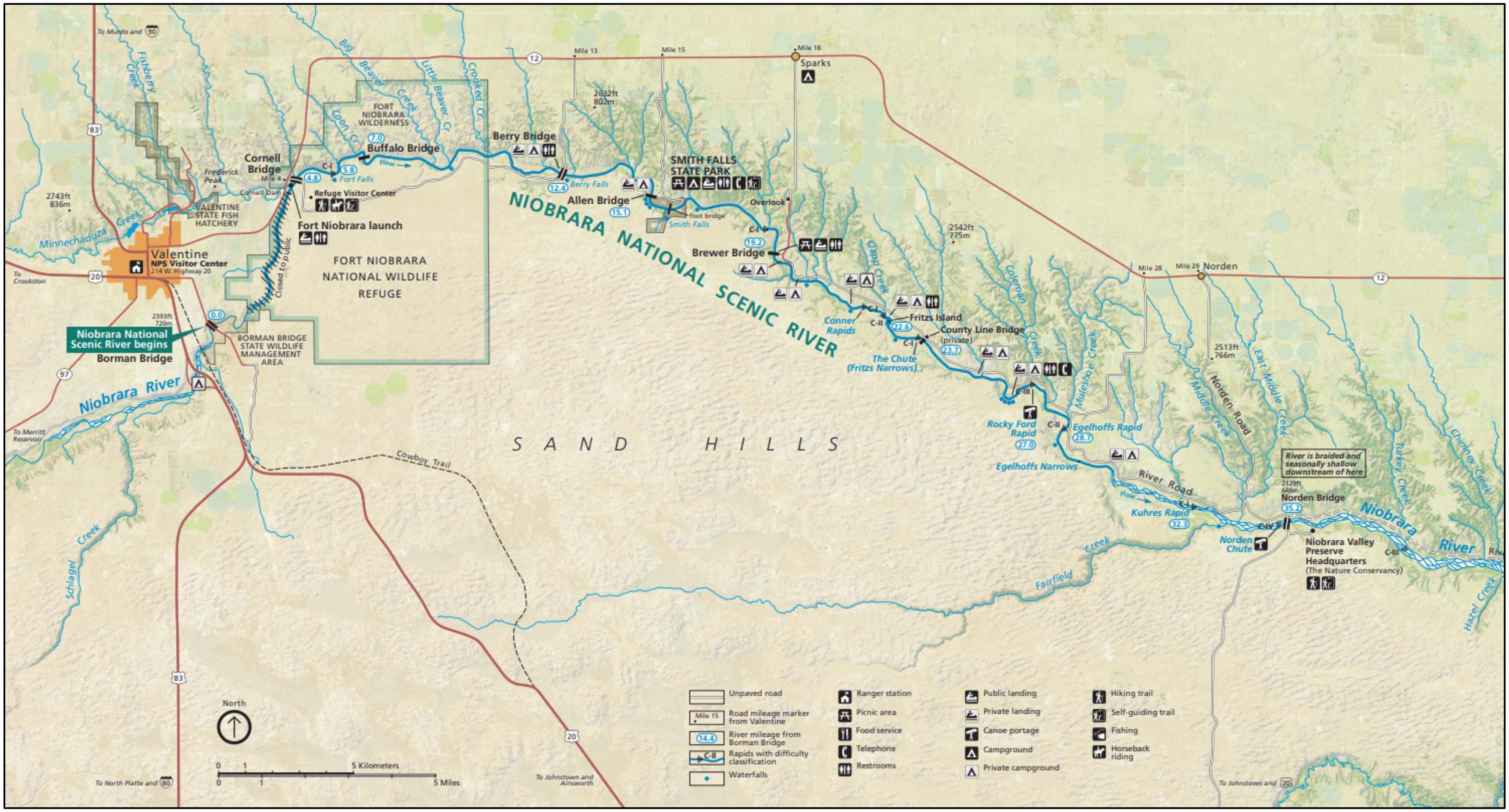


Figure 37a. Park map of western NIOB, Nebraska (NPS).

Figure 37b. Park map of eastern NIOB, Nebraska (NPS).

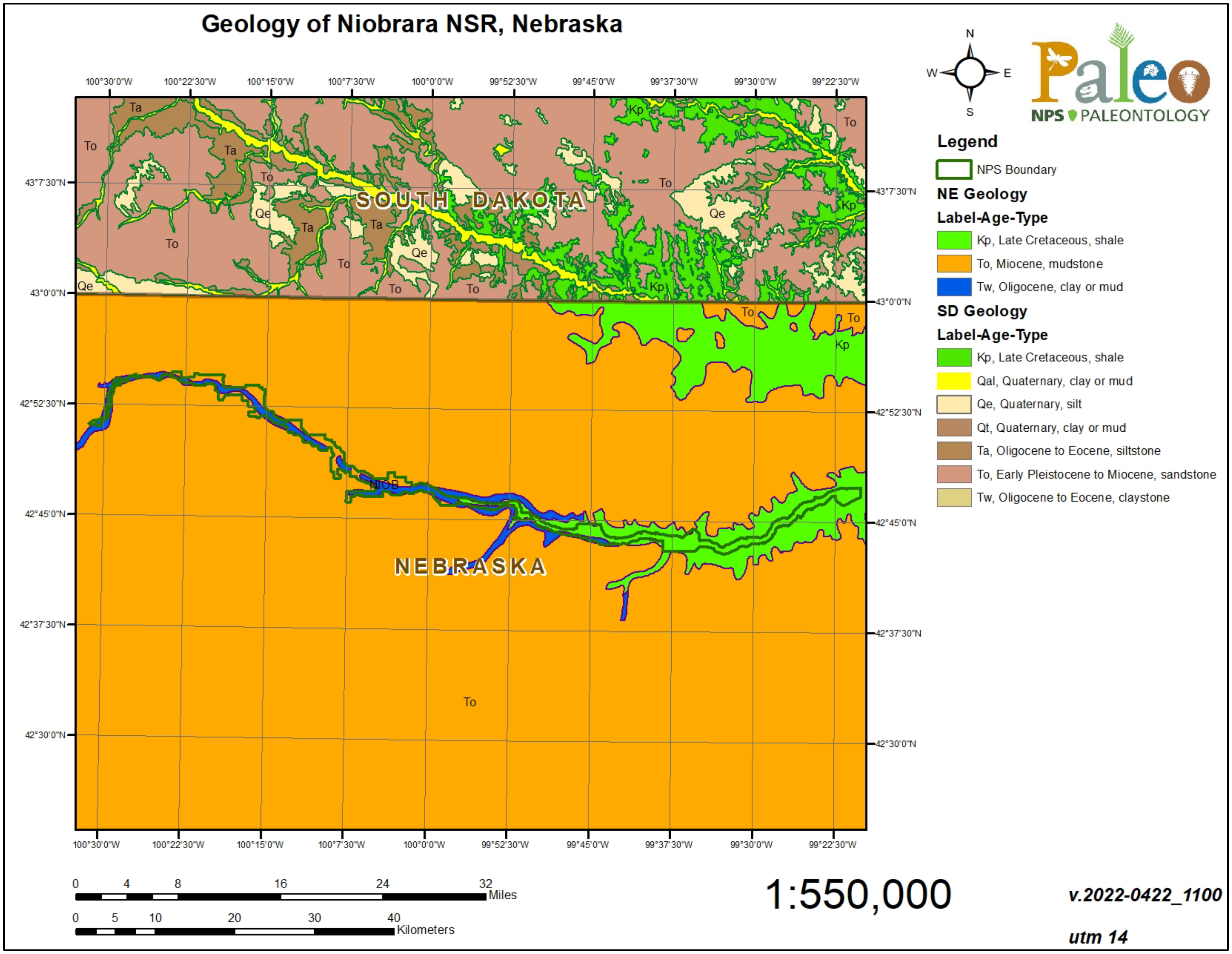


Figure 38. Geologic map of NIOB, Nebraska. NPS is expecting an updated geologic map for NIOB from the USGS for "Geologic Map of the Valley Corridor of the Niobrara National Scenic River, Nebraska" to supersede this smaller-scale geology.

Table 5. List of NIOB stratotype units sorted by age with associated reference publications and locations.

Unit Name (GRI map symbol)	Reference	Stratotype Location	Age
Fort Niobrara Formation	Osborn 1918	Type locality: on the Niobrara River near Fort Niobrara, in Cherry County, NE. ***Note: Unit superseded by the Valentine Formation	Pliocene
Cornell Dam Member, Valentine Formation	Skinner and Johnson 1984	Type section: roadcut a few miles northeast of the town of Valentine on the west side of Nebraska State Highway 12, west of the original mouth of Minnechaduza Creek and its junction with the Niobrara River, in SE/4 sec. 22, T. 34 N., R. 27 W., Cornell Dam 7.5′ Quadrangle, in Cherry County, NE. Reference sections: 1. On the north side of the Niobrara River at Rock Rapids [Rocky Ford], in secs. 9 and 16, T. 33 N., R. 24 W., Muleshoe Creek 7.5′ Quadrangle, in Keya Paha County, NE; 2. On the south side of the Niobrara River at Norden Bridge, in SW/4 NE/4 SW/4 sec. 33, T. 33 N., R. 23 W., Norden 7.5′ Quadrangle, in Brown County, NE.	Miocene

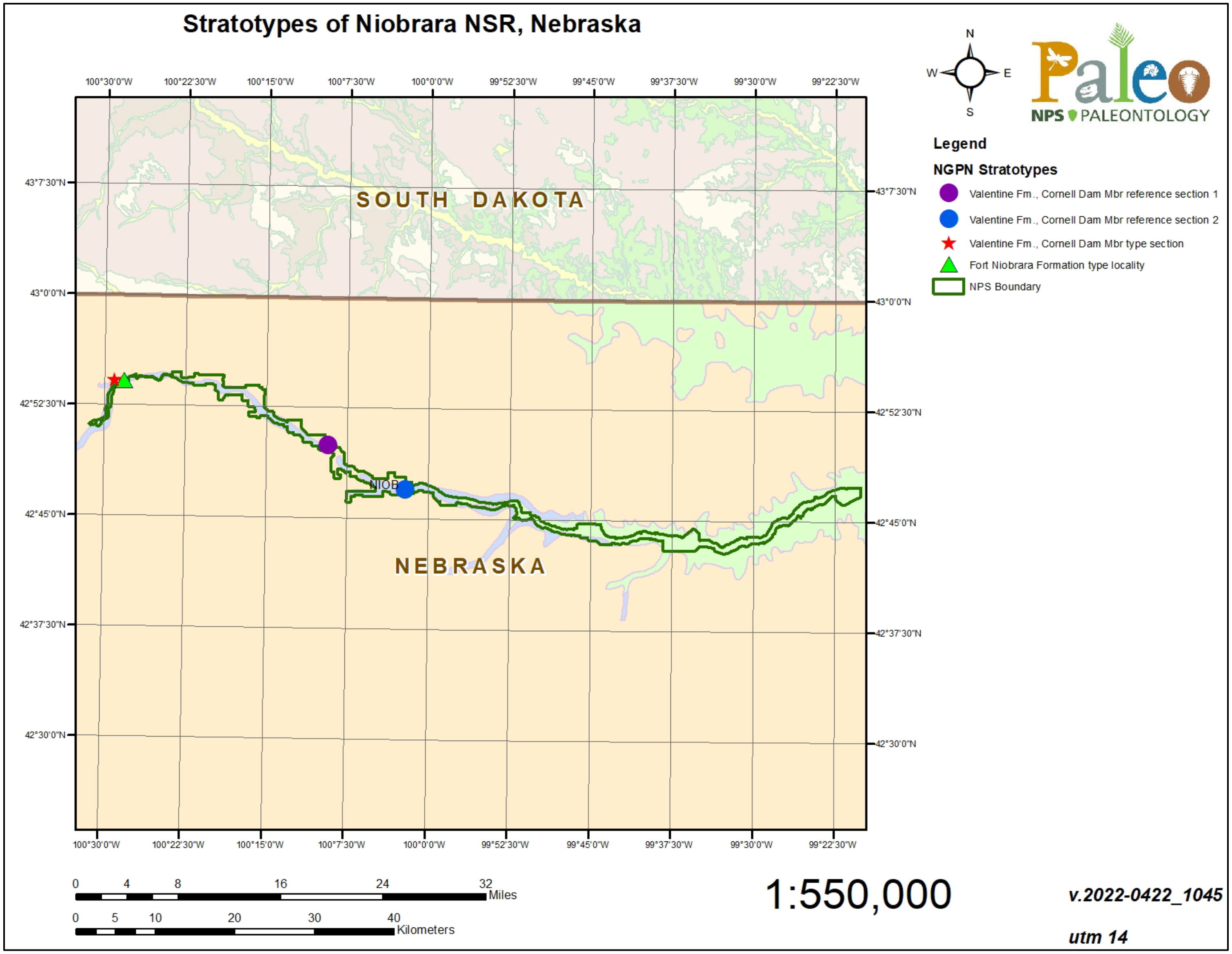


Figure 39. Modified geologic map of NIOB showing stratotype locations. The transparency of the geologic units layer has been increased.

Fort Niobrara Formation

Osborn (1918) applied the name “Fort Niobrara Formation” to a succession of fossiliferous sandstone beds located along the Niobrara River in north-central Nebraska. Osborn’s “Fort Niobrara Formation” was presumed to be Pliocene in age, but the unit is now superseded by the Miocene Valentine Formation. The type locality of the “Fort Niobrara Formation” was designated on the Niobrara River near Fort Niobrara, located east of Valentine in Cherry County, Nebraska (Table 5; Figure 39; Osborn 1918). Although Fort Niobrara no longer exists, the general location of the fort was 64 km (40 mi) upstream from Devils Gulch on the south side of the Niobrara River within the Fort Niobrara National Wildlife Refuge. Fossil specimens reported by Osborn (1918) include several extinct relatives of the modern horse. Johnson (1936, 1938) rejected the concept of a “Fort Niobrara Formation” and attributed its strata to the Miocene Valentine Formation.

Cornell Dam Member, Valentine Formation

The Miocene Cornell Dam Member is the basal member assigned to the Valentine Formation by Skinner and Johnson (1984). It is named after the nearby Cornell Dam along the Niobrara River, Nebraska. The type locality of the unit is designated in a roadcut exposure a few miles northeast of Valentine on the west side of Nebraska State Highway 12, west of the original mouth of Minnechaduza Creek and its junction with the Niobrara River, near the center of the west line of the SE/4 sec. 22, T. 34 N., R. 27 W., latitude 42°53′50″ N., longitude 100°29′05″ W., Cornell Dam 7.5′ Quadrangle, in Cherry County, north-central Nebraska (Table 5; Figures 39 and 40; Skinner and Johnson 1984). The type section exposure consists of a 13 m (42 ft)-thick succession gray, massive, silty sandstone and clay that contains manganese nodules in the upper 1.5 m (5 ft) (Skinner and Johnson 1984). A distinctive feature of the member are glass shards that give the unit a tuffaceous character: ash beds such as the Hurlbut Ash are contained within the Cornell Dam Member but are best displayed in Hurlbut Canyon in Brown County, Nebraska (Skinner and Johnson 1984). Thicker, more extensive reference sections provided by Skinner and Johnson (1984) exist in NIOB downstream from the type section. These reference sections include: (1) a 50 m (164 ft) thick exposure on the north side of the Niobrara River at Rock Rapids [Rocky Ford], in secs. 9 and 16, T. 33 N., R. 24 W., Muleshoe Creek 7.5′ Quadrangle, in Keya Paha County, Nebraska; and (2) a 14 m (47 ft) thick section on the south side of the Niobrara River at Norden Bridge, in SW/4 NE/4 SW/4 sec. 33, T. 33 N., R. 23 W., Norden 7.5′ Quadrangle, in Brown County, Nebraska (Table 5; Figure 39). The Cornell Dam Member occurs unconformably between the overlying Crookston Bridge Member (Valentine Formation) and underlying Rosebud Formation of the Arikaree Group.

Figure 40. Type section exposure of the Cornell Dam Member on the side of NE Highway 12 near Valentine, Nebraska. Silty sandstone and silty claystone exposures of the Cornell Dam Member measure 13 m (42 ft) and unconformably underlie the Crookston Bridge Member. Figure 6 from Skinner and Johnson (1984) (Skinner, M. F., and F. W. Johnson. 1984. Tertiary stratigraphy and the Frick Collection of fossil vertebrates from north-central Nebraska. Bulletin of the American Museum of Natural History 178:215–368.); used with permission of the American Museum of Natural History.

Scotts Bluff National Monument (SCBL)

Park Establishment

Scotts Bluff National Monument (SCBL) is located in the panhandle of Nebraska just west of the cities of Scottsbluff, Terrytown, and Gering in Scotts Bluff County (Figure 41). Proclaimed on December 12, 1919, SCBL encompasses about 1,216 hectares (3,005 acres) and preserves the massive Scotts Bluff promontory as well as historic emigrant trail corridors associated with the Oregon and California Trails (National Park Service 2016a). The predominant feature of SCBL is Scotts Bluff, a stunning geologic landmark that rises 244 m (800 ft) above the surrounding landscape. Named after fur trader Hiram Scott, Scotts Bluff represented a notable waypoint for emigrant travelers and is a site of cultural significance to Native Americans (National Park Service 2015). Both the Old Oregon Trail and Oregon National Historic Trail traverse SCBL through Mitchell Pass in the southern portion of the monument between Sentinel Rock and Eagle Rock.

Geologic Summary

Situated in the Great Plains physiographic province of western Nebraska, the landscape of SCBL features badlands, ridges, broad alluvial fans, and the prominent steep-sided cliffs of Scotts Bluff and South Bluff. Exposed sedimentary and igneous strata at Scotts Bluff date back to the Oligocene Epoch and reveal more geologic history than any location in the state of Nebraska (Graham 2009c). The vertical succession of rocks at Scotts Bluff and South Bluff includes formations associated with the Oligocene White River Group (Brule Formation) and Oligocene–Miocene Arikaree Group (Gering Formation, Monroe Creek Formation, and Harrison Formation). Dissected badlands located in the northeastern area of the monument are composed of mudstone, siltstone, sandstone, and volcanic tuffs of the Brule Formation, the same unit that forms part of the iconic badlands-style topography of BADL. Quaternary surficial deposits such as sand dunes, rockfalls, loess, alluvium, and colluvium are widely distributed across SCBL (Figure 42).

Stratotypes

SCBL contains one identified stratotype, a reference section for the Oligocene–Miocene Mitchell Pass Member of the Gering Formation (Table 6; Figure 43). In addition to the designated stratotype located within SCBL, there are 15 stratotypes located within 48 km (30 mi) of SCBL boundaries; they are listed in Appendix C for reference in case of future boundary expansion.

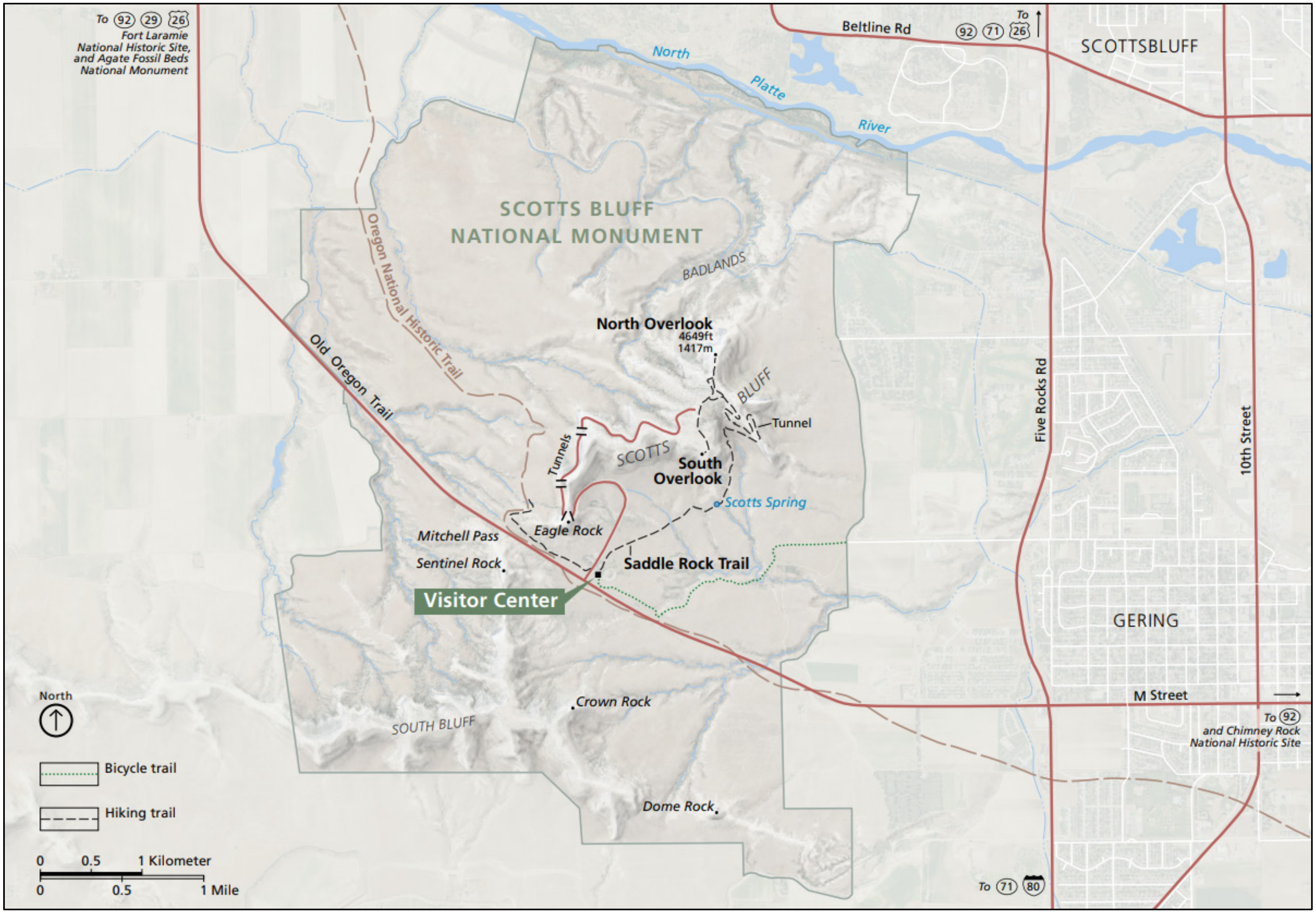


Figure 41. Park map of SCBL, Nebraska (NPS).

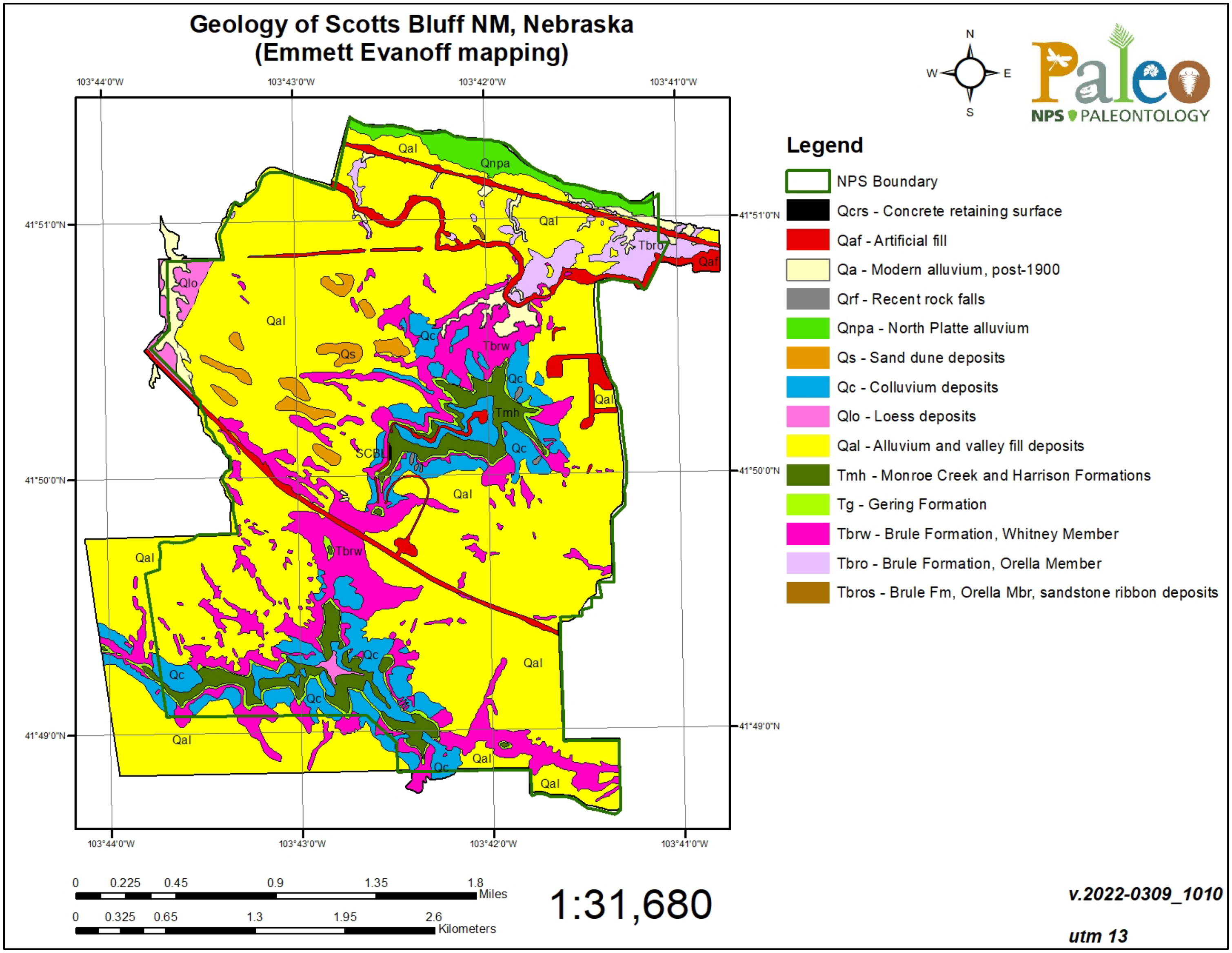


Figure 42. Geologic map of SCBL, Nebraska. Data modified from SCBL GRI digital geologic map data at https://irma.nps.gov/DataStore/Reference/Profile/2216626.

Table 6. List of SCBL stratotype units sorted by age with associated reference publications and locations.

Unit Name (GRI map symbol)	Reference	Stratotype Location	Age
Mitchell Pass Member, Gering Formation	Vondra et al. 1969	Reference section: at Mitchell Pass and the west to north sides of Scotts Bluff, approximately 3.5 km (2.2 mi) west and 1.3 km (0.8 mi) north of Gering, in the SW/4 and NE/4 sec. 33, T. 22 N., R. 55 W. (Scottsbluff South and Scotts Bluff National Monument 7.5′ Quadrangles), in Scotts Bluff County, NE.	late Oligocene–early Miocene

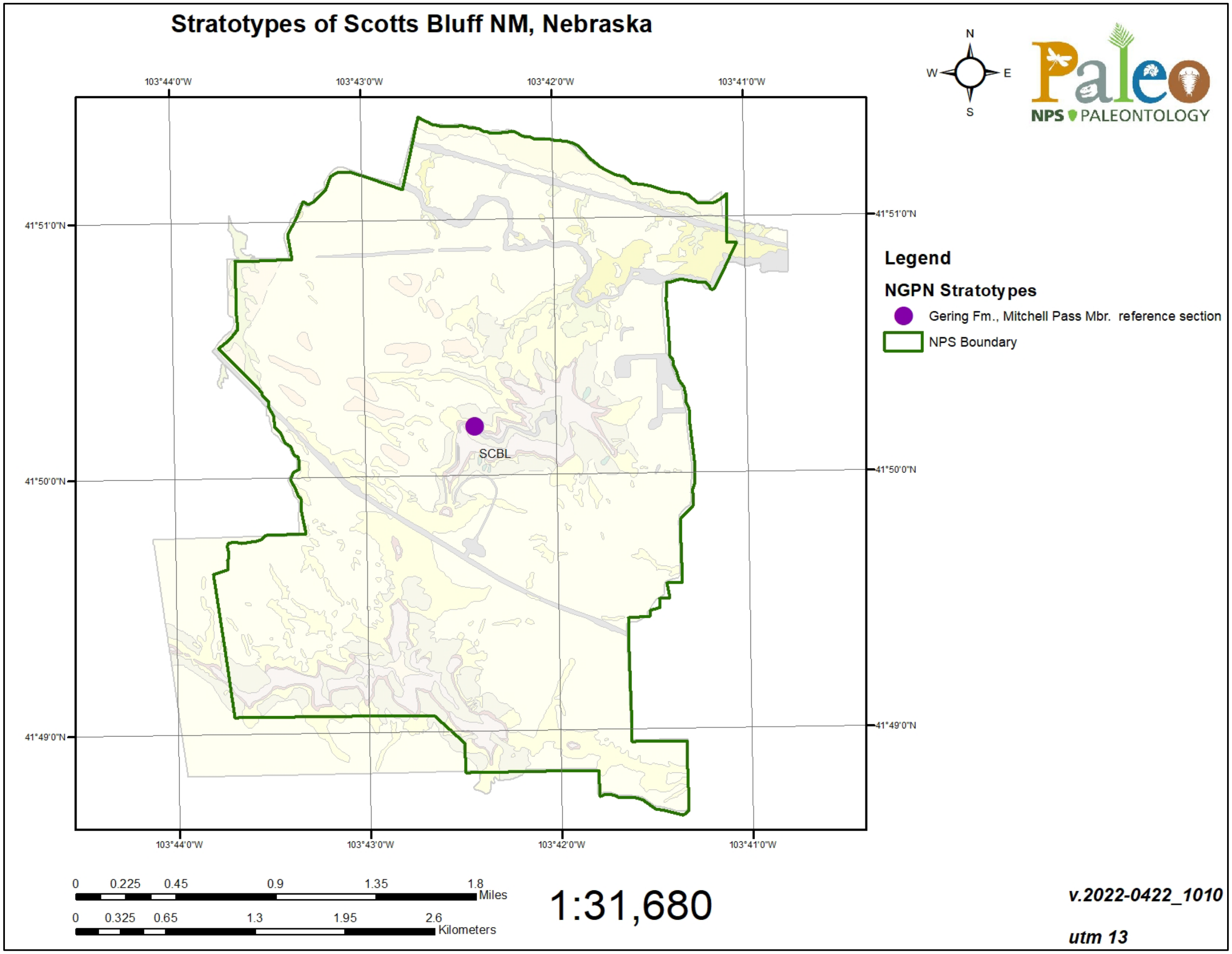


Figure 43. Modified geologic map of SCBL showing stratotype locations. The transparency of the geologic units layer has been increased.

Mitchell Pass Member, Gering Formation

The Oligocene–Miocene Mitchell Pass Member of the Gering Formation was named by Vondra et al. (1969) after Mitchell Pass in SCBL, but the authors designated the type locality in Helvas Canyon in the Wildcat Hills State Recreation Area approximately 8 km (5 mi) south of the monument. A reference section designated by Vondra et al. (1969) is located at Mitchell Pass and the west to north sides of Scotts Bluff, approximately 3.5 km (2.2 mi) west and 1.3 km (0.8 mi) north of Gering, in the SW/4 and NE/4 sec. 33, T. 22 N., R. 55 W., Scottsbluff South and Scotts Bluff National Monument 7.5′ Quadrangles in Scotts Bluff County, Nebraska (Table 6; Figures 43–45). The reference section measures 15 m (48 ft) thick and consists of buff, thinly bedded, very-fine grained sandstone that contains thin, resistant calcareous ledges in the upper interval (Vondra et al. 1969). At the reference section the Mitchell Pass Member overlies the Helvas Canyon Member (Gering Formation) and underlies the Monroe Creek Formation.

Figure 44. The north face of Scotts Bluff, consisting of the Arikaree Group (Gering Formation, Monroe Creek Formation, Harrison Formation) overlying the Brule Formation. The reference section of the Mitchell Pass Member of the Gering Formation is located on the west and north sides of Scotts Bluff, consisting of thinly bedded sandstone and thin, resistant calcareous ledges measuring 15 m (48 ft) thick. Plate 47 from Darton (1905).

Figure 45. View of the northern side of Scotts Bluff and adjacent badlands taken near the Union Pacific railroad tracks in northern SCBL. Photograph courtesy of Ryan W. Barker with permission.

Theodore Roosevelt National Park (THRO)

Park Establishment

Theodore Roosevelt National Park (THRO) consists of three separate park units—the North, South, and Elkhorn Ranch Units—situated along the Little Missouri River in Billings and McKenzie Counties, western North Dakota (Figures 46 and 47). Originally established as Theodore Roosevelt National Memorial Park on April 25, 1947, the park unit was redesignated as a national park on November 10, 1978 (National Park Service 2016a). THRO contains approximately 28,508 hectares (70,447 acres) and features scenic badlands and part of President Theodore Roosevelt's Elkhorn Ranch. THRO is named in commemoration of Roosevelt for his significant contributions to the conservation of America's natural resources, including the establishment of the U.S. Forest Service, five national parks, 18 national monuments, 150 national forests, and numerous wildlife preserves (Brinkley 2009). The North Dakota Badlands of THRO form a rugged, colorful landscape that inspired Roosevelt to adopt a conservation ethic and continues to inspire visitors today (National Park Service 2014b).

Geologic Summary

THRO is situated in the Great Plains physiographic province along the boundary separating the glaciated and unglaciated regions of the Missouri Plateau. The bedrock underlying THRO consists of Paleocene rocks (Figures 48–50). The Paleocene Bullion Creek Formation and Sentinel Butte Formation are well-exposed in the scenic badlands. The Bullion Creek Formation is comprised of yellowish-brown sedimentary deposits of sandstone, siltstone, and mudstone that occur in the Elkhorn and South Units. The overlying Sentinel Butte Formation is widely distributed across the North and South Units of THRO and consists of grayish-brown sedimentary deposits, tuffs, and bentonite beds (Biek and Gonzalez 2001). A variety of Quaternary surficial deposits are mapped throughout THRO, including upland gravel deposits, mantled pediment deposits, landslide debris, alluvial sediments, and alluvium.

Stratotypes

There are no designated stratotypes identified within the boundaries of THRO. There are six identified stratotypes located within 48 km (30 mi) of THRO boundaries; they are listed in Appendix C for reference in case of future boundary expansion.

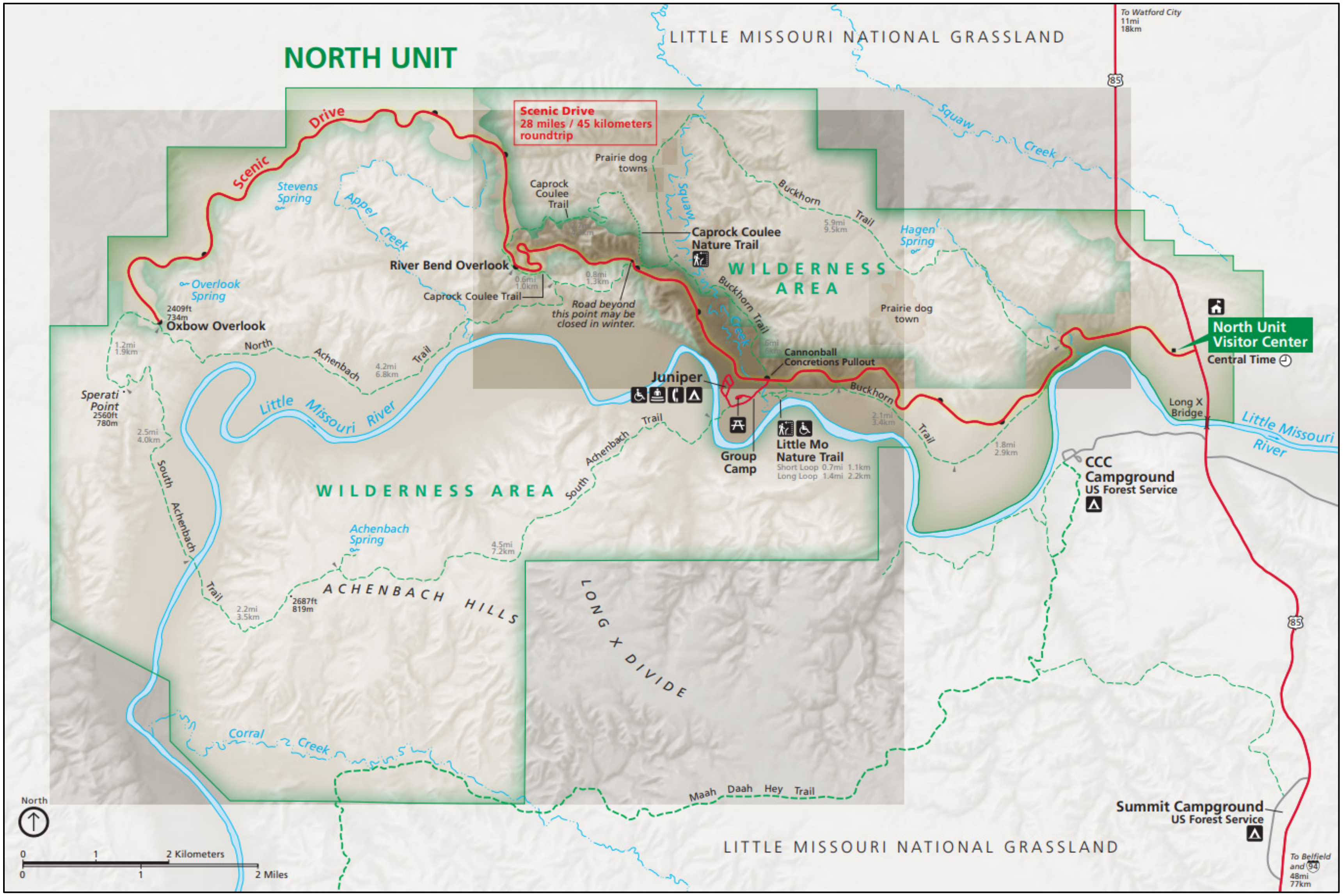


Figure 46. Park map of the North Unit of THRO, North Dakota (NPS).

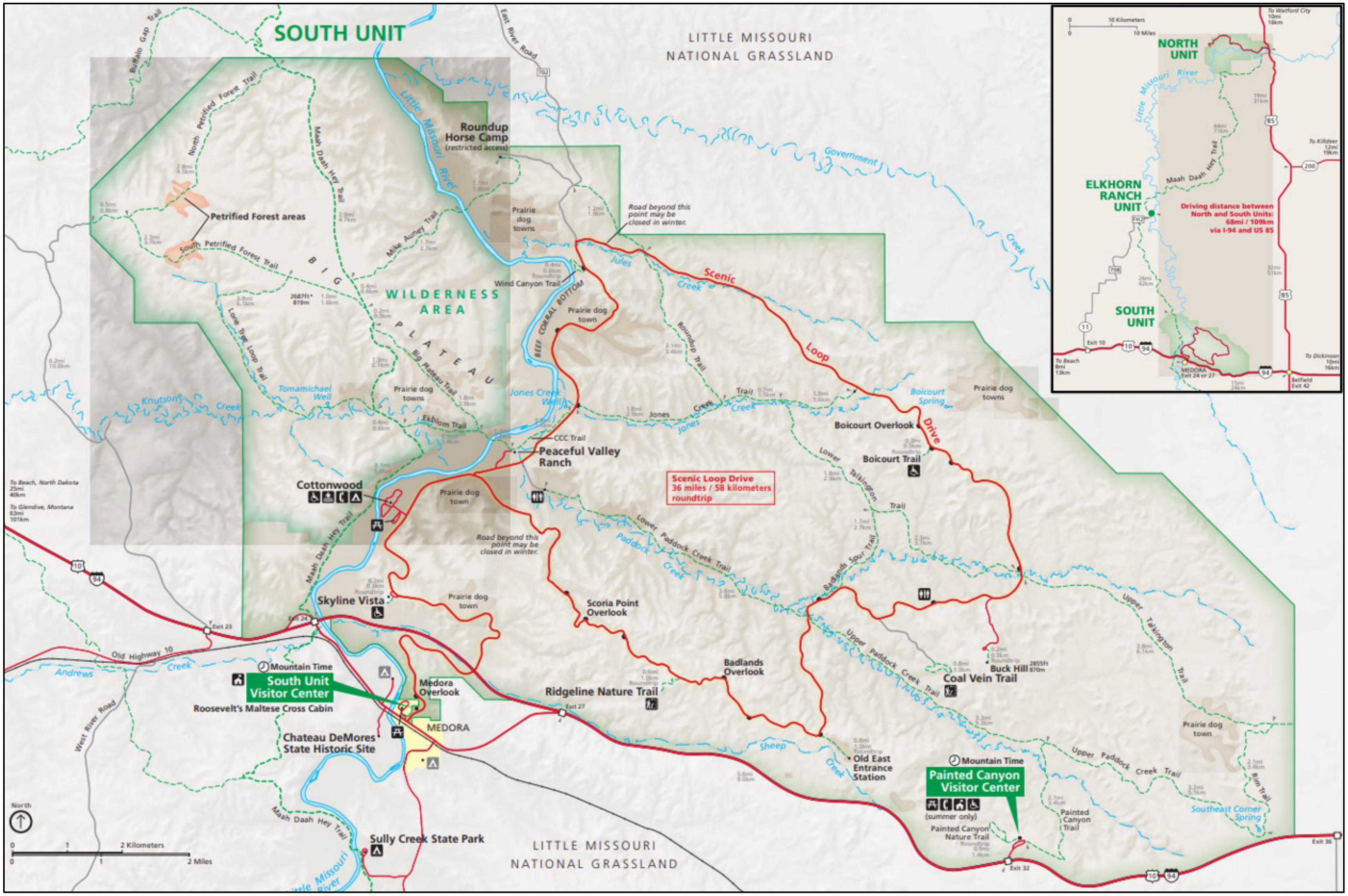


Figure 47. Park map of the South Unit of THRO and regional inset map, North Dakota (NPS).

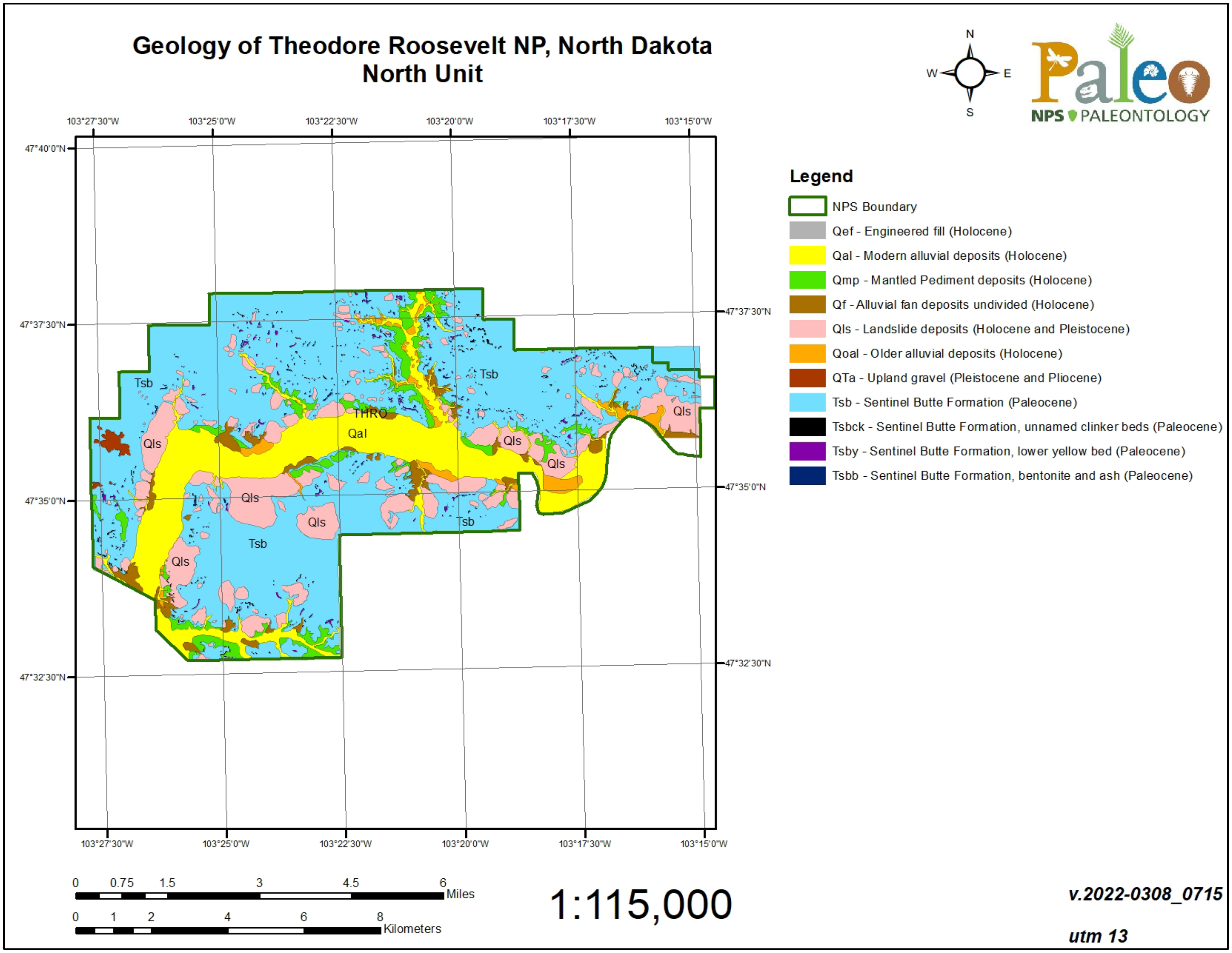


Figure 48. Geologic map of the North Unit of THRO, North Dakota. Data modified from THRO GRI digital geologic map data at https://irma.nps.gov/DataStore/Reference/Profile/1044329.

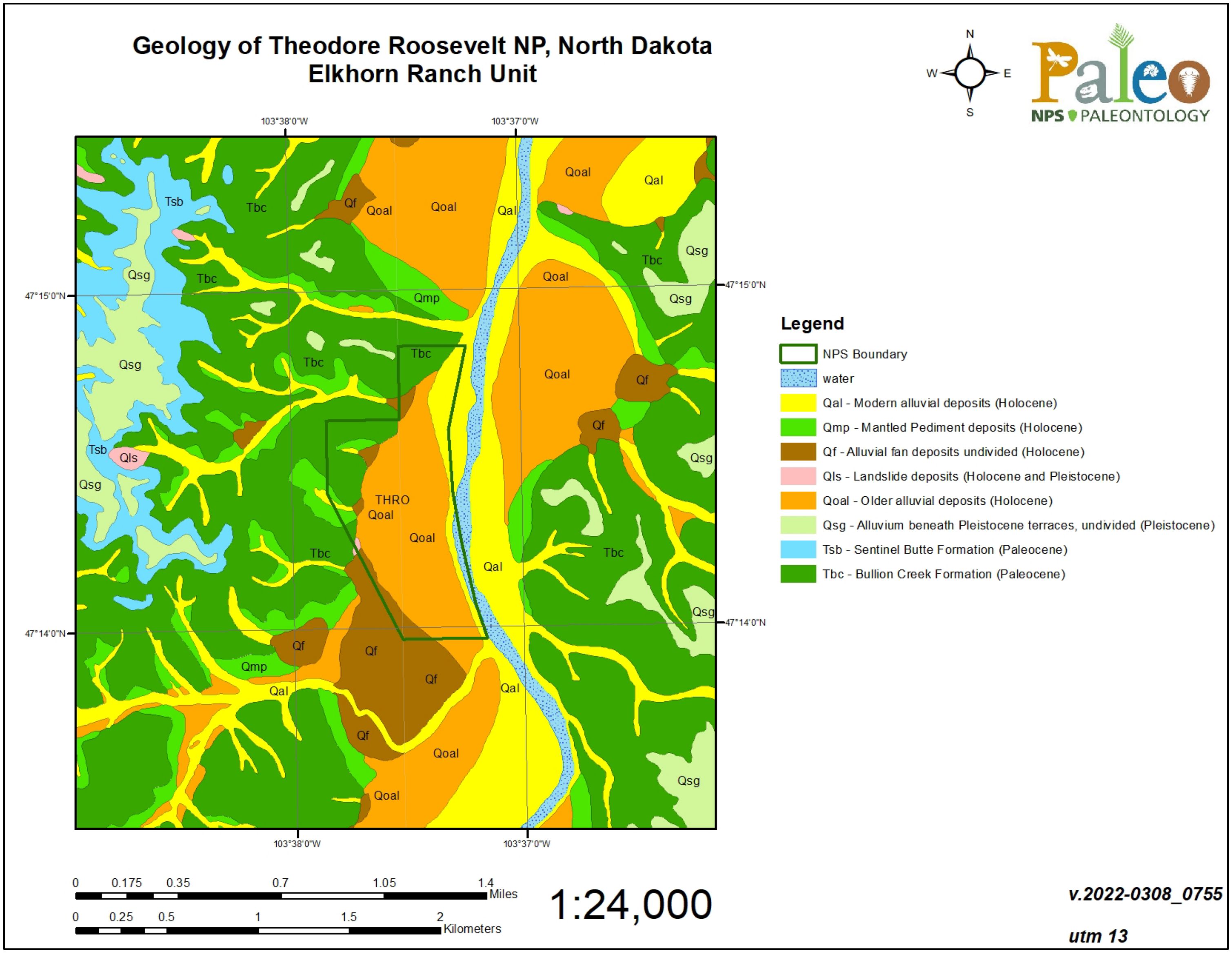


Figure 49. Geologic map of the Elkhorn Ranch Unit of THRO, North Dakota. Data modified from THRO GRI digital geologic map data at https://irma.nps.gov/DataStore/Reference/Profile/1044329.

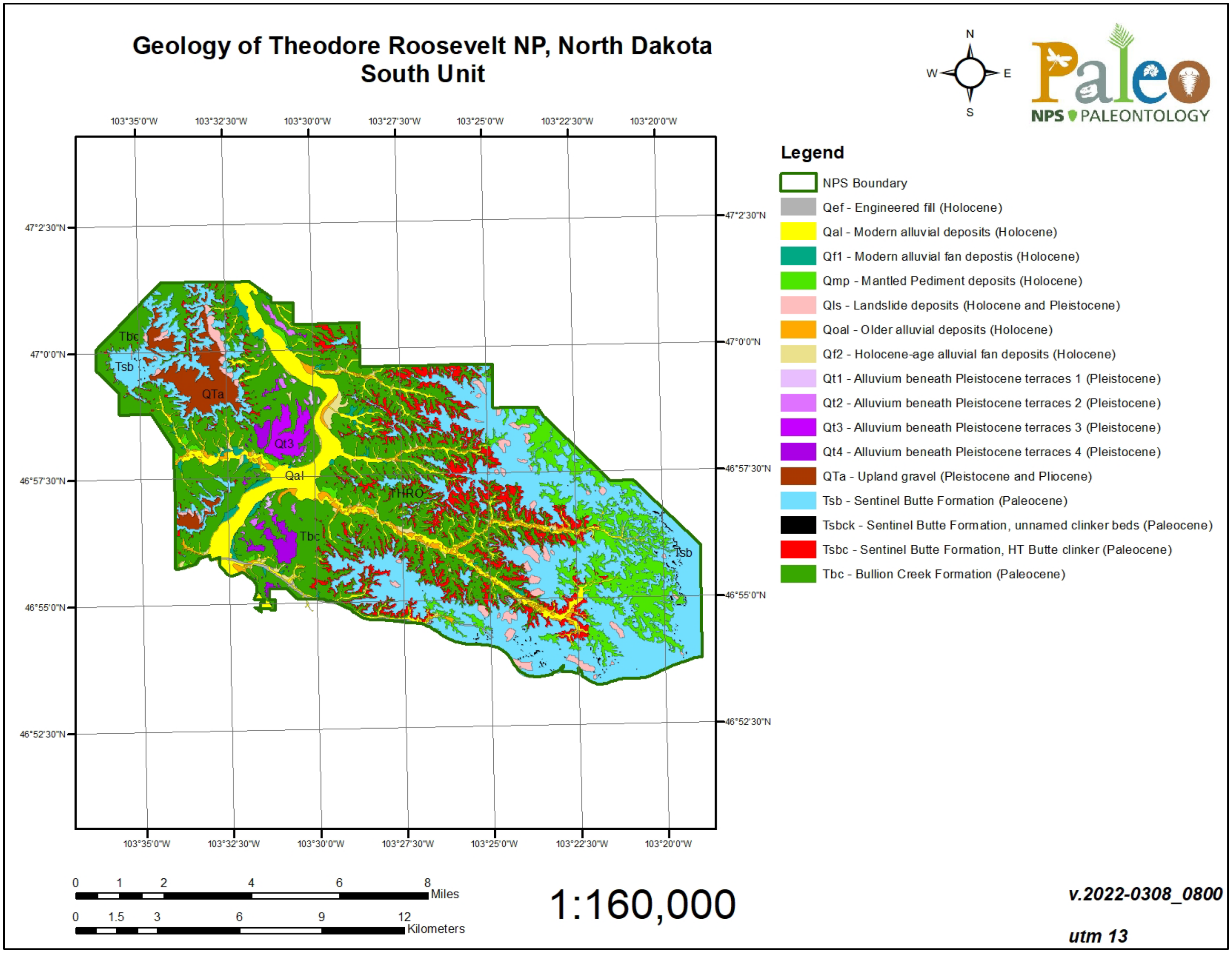


Figure 50. Geologic map of the South Unit of THRO, North Dakota. Data modified from THRO GRI digital geologic map data at https://irma.nps.gov/DataStore/Reference/Profile/1044329.

Wind Cave National Park (WICA)

Park Establishment

Wind Cave National Park (WICA) is located on the southeastern edge of the Black Hills approximately 8 km (5 mi) north of Hot Springs in Custer County, southwestern South Dakota (Figure 51). Established on January 9, 1903, WICA contains about 13,728 hectares (33,924 acres) and protects Wind Cave, one of the longest, oldest, and most complex caves on Earth. Although Native Americans have known about the entrance to Wind Cave for thousands of years, the first white discovery of the cave occurred in 1881 when Jesse and Tom Bingham experienced strong winds blowing from the cave's natural opening (National Park Service 2011). Wind Cave features an assemblage of unique cave resources that include beautiful boxwork and calcite crystal formations, and the park represents a premier location to view remnants of ancient sediment-filled caves (Palmer et al. 2016). Above the cave system, WICA supports one of the most intact prairie communities in North America, hosting bison, pronghorn, deer, elk, the endangered black-footed ferret, prairie dogs, and mountain lions.

Geologic Summary

WICA is situated in the Great Plains physiographic province on the southeastern flank of the Black Hill Uplift, an elongate domal uplift stretching across approximately 0.8 million hectares (2 million acres) along the South Dakota–Wyoming border. Development of the Black Hills primarily occurred during the Paleocene approximately 60 to 50 million years ago due to collisional tectonic forces associated with the Laramide Orogeny (Lisenbee 1988; Lisenbee and DeWitt 1993). Uplifted Paleozoic and Mesozoic strata were eroded away from the central region of the Black Hills, exposing a core of ancient Precambrian metamorphic and igneous rocks. The bedrock underlying WICA consists of Paleoproterozoic crystalline rocks that include quartzite, metapelite, and the Harney Peak Granite—the same unit that provided a medium for the busts of U.S. Presidents Washington, Jefferson, Roosevelt, and Lincoln at MORU. A diverse assemblage of Cambrian through Cretaceous-age sedimentary strata is widely distributed across WICA, generally dipping away from the central Black Hills region (Figure 52; Palmer et al. 2016). Wind Cave and nearby Jewel Cave share the same regional geologic history, and both cave systems have primarily developed within carbonate rocks of the Mississippian Pahasapa Limestone.

Stratotypes

There are no designated stratotypes identified within the boundaries of WICA. Although Darton's (1901) Pahasapa Limestone is derived from the Dakota tribal term "Pahasapa" meaning the Black Hills, there is currently no stratotype designation (see "Recommendations"). There are 11 identified stratotypes located within 48 km (30 mi) of WICA boundaries; they are listed in Appendix C for reference in case of future boundary expansion.

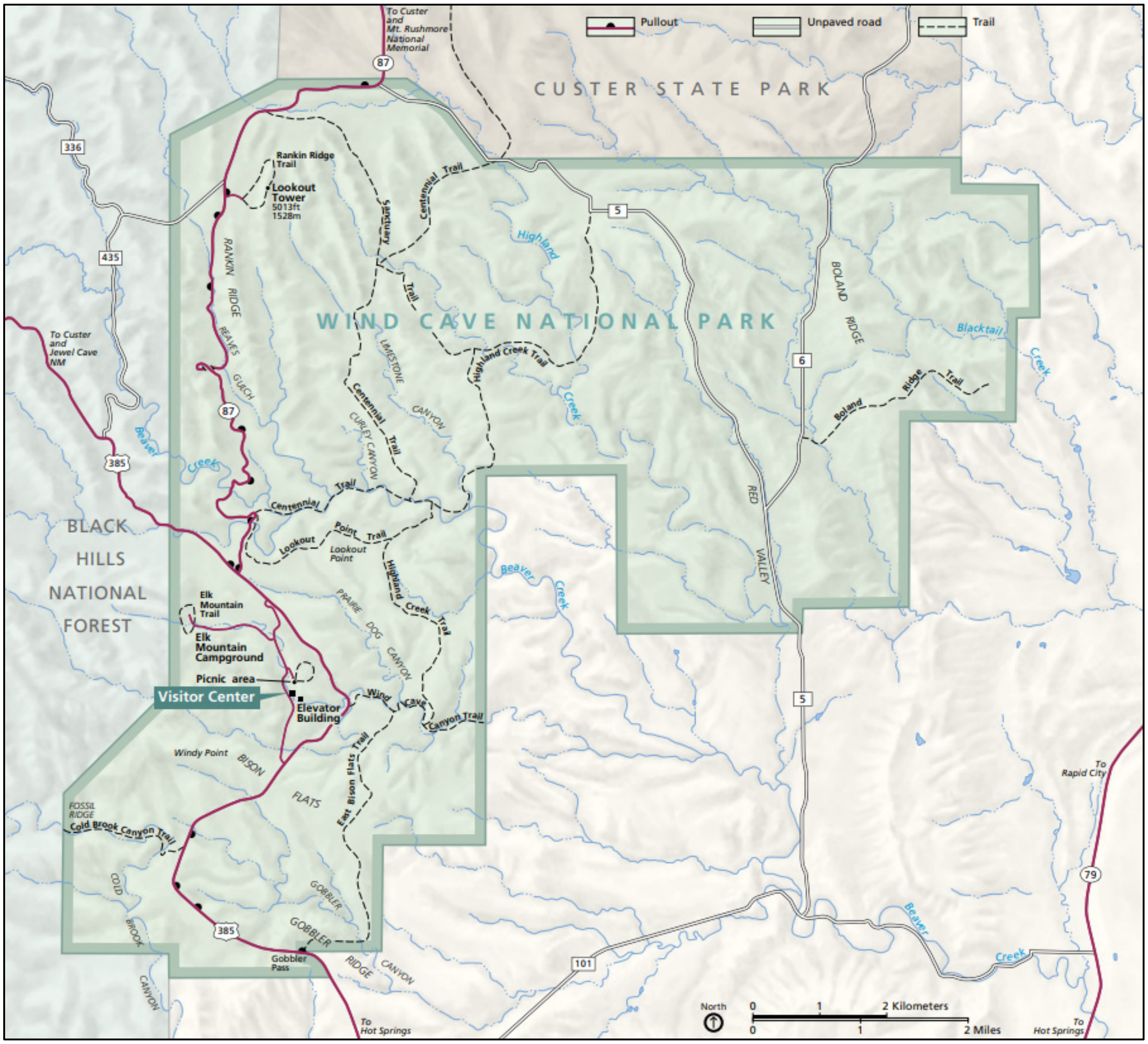


Figure 51. Park map of WICA, South Dakota (NPS); map boundaries do not include recent expansion (see Figure 52).

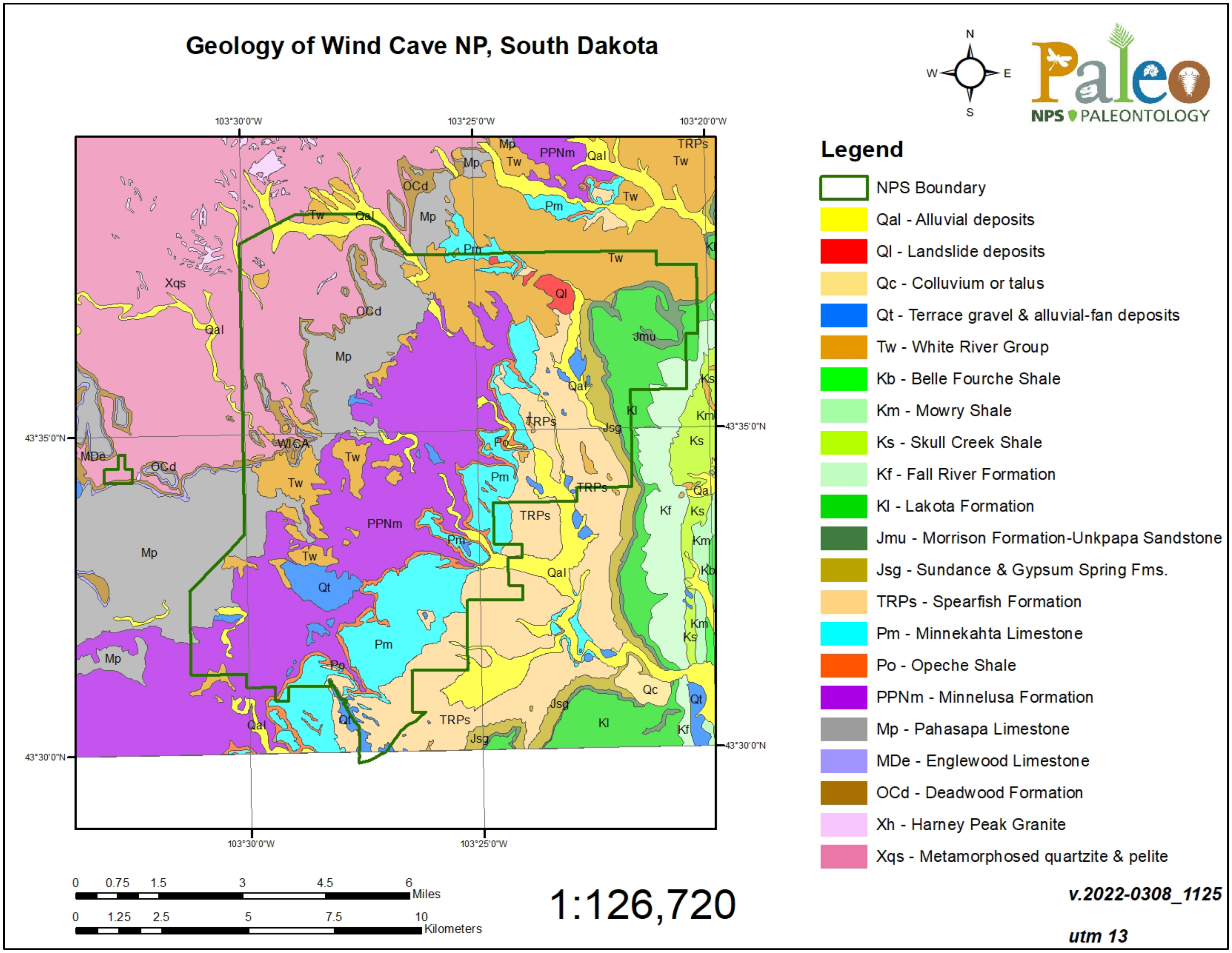


Figure 52. Geologic map of WICA, South Dakota. Data modified from WICA GRI digital geologic map data at https://irma.nps.gov/DataStore/Reference/Profile/2253881.

Recommendations

Stratotypes represent unique geologic exposures and are important to manage due to the scientific and educational values they hold for future generations. Stratotypes occur where rocks are exposed naturally (cliff face, river bluff, canyon wall, etc.) or artificially (quarry wall, road/rail/trail/canal cut, tunnel). Therefore, continued stratotype utility derives from the following three characteristics:

- Visibility: described rock layers remain visible and not totally or partially obscured
- Accessibility: the exposures at the stratotype remain reasonably accessible via road, trail, or other method
- Unaltered Integrity: the rock exposures are not altered significantly following description

Stratotype management strategies should focus on maintaining these characteristics to the extent practical when there are multiple management priorities at the site. The extent of the stratotype also impacts resource management considerations. For example, type areas occur over large geographic areas with less emphasis or significance placed on individual exposures, while type sections are specific localities that may warrant more focused management attention.

The recommendations below generally follow the protocol suggested by Brocx et al. (2019) with changes to fit NPS resource management framework.

1. The NPS Geologic Resources Division should work with park, regional and network staff to increase their awareness and understanding about the historic and geologic heritage significance of geologic stratotypes (type sections/localities/areas, reference sections, lithodemes). This report is a first step toward building that awareness.
2. The NPS Geologic Resources Division should work with park, regional and network staff to ensure they are aware of the locations of stratotypes in park areas. This information is necessary to ensure that proposed park activities or development do not adversely impact the stability and condition of these geologic exposures. Preservation of stratotypes should not limit accessibility for future scientific research but help safeguard these exposures from infrastructure development.
3. For significant sites without formal stratotype designations, GRD can provide assistance and liaison with the U.S. Geological Survey or other agencies to establish formal designations. It is recommended that stratotype designations of the following units be made to: (A) provide a standard reference for scientific research; (B) educate park staff and visitors about the geoheritage significance of these units; and (C) help safeguard these exposures.
    a. The phonolite porphyry of Devils Tower, DETO is listed as a unit in GEOLEX, attributed to Bassett (1961). Inspection of the latter article shows no indication of intent to name a geologic unit. That said, the tower is an obvious location to serve as a stratotype.
    b. The Paleogene Fort Union Formation was named by Meek and Hayden (1862) after Fort Union near the mouth of the Yellowstone River. Although GEOLEX credits the name to “Old Fort Union”, the archive mistakenly states that Fort Union later became

Fort Buford (https://ngmdb.usgs.gov/Geolex/Units/FortUnion_8173.html, accessed August 2, 2022). Fort Buford was constructed downstream from Fort Union in 1866, four years after the Fort Union Formation had been officially named by Meek and Hayden (1862). Exposures of the Fort Union Formation and its Sentinel Butte Member and Tongue River Member form bluffs and terraces in FOUS, but the formation currently lacks a formal stratotype designation.

   c. The Mississippian Pahasapa Limestone was proposed by Darton (1901), who derived the name from the Dakota tribal term "Pahasapa" meaning the Black Hills. Darton (1901) described the Pahasapa Limestone as a massive, gray limestone approximately 70–150 m (225–500 ft) thick in the central and southern Black Hills, a region occupied by JECA and WICA that features outstanding cave networks developed within the limestone. However, no stratotype has been designated.

4. For stratotypes designated external to an NPS area that may face destruction, alteration, or other significant impacts, GRD can work with park staff to potentially set up a reference section within an NPS area, which affords a baseline level of protection.
5. The NPS Geologic Resources Division should work with park, regional, and network staff, the U.S. Geological Survey, state geological surveys, academic geologists, and other partners to formally assess potential new stratotypes as to their significance (international, national, or statewide), based on lithology, stratigraphy, fossils or notable features using procedural code outlined by the North American Commission on Stratigraphic Nomenclature (after Brocx et al. 2019).
6. From the assessment in (5), the NPS Geologic Resources Division, the U.S. Geological Survey, state geologic surveys, academic geologists, and other partners should focus on registering new stratotypes at state and local government levels where current legislation allows, followed by a focus on registering at federal and state levels where current legislation allows (after Brocx et al. 2019).
7. The NPS Geologic Resources Division should work with park, regional and network staff to:
   a. Compile, update, and maintain a central inventory of all designated stratotypes and potential future nominations. The USGS GEOLEX serves this function for the United States. This report is part of an effort to inventory stratotypes specific to National Park Service areas and eventually provide that data in a spatial, searchable format and integrate with GEOLEX.
   b. Establish appropriate monitoring protocols to regularly assess stratotype locations to identify any threats or impacts to these geologic heritage features in parks. See bullet points below for potential threats. Crofts et al. (2020) provides additional details on potential threats. Brocx et al. (2019) includes examples of destroyed stratotypes and suggests protocols for conservation in Australia. Criteria to access the stability of stratotype exposure sites should follow the guidance of the Unstable Slope Management Program (USMP) for federal land management agencies found here:

https://highways.dot.gov/sites/fhwa.dot.gov/files/docs/federal-lands/tech-resources/31011/usmp-field-manual.pdf.

c. Develop appropriate management actions based on significance of site and consideration of other resource management needs. See bullet points below for suggested management considerations.
d. Obtain good photographs of each geologic stratotype within the parks. Photographs of each stratotype are rare and thus obtaining photographs of NPS stratotypes is a first step for resource management. In some cases, where there may be active geologic processes (rock falls, landslides, coastal erosion, etc.), the use of photogrammetry may be considered for monitoring of stratotypes. GPS locations should also be recorded and kept in a database when the photographs are taken.
e. Consider the collection and curation of geologic samples (new or extant) from stratotypes within respective NPS areas. Samples collected from stratotype exposures can be useful as reference specimens to support future studies, especially where stratotypes may be lost through natural processes or human activities.
f. Use selected robust internationally and nationally significant stratotypes as formal teaching/interpretation sites and for geotourism so that the importance of the national- and international-level assets are more widely (and publicly) known, using wayside panels, educational sites (on site or virtual), and walkways (after Brocx et al. 2019).
g. Develop conservation protocols of significant stratotypes, either by appropriate fencing, guard rails, trails, boardwalks, and information boards or other means (e.g., phone apps) (after Brocx et al. 2019).

Natural processes that have the potential to impact visibility, accessibility, or unaltered integrity of stratotypes include the following:

- Slope movements (e.g., rock falls, landslides)
- Erosion
- Vegetation encroachment (exotic, invasive, or native)
- Sea level rise (e.g., inundation and submersion)
- Tectonism and volcanism

Note that the rate, frequency, or severity of these natural processes will likely change as climate continues to change.

Human activities that have the potential to impact visibility, accessibility, or unaltered integrity of stratotypes include the following:

- Road, trail, or other infrastructure development that may remove or obscure stratotypes.
- Installation of guard rails, sprayed concrete (e.g., “Shotcrete” or gunite), wire mesh, rock bolts, or other cliff stabilization techniques.
- Restoration of a quarry or other abandoned site that was used as a stratotype location

- Graffiti, vandalism, or unauthorized fossil/mineral/rock collection
- Scientific research permits that include fossil/mineral/rock sampling or paleomagnetism coring.
- Visitor use (e.g., trails that cross stratotypes) can degrade stratotype integrity.

Potential resource management actions include the following:

- As general guidance, NPS Management Policies (section 4.8.2) states that "The Service will protect geologic features from the unacceptable impacts of human activity while allowing natural processes to continue" (National Park Service 2006).
- All stratotypes should, at minimum, be photographed at high resolution with a common object or scale bar included.
- Photogrammetry is an ideal documentation method for significant stratotypes.
- If obscuring or destruction of the outcrop is necessary for other resource management priorities (e.g., road/trail alterations, AML [Abandoned Mineral Lands] restoration [should consider stratotypes where possible], visitor safety concerns, natural rockfall or slope movement at/near the stratotype) photogrammetric documentation should be considered. Designation of a reference section at a less threatened or dangerous exposure is another possibility.
- If other geologic resources are present at the stratotype, such as fossils, significant minerals, or cave features, additional resource management and monitoring may be necessary. See for example Young and Norby (2009).
- Clear exotic or invasive vegetation from stratotypes or manage native vegetation to maximize visibility and accessibility.
- Utilize the Unstable Slope Monitoring Program (USMP) Tool to determine stability of stratotype exposure and potential hazards to human safety.
- For exceptionally significant stratotypes (international, national, or related to park fundamental purposes), consider utilizing them as formal interpretation or education sites (on site or virtual), or protecting them with fencing/guard rails, constructing boardwalks or trails to focus visitor access, or installing wayside panels.

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Appendix A: Source Information for GRI Maps of NGPN Parks

GMAP = Unique identifier assigned to geologic source maps by the GRI program.

The GRI program converted these source maps to the GRI digital geologic map data for each park. GRI data sets are available at their publications page: https://www.nps.gov/subjects/geology/geologic-resources-inventory-products.htm. For information on how source maps are converted and what the GRI data model includes, refer to the GRI data models here: https://irma.nps.gov/DataStore/Reference/Profile/2259192.

AGFO

- GMAP 1313: Hunt, R. M. 1988. Geologic map of the Agate Fossil Beds National Monument. University of Nebraska-Lincoln, Lincoln, Nebraska. Scale 1:16,896.
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Appendix B: Geologic Time Scale

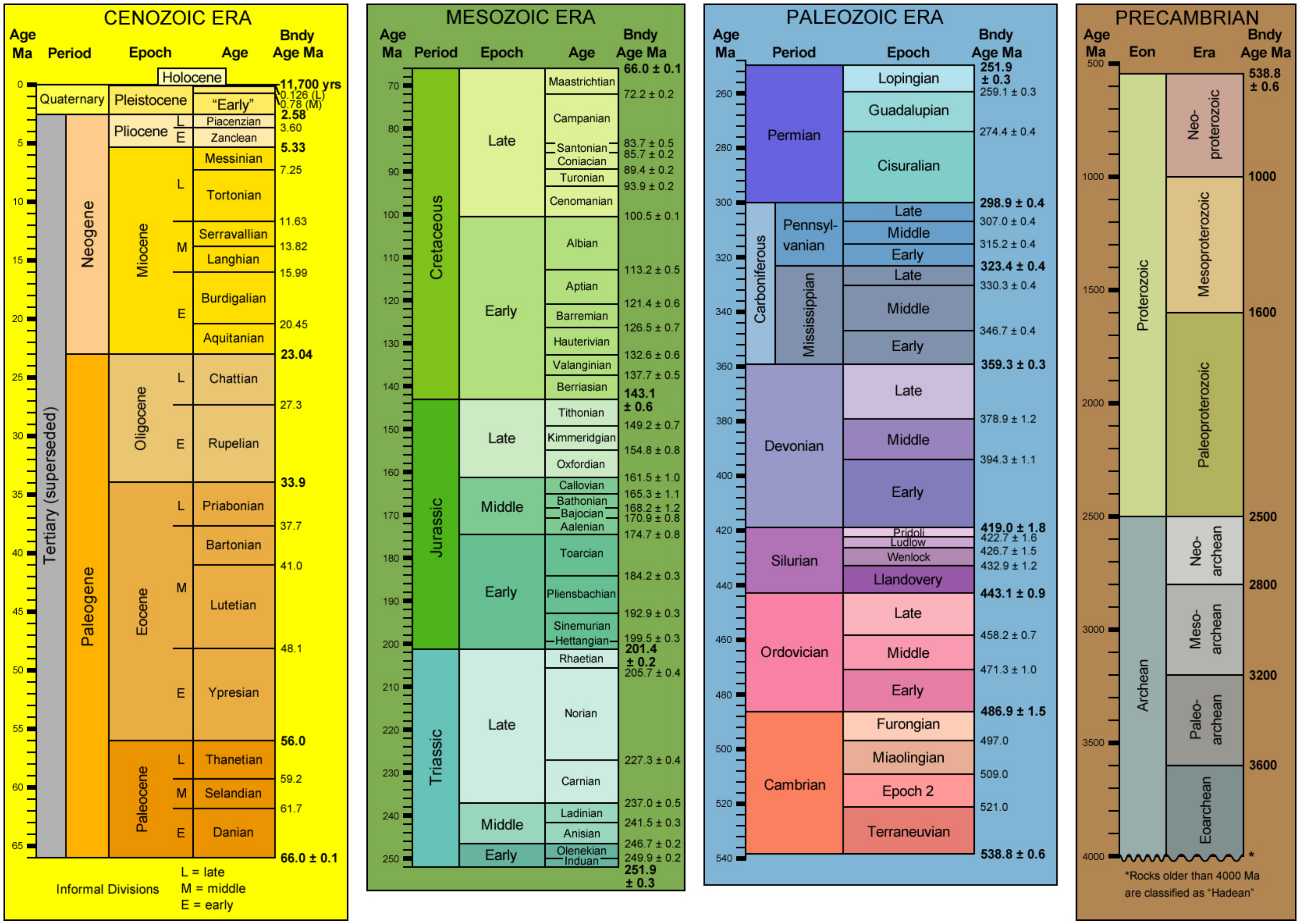

Figure B1. Geologic Time Scale. Ma=Millions of years old. Bndy Age=Boundary Age. Layout after 1999 Geological Society of America Time Scale (https://www.geosociety.org/documents/gsa/timescale/timescl-1999.pdf). Dates after Gradstein et al. (2020).

Appendix C: Stratotypes Located Within 48 km (30 mi) of NGPN Parks

AGFO

- Eocene
  - Chadron Formation, Big Cottonwood Creek Member (type area and 4 reference sections)
- Eocene–Oligocene
  - Chadron Formation (type section of Schultz and Stout 1955)
- Oligocene
  - Brule Formation (type section of Schultz and Stout 1955)
  - Brule Formation, Orella Member (type locality)
  - Brule Formation, Whitney Member (type locality)
- Miocene
  - Snake Creek Formation (type locality)
  - Snake Creek Formation, Johnson Member (type section)
  - Snake Creek Formation, Laucomer Member (type section)
  - Snake Creek Formation, Murphy Member (type section)
  - Snake Creek Formation, Spottedtail Member (type locality)
  - Sheep Creek Formation (principal reference section)
  - Olcott Formation (type section)
  - Marsland Formation (type area)
  - Marsland Formation, "Lower Member" of Yatkola (1978) (type section)
  - Box Butte Formation, Dawes Clay Member (3 reference sections)
  - Runningwater Formation (type section)
  - Monroe Creek Formation (type area and reference section)
  - Harrison Formation (type locality and reference section)

BADL

- Permian
  - Minnekahta Limestone (type locality)
- Jurassic
  - Morrison Formation, Unkpapa Sandstone Member (type locality)
- Cretaceous
  - Fuson Formation (type section)
  - Pierre Shale, Interior Beds/Interior Paleosol Complex (type area and type locality)

- Lakota Formation (type locality and reference section)
- Lakota Formation, Minnewaste Limestone Member (reference section)
- Fall River Formation (type section)

- Eocene
  - Chadron Formation, Big Cottonwood Creek Member (reference section)
  - Chamberlain Pass Formation (type section)
- Eocene–Oligocene
  - Chadron Formation (type section, principal reference section, reference section)
- Oligocene
  - Chadron Formation, Ahearn Member (type locality)
  - Chadron Formation, Crazy Johnson Member (type locality)
  - Chadron Formation, Peanut Peak Member (type locality)
  - Brule Formation (lower composite type section)
  - Brule Formation, Scenic Member (type section)
  - Sharps Formation (upper composite type section)

DETO

- Jurassic
  - Sundance Formation (type locality)
  - Sundance Formation, Hulett Sandstone Member (type section)
- Cretaceous
  - Fall River Formation, Keyhole Member (type section)
  - Pierre Shale, Mitten Member (type locality)
  - Lewis Shale, Teckla Sandstone Member, Kara Bentonite Bed (type section)

FOLA

- Devonian–Mississippian
  - Guernsey Formation (type section)
- Pennsylvanian
  - Hartville Formation, Fairbank Member (type locality)
  - Hartville Formation, Hayden Member (type locality)
  - Hartville Formation, Meek Member (type locality)
  - Hartville Formation, Reclamation Member (type locality)
  - Hartville Formation, Roundtop Member (type locality)
  - Hartville Formation, Wendover Member (type locality)

- Permian
    - Hartville Formation, Broom Creek Member (type locality)
    - Hartville Formation, Cassa Member (type locality)

JECA

- Permian
    - Minnekahta Limestone (type locality)
- Jurassic
    - Morrison Formation, Unkpapa Sandstone Member (type locality)
    - Sundance Formation, Lak Member (type section)
    - Sundance Formation, Stockade Beaver Shale Member (type section)
- Cretaceous
    - Fuson Formation (type section and reference section)
    - Lakota Formation (type locality and reference section)
    - Lakota Formation, Chilson Member (type section)
    - Lakota Formation, Minnewaste Limestone Member (reference section)
    - Fall River Formation (type section)
    - Newcastle Sandstone (type section)

KNRI

- Quaternary
    - Oahe Formation (type section)
- Pleistocene
    - Coleharbor Formation (type section)
    - Oahe Formation, Mallard Island Member (type section)
- Holocene
    - Oahe Formation, Aggie Brown Member (type section)
    - Oahe Formation, Pick City Member (type section)
    - Oahe Formation, Riverdale Member (type section)

MNRR

- Cretaceous
    - Pierre Shale, Gregory Member (type section)
    - Dakota Formation (type locality)

MORU

- Devonian–Mississippian
  - Englewood Formation (type section)
- Pennsylvanian–Permian
  - Minnelusa Formation (type section)
- Permian
  - Minnekahta Limestone (type locality)
- Cretaceous
  - Fuson Formation (type section and reference section)
  - Lakota Formation (type locality and reference section)

NIOB

- Miocene
  - Ash Hollow Formation, Cap Rock Member (type locality)
  - Ash Hollow Formation, Merritt Dam Member (type section and reference section)
  - Valentine Formation (type locality)
  - Valentine Formation, Burge Member (type locality)
  - Valentine Formation, Crookston Bridge Member (type section)
  - Valentine Formation, Devils Gulch Member (type locality)
  - Rosebud Formation (type section)
- Pliocene–Pleistocene
  - Keim Formation (type locality)
- Pleistocene
  - Long Pine Formation (type section)

SCBL

- Oligocene–Miocene
  - Gering Formation (type locality)
  - Gering Formation, Helvas Canyon Member (type locality)
  - Gering Formation, Mitchell Pass Member (type locality)
- Miocene
  - Gering Formation, Helvas Canyon Member, Carter Canyon Ash Bed (type locality)
  - Gering Formation, Mitchell Pass Member, Twin Sisters Pumice Conglomerate Bed (type locality and reference section)
  - Gering Formation, Mitchell Pass Member, Wildcat Ridge Ash Bed (type locality and reference section)

- Snake Creek Formation (type locality)
- Snake Creek Formation, Johnson Member (type section)
- Snake Creek Formation, Laucomer Member (type section)
- Snake Creek Formation, Murphy Member (type section)
- Snake Creek Formation, Spottedtail Member (type locality)
- Sheep Creek Formation (principal reference section)
- Olcott Formation (type section)

THRO

- Paleocene
  - Sentinel Butte Formation (type section)
  - Bullion Creek Formation (type section and type area)
  - Golden Valley Formation, Camels Butte Member (type section)
- Eocene
  - Chadron Formation, South Heart Member (type section)
  - Golden Valley Formation, Bear Den Member (type section)

WICA

- Pennsylvanian–Permian
  - Minnelusa Formation (type section)
- Permian
  - Minnekahta Limestone (type locality)
- Jurassic
  - Morrison Formation, Unkpapa Sandstone Member (type locality)
- Cretaceous
  - Fuson Formation (type section and reference section)
  - Lakota Formation (type locality and reference section)
  - Lakota Formation, Chilson Member (type section)
  - Lakota Formation, Minnewaste Limestone Member (reference section)
  - Fall River Formation (type section)
- Eocene
  - Chadron Formation, Big Cottonwood Creek Member (reference section)

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National Park Service
U.S. Department of the Interior

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