



# National Park Service Geologic Type Section Inventory

## *Southern Plains Inventory & Monitoring Network*

Natural Resource Report NPS/SOPN/NRR—2022/2411



**ON THE COVER**

Type area exposures of the Pleistocene Capulin Basalt that form the namesake Capulin Volcano in CAVO. Capulin Volcano is one of more than 100 volcanic features of the Raton-Clayton volcanic field. Photograph by R. D. Miller, USGS.

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Fort Collins, Colorado

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## Executive Summary

Type sections are one of several kinds of stratotypes. 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 two stratotypes designated within two park units of the Southern Plains Inventory & Monitoring Network (SOPN): Alibates Flint Quarries National Monument (ALFL) has one type locality; and Capulin Volcano National Monument (CAVO) contains one type area. Table 1 provides information regarding the two stratotypes currently identified within the SOPN.

There are currently no designated stratotypes within Bent's Old Fort National Historic Site (BEOL), Chickasaw National Recreation Area (CHIC), Fort Larned National Historic Site (FOLS), Fort Union National Monument (FOUN), Lake Meredith National Recreation Area (LAMR), Lyndon B. Johnson National Historical Park (LYJO), Pecos National Historical Site (PECO), Sand Creek Massacre National Historic Site (SAND), Waco Mammoth National Monument (WACO), and Washita Battlefield National Historic Site (WABA).

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 SOPN.

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 SOPN 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
ALFL	Alibates Dolomite (Pqwa)	Gould 1907; Fay 1965; Pabian 2007	Type locality: considered to be on Alibates Creek near latitude 35°35'39" N., longitude 101°41'08" W., Alibates Ranch 7.5' Quadrangle, northeastern Potter County, TX.	Permian
CAVO	Capulin Basalt (CZign)	Collins 1949; Scott et al. 1990	Type area: occurs at and near Capulin Volcano in section 4, T. 29 N., R. 28 E. (approximate latitude 36°46'48" N., longitude 103°57'59" W.), Union County, New Mexico. Folsom, New Mexico 7.5' Quadrangle.	Pleistocene

## Acknowledgments

Many individuals were consulted in the preparation of this report on the geologic type sections for the national parks of the Southern Plains Inventory & Monitoring Network (SOPN). 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 Vance Holliday (University of Arizona) and Matthew Zimmerer (New Mexico Institute of Mining and Technology) for review of this manuscript.

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 SOPN and various network parks including: Heidi Sosinski (SOPN), Grenade Fiedler (ALFL/LAMR), and Dale Kissner (CAVO). Heidi served as peer review coordinator for this report. Additional thanks to Michael Bozek and Don Weeks for continued support for this and other important geology projects in the former Intermountain Region of the NPS (now DOI Regions 6, 7, and 8).

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, Rebecca Port, and the Geologic Resource Inventory Team.





## Dedication

We are proud to dedicate this Southern Plains Inventory & Monitoring Network Geologic Type Section Inventory to Don Weeks, Physical Resources Program Manager for the NPS Intermountain Region (DOI Regions 6–8). While completing his M.S. in Geology, Don joined the NPS at Buffalo National River in 1985 to help develop the water quality program. Between 1988 and 1989, Don served as a term hydrologist at Big Cypress National Preserve, where he returned in 1995 as a permanent employee. In 1997, Don began work for the NPS Water Resources Division and was affiliated with the NPS Climate Change Response Program from 2010 to 2015. Beginning in 2015, Don joined the Intermountain Region to serve in his current position. Don have been a great friend to NPS geology and paleontology in the Intermountain Region parks and has supported and enhanced quite a few collaborative projects. In celebration of and in appreciation for Don’s 30-plus year career, we recognize his service through the dedication of this report in his honor.



Don Weeks, Physical Resources Program Manager for the NPS Intermountain Region (DOI Regions 6–8).



# 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 Southern Plains Inventory & Monitoring (I&M) Network (SOPN), (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 two stratotypes with two SOPN parks: Alibates Flint Quarries National Monument (ALFL) has one type locality; and Capulin Volcano National Monument (CAVO) contains one type area. Table 1 provides information regarding the two stratotypes currently identified within the SOPN. 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 SOPN 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 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 SOPN 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 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

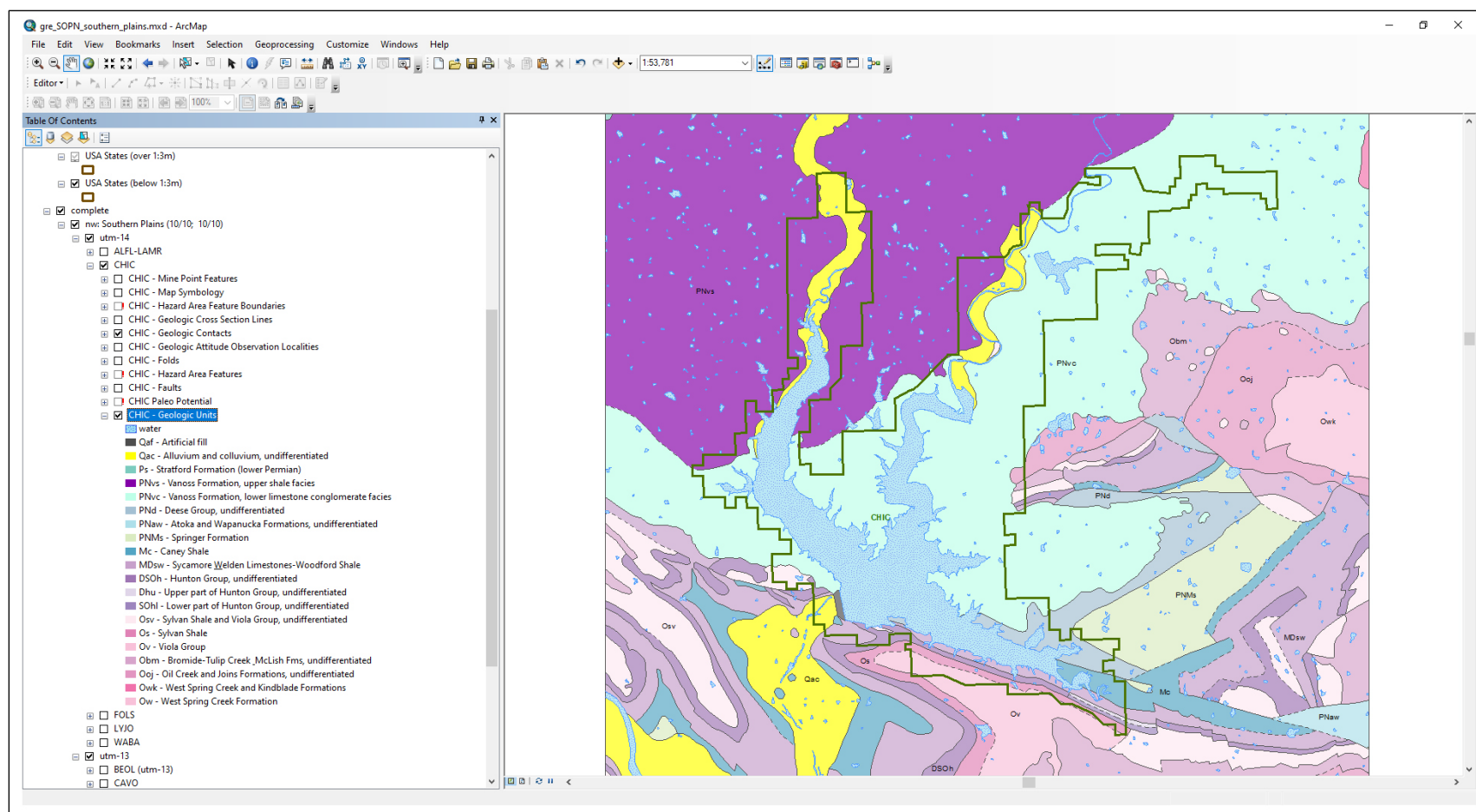
The process of determining whether a specific stratotype occurs within an NPS area involves multiple steps. The process begins with an evaluation of a park-specific Geologic Resources Inventory (GRI) map to prepare a full list of recognized map units (Figure 1). More information about the GRI data can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

Each map unit name is then 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 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 Alibates Dolomite, which is mapped within ALFL.

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<sup>2</sup> (36 mi<sup>2</sup>) township into 36 individual 2.59 km<sup>2</sup> (1 mi<sup>2</sup>) 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 "section [#], T. [#] [N. or S.], R. [#] [E. or W.].". The most accurate GEOLEX descriptions using TRS coordinates can help locate features within 0.1618 km<sup>2</sup> (0.0625 mi<sup>2</sup>). 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 Chickasaw National Recreation Area showing mapped 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?Inv=True>.

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## National Geologic Map Database

### Geolex — Unit Summary

#### Geologic Unit: Alibates

**Usage:**

Alibates Formation (TX\*)

Alibates Dolomite Lentil of Quartermaster Formation (NM\*)

[?] Alibates Dolomite Bed of Doxey Shale (OK\*)

**Geologic age:**

Early Permian\*

**Type section, locality, area and/or origin of name:**

Named from Alibates Creek, Potter Co., TX Panhandle. Occurs along Canadian River, Texas Panhandle (US geologic names lexicons, USGS Bull. 896, 1200). Type locality considered to be on Alibates Creek near Lat. 35 deg. 35 min. 39 sec. N., Long. 101 deg. 41 min. 08 sec. W., Alibates Ranch 7.5-min quadrangle, Potter Co., TX Panhandle. [From R.K. Pabian, 2007, Agate Lexicon, Univ. Nebraska-Lincoln; available online <http://snr.unl.edu/Data/AgateLexicon.asp>]

**AAPG geologic province:**

Anadarko basin\*

Palo Duro basin\*

**Significant Publications**

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- [GNC Archives](#)
- [N.A. Stratigraphic Code](#)
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For more information, please contact [Nancy Stamm](#), Geologic Names Committee Secretary.

Asterisk (\*) indicates published by U.S. Geological Survey authors.

"No current usage" (†) implies that a name has been abandoned or has fallen into disuse. Former usage and, if known, replacement name given in parentheses ().

Slash (/) indicates name does not conform with nomenclatural guidelines (CSN, 1933; ACSN, 1961, 1970; NACSN, 1983, 2005). This may be explained within brackets ([ ]).

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**Figure 2.** GEOLEX search result for the Alibates Dolomite.

AutoSave Off SOPN Type Section Inventory Search (Alt+Q) Timothy Henderson

File Home Insert Page Layout Formulas Data Review View Help

Clipboard Font Alignment Number Styles Cells Editing Analysis

A38 Olcott Formation

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
	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	Alluvium	X							Cenozoic	Holocene		NO	Qal	
3	Windblown sand, sheet	X							Cenozoic	Holocene		NO	Qs	
4	Windblown sand, dunes	X							Cenozoic	Holocene		NO	Qsd	
5	Fluviatile terrace deposits	X							Cenozoic	Pleistocene		NO	Qt	
6	Playa deposit	X							Cenozoic	Pleistocene		NO	Qp	
7	Loess	X							Cenozoic	Pleistocene		NO	Ql	
8	Blackwater Draw Formation		NO		Type section: outcrop on the w	Reeves 1976; Barnes 1983, 1993			Cenozoic	Pleistocene		YES	Qbd	
9	Ogallala Formation		NO		Type section: on Feldt Ranch, in	Hesse 1935			Cenozoic	Pliocene		YES	To	
10	Trujillo Formation	X	NO			Gould 1907			Mesozoic	Triassic		YES	TRdj	Named from
11	Tecovas Formation	X	NO			Gould 1907			Mesozoic	Triassic	Dockum C	YES	TRdv	Named from
12	Quartermaster Formation	X	NO			Gould 1902			Paleozoic	Permian		YES	Pqw	Named from
13	Cloud Chief Gypsum		NO		Type locality: exposed near tow	Gould 1924; Green 1936			Paleozoic	Permian		YES	Pqw	Typically ex
14	Whitehorse Sandstone		NO		Type section: SE/4 SE/4 sec. 8,	Fay 1965			Paleozoic	Permian		YES	Pqw	
15	Alibates Dolomite		YES - ALFL	YES		Gould 1907; Fay 1965; Pabian 20	Type locality: considered to l		Paleozoic	Permian		YES	Pqwa	
16														
17														
18														
19	<a href="#">Bulletins (ou.edu)</a>													
20	UNITS BELOW THIS ROW ARE NOT INCLUDED IN NPS GRI STRAT LISTING BUT ARE FOUND IN PROXIMITY TO PARK UNIT BOUNDARIES													
21	Ash Hollow Formation		NO		Type section: exposures in Ash	Engelmann, 1876; Lugn, 1938, 1939			Cenozoic	Miocene	Ogallala G	YES		
22	Box Butte Formation		NO		Type section: in sec. 27, T. 28 N	Cady 1940; Galusha 1975			Cenozoic	Miocene	Ogallala G	YES		
23	Ogallala Formation, Bridwell Member		NO		Type locality: exposures on the	Evans 1949			Cenozoic	Pliocene		YES		
24	Valentine Formation, Burge Member		NO		Type locality: Burge quarry, [on	Johnson 1936			Cenozoic	Miocene	Ogallala G	YES		
25	Ash Hollow Formation, Cap Rock Member		NO		Type locality (=Burge type): Bur	Skinner et al. 1968			Cenozoic	Miocene	Ogallala G	YES		
26	Valentine Formation, Cornell Dam Member		NO		Type section: roadcut a few mi	Skinner and Johnson 1984			Cenozoic	Miocene	Ogallala G	YES		
27	Ogallala Formation, Couch Member		NO		Type locality: about 7 mi east o	Evans 1949			Cenozoic	Miocene		YES		
28	Valentine Formation, Crookston Bridge Member		NO		Type section: Crookston Bridge	Johnson 1936; Skinner et al. 1968			Cenozoic	Miocene	Ogallala G	YES		
29	Box Butte Formation, Cowie Clay Member		NO		Type section: on SW 1/4 Sec. 10	Galusha 1975			Cenozoic	Miocene	Ogallala G	YES		

ALFL-LAMR BEOL CAVO CHIC FOLS FOUN LYJO PECO SAND WABA WACO

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**Figure 3.** Stratotype inventory spreadsheet of SOPN displaying attributes appropriate for geolocation assessment.

## **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 datasets for the SOPN 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 that 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 transcend state boundaries. Geologic formations and other units that cross state boundaries may have different names in each of the states the units are mapped. For example, what is

identified as the Fort Union Formation in Montana is identified as the Fort Union Group in North Dakota.

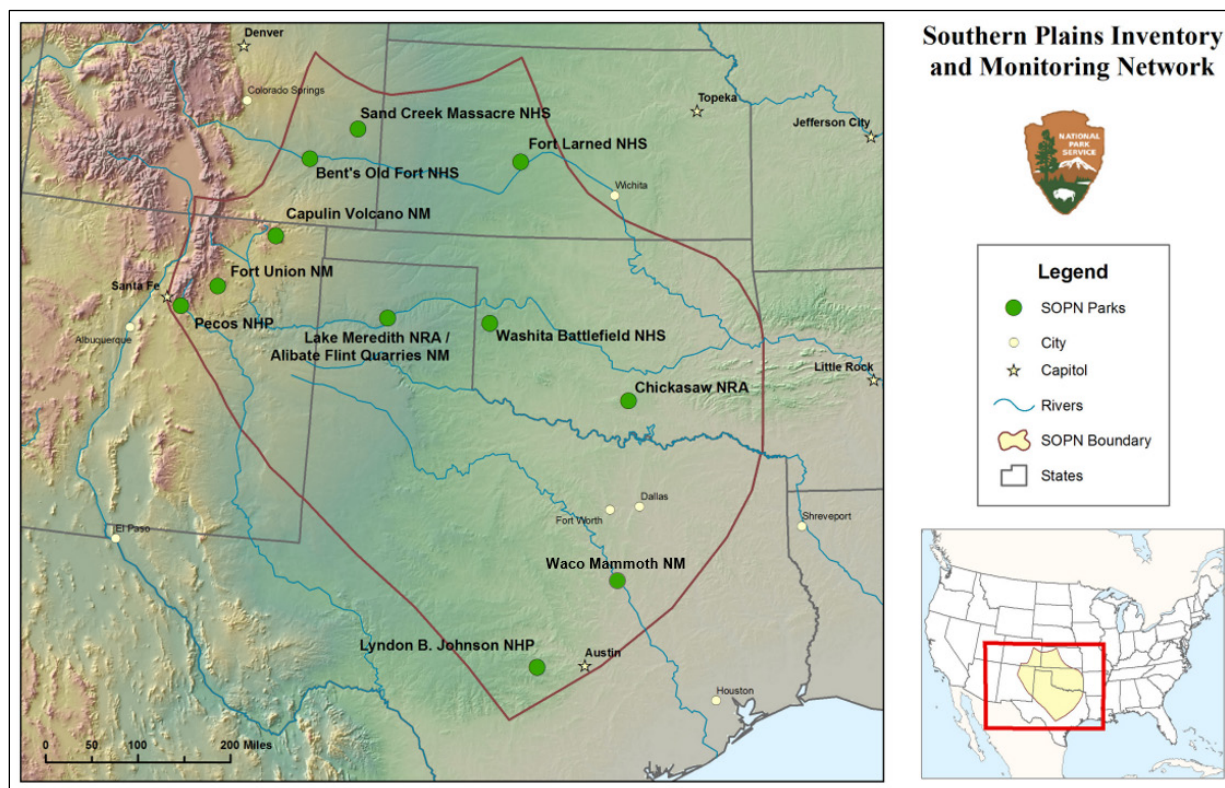
The lack of a designated and formal type section, or inadequate and vague geospatial information associated with a type section, limits the ability to capture precise information for this inventory. The available information related to the geologic type sections is included in this report.

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 NPS areas.

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 SOPN I&M Network Parks

The Southern Plains Inventory & Monitoring Network (SOPN) consists of 12 national park units in southeastern Colorado, northeastern New Mexico, western Kansas, Oklahoma, and north and central Texas (Figure 4). These units are Alibates Flint Quarries National Monument (ALFL), Bent's Old Fort National Historic Site (BEOL), Capulin Volcano National Monument (CAVO), Chickasaw National Recreation Area (CHIC), Fort Larned National Historic Site (FOLS), Fort Union National Monument (FOUN), Lake Meredith National Recreation Area (LAMR), Lyndon B. Johnson National Historical Park (LYJO), Pecos National Historical Park (PECO), Sand Creek Massacre National Historic Site (SAND), Waco Mammoth National Monument (WACO), and Washita Battlefield National Historic Site (WABA). The parks that comprise the SOPN protect a combined 32,596 hectares (80,548 acres) of wilderness and vary in size from 43 hectares (107 acres) in WACO to 18,201 hectares (44,978 acres) in LAMR.



**Figure 4.** Map of Southern Plains I&M Network parks, including: Alibates Flint Quarries National Monument (ALFL), Bent's Old Fort National Historic Site (BEOL), Capulin Volcano National Monument (CAVO), Chickasaw National Recreation Area (CHIC), Fort Larned National Historic Site (FOLS), Fort Union National Monument (FOUN), Lake Meredith National Recreation Area (LAMR), Lyndon B. Johnson National Historical Park (LYJO), Pecos National Historical Park (PECO), Sand Creek Massacre National Historic Site (SAND), Waco Mammoth National Monument (WACO), and Washita Battlefield National Historic Site (WABA) (NPS).



Geographically, the southern Great Plains is an immense sweep of country that reaches from south-central Texas to the northern border of Kansas and spreads out east of the Rocky Mountains. There is often a misconception of the Great Plains as a drab, flat, featureless area, when in fact the region encompasses a suite of diverse geologic landscapes that include canyons carved into solid rock by the waters of the Pecos River, the seemingly endless grainfields of Kansas, the precipitous peaks of the Sangre de Cristo Mountains, and the volcanic terranes of New Mexico.

Most of the park units of the SOPN occupy one of several sections of the Great Plains physiographic province such as the Central Texas Uplift (LYJO, WACO), High Plains (ALFL, LAMR, SAND), Pecos Valley (PECO), Raton (CAVO, FOUN), Colorado Piedmont (BEOL), and Plains Border (FOLS). The Central Texas Uplift is a forested prominence at the southern end of the Great Plains. The High Plains is characterized by an expansive, nearly flat plateau that extends from the Texas Panhandle north to Nebraska and forms the central backbone of the Great Plains. The South Platte and Arkansas Rivers and their tributaries have dissected an area along the Rocky Mountain front that is called the Colorado Piedmont. The Pecos Valley section is a broad excavated valley of the Pecos River that stretches southward from the Sangre de Cristo Mountains in New Mexico into Texas. Green, crop-filled valleys with gently sloping valley walls and rounded stream divides trend eastward from the High Plains of western Kansas and characterize the Plains Border section (Trimble 1980). Situated between the Colorado Piedmont on the north and the Pecos Valley on the south are the volcanic vents, cinder cones, and lava fields that define the distinctive Raton section.

The mountainous sections of the southern Great Plains were formed long before the remaining areas were outlined by erosion. One of the oldest structural features is the Llano Uplift, which represents the crystalline core of a mountain belt produced during the Precambrian (see Appendix B for a geologic time scale). Basement uplifts such as the Arbuckle and Amarillo were formed around the Pennsylvanian–Permian during the final collisional stages that resulted in the supercontinent Pangea. The Central Texas Uplift began as the continental interior was raised and the last Cretaceous inland sea retreated approximately 70 million to 65 million years ago. These regions stood well above the surrounding plains long before any sediments from the distant Rocky Mountains began to accumulate at their bases (Trimble 1980).

In southern Colorado and northern New Mexico, molten rock (magma) was emplaced into older Precambrian basement rocks and Paleozoic and Mesozoic sedimentary strata during the Oligocene (~29 million and 22 million years ago), leading to widespread volcanic eruptions. Another pulse of intermittent volcanism began about 9 million years ago during the Miocene, with eruptions as young as 37 thousand years ago associated with the Raton-Clayton volcanic field (CAVO) and Ocaté volcanic field (FOUN). A thick sequence of basalt flows accumulated at Raton Mesa and Mesa de Maya between 8 million and 2 million years ago. The archetype cinder cone of Capulin Volcano was created by a violent eruption during the Pleistocene only 54,000 years ago (Trimble 1980; KellerLynn 2015a). Many of these volcanic masses were present before major downcutting by streams began, which provided huge quantities of sediment that were subsequently transported to the plains and deposited. Regional uplifts that occurred between 10 and 5 million years ago enhanced stream incision that sculpted the modern landscape of the Colorado Piedmont, Pecos Valley, and



Plains Border sections. Many of the individual landforms of the southern Great Plains that now attract the eye have been created by geologic processes during the last 2 million years (Trimble 1980).

### **Precambrian (4.6 billion to 541 million years ago)**

Precambrian basement rocks are found in only one park of the SOPN, underlying the western portion of the Cañoncito subunit in PECO. These ancient igneous and metamorphic rocks date to the Paleoproterozoic Era (2.5 to 1.6 billion years ago) and consist of granite to granitic gneiss.

### **Paleozoic (541 to 252 million years ago)**

Paleozoic strata are mapped in nearly half of the park units of the SOPN, with some of the oldest exposures represented by the Cambrian Wilberns Formation in LYJO. A thick sequence of Ordovician rocks occurs in CHIC and includes the Simpson Group (Joins, Oil Creek, McLish, Tulip Creek, and Bromide Formations), Viola Group, and Sylvan Shale. These are followed by the Silurian–Devonian Hunton Group (Cochrane, Clarita, Henryhouse, Haragan, and Bois d’Arc Formations). The later Devonian is represented by the Woodford Shale in CHIC. Mississippian sedimentary rocks also underlie CHIC and consist of the Sycamore Limestone, Caney Shale, and Springer Formation. Pennsylvanian strata are mapped in two park units of the SOPN and include the Deese Group, Collings Ranch Conglomerate, and Vanoss Formation in CHIC, as well as the Alamitos and Sangre de Cristo Formations at PECO. Rocks of the Permian Period are represented by the Alibates Dolomite and Quartermaster Formation in ALFL/LAMR, the Yeso Formation, Glorieta Sandstone, San Andres Formation, and Artesia Formation in PECO, and the Cloud Chief and Doxey Formations in WABA.

### **Mesozoic (252 to 66 million years ago)**

Rocks of the Mesozoic Era form the bedrock of six park units of the SOPN. Triassic-age strata of the Tecovas and Trujillo Formations are found in southern LAMR, and Triassic rocks of the Moenkopi, Santa Rosa, and Chinle Formations are found in the Cañoncito subunit at PECO. The Cretaceous Period is represented by the Greenhorn Limestone in BEOL, Graneros Shale in FOUN, Shingle Hills Formation in LYJO, and the Niobrara Formation in SAND.

### **Cenozoic (66 million years ago to the present)**

Cenozoic strata are mapped in every park unit of the SOPN, with formally named units that include the Neogene Ogallala Formation in ALFL/LAMR, Pleistocene Broadway Alluvium in BEOL, and the Pleistocene Capulin Basalt in CAVO. Geologically young, Quaternary-age surficial deposits include alluvium (BEOL, CHIC, FOLS, FOUN, LAMR, LYJO, PECO, SAND, WACO), colluvium (CHIC, PECO), fluvial river terraces (ALFL/LAMR, PECO, WABA, WACO), terrace valley fill (FOLS), floodplain deposits (WABA), loess (FOLS), and eolian sand deposits or paleodunes (LAMR, SAND, WABA).



# **Alibates Flint Quarries National Monument (ALFL)**

## **Park Establishment**

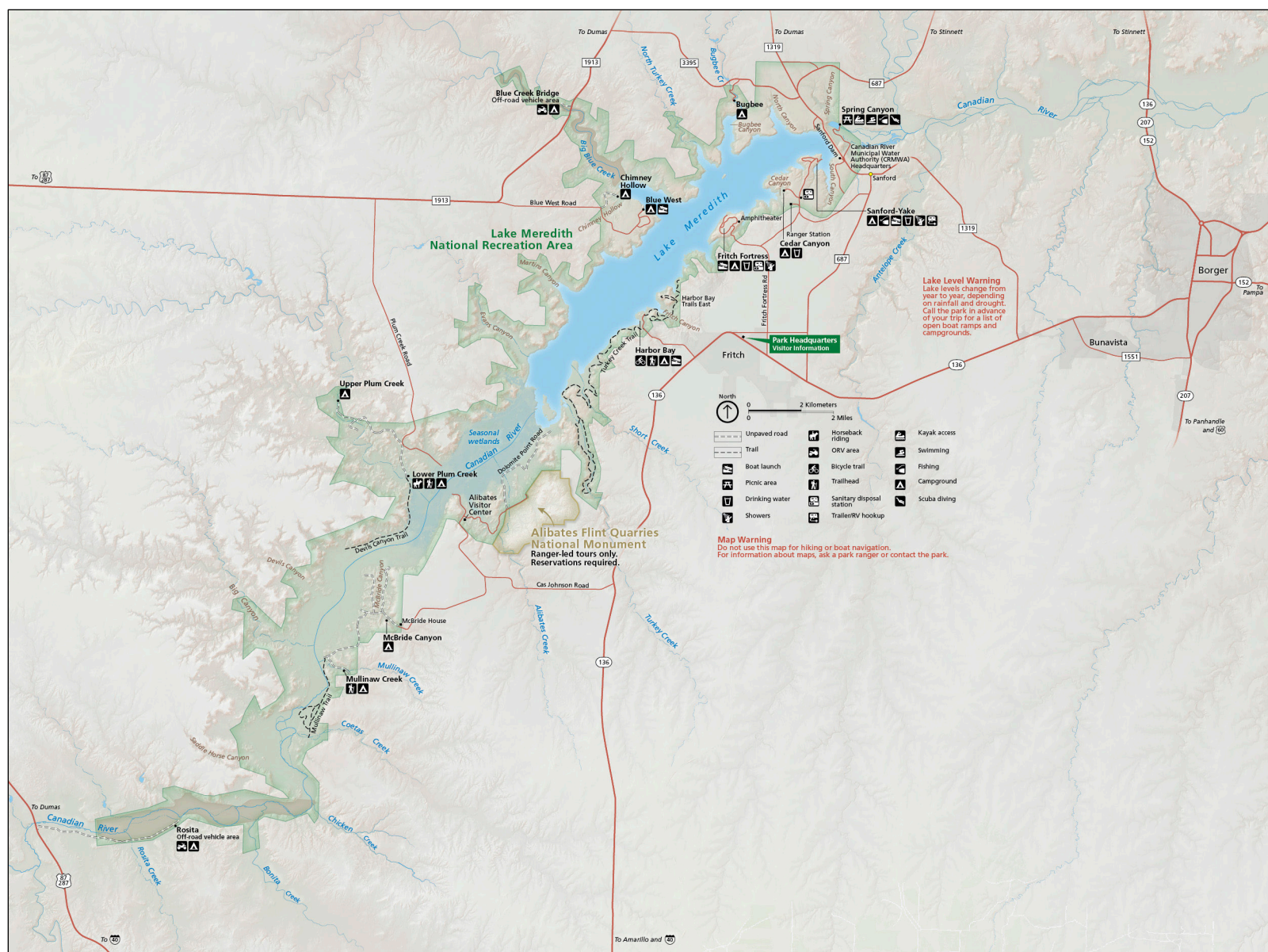
Alibates Flint Quarries National Monument (ALFL) is located adjacent to Lake Meredith National Recreation Area (LAMR) about 8 km (5 mi) southwest of Fritch in Potter County, Texas (Figure 5). Originally authorized as Alibates Flint Quarries and Texas Panhandle Pueblo Culture National Monument on August 21, 1965, the park unit was redesignated as a national monument on November 10, 1978 (National Park Service 2016a). Encompassing approximately 554 hectares (1,371 acres), ALFL was established for the preservation and scientific study of Alibates flint deposits associated with the activities and cultural resources of Native American civilizations dating back more than 13,000 years. Situated in the red bluffs overlooking the Canadian River in the ALFL region are relatively high concentrations of the Alibates Dolomite (or Alibates Flint), a colorful agatized dolomite that was a desirable tool-making material as it holds a hard sharp edge and has a distinctive color pattern. ALFL contains approximately 700 quarry pits that provide opportunities for scientific research of aboriginal quarrying techniques (National Park Service 2014a). The monument also contains a series of petroglyphs and Plains Village archeological sites that include the only protected type-site for the Antelope Creek people, who occupied the region between 1150 and 1450 AD.

## **Geologic Summary**

ALFL is situated in the High Plains section of the Great Plains physiographic province, with prominent landscape features that include upland hills, ridges, and canyons. The Northern and Southern High Plains region of the Texas Panhandle are divided by the Canadian River Valley, which flows eastward from the Sangre de Cristo Mountains into the western part of LAMR, and onward to Oklahoma (KellerLynn 2015b). The bedrock underlying ALFL consists of the Permian Quartermaster Formation, Permian Alibates Dolomite, and Neogene Ogallala Formation, with younger Quaternary-age fluvial terrace deposits mapped along Alibates Creek (Figure 6). In many places the Alibates Dolomite has been replaced by silica in a process called “chertification”, creating the multi-hued, mottled, or banded Alibates agate that was mined by Native American communities from more than 700 quarries. Boulders of the Alibates Dolomite found in ALFL provided a medium for Native American peoples to carve or peck petroglyphs, leaving behind rare archeological resources in the Texas Panhandle region (KellerLynn 2015b).

## **Stratotypes**

ALFL contains one identified stratotype that represents the Permian Alibates Dolomite (Table 2; Figure 7).



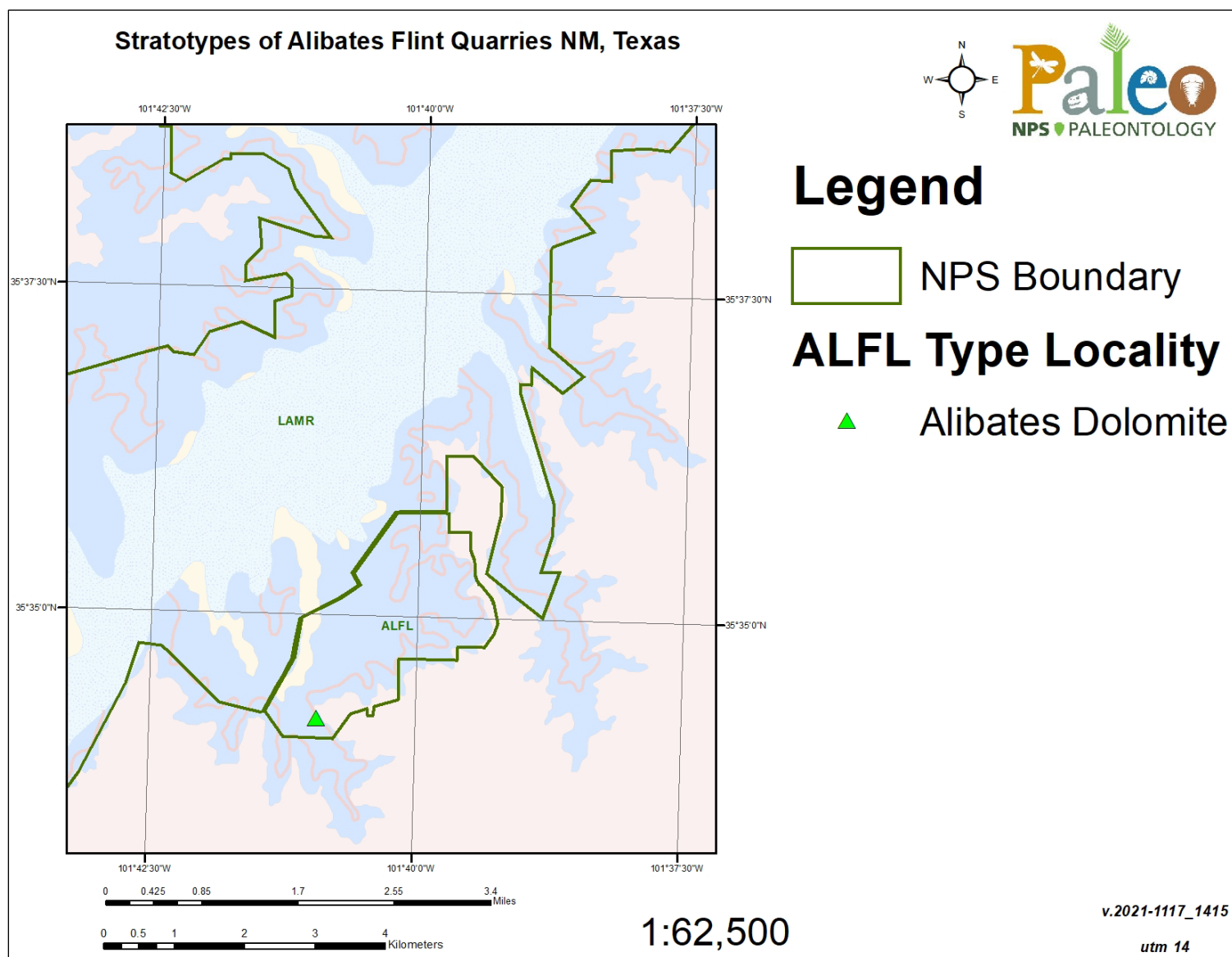
**Figure 5.** Park map of ALFL and LAMR, Texas (NPS).



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

Unit Name (GRI map symbol)	Reference	Stratotype Location	Age
Alibates Dolomite (Pqwa)	Gould 1907; Fay 1965; Pabian 2007	Type locality: considered to be on Alibates Creek near latitude 35°35'39" N., longitude 101°41'08" W., Alibates Ranch 7.5' Quadrangle, northeastern Potter County, TX.	Permian





**Figure 7.** Modified geologic map of ALFL showing a stratotype location. The transparency of the geologic units layer has been increased.

### ***Alibates Dolomite***

The Permian Alibates Dolomite was first introduced by Gould (1907) as the “Alibates dolomite lentil” of the Quartermaster Formation. The formation is named after its type locality exposures along Alibates Creek in northeastern Potter County, Texas (Table 2; Figure 7; Fay 1965; Pabian 2007 citing Gould 1907). Type locality exposures measure approximately 4.5 m (15 ft) thick and consist of two white, massive dolomite beds separated by 1.5 m (5 ft) of orangish-brown shale and siltstone (Gould 1907; Fay 1965). The thicker basal dolomite bed is about 2.4 m (8 ft) thick, and the upper dolomite bed varies from 0.6–1.5 m (2–5 ft) thick. In the type locality the Alibates Dolomite occurs within the upper interval of the Quartermaster Formation and forms a very persistent ledge that in some places caps the steep bluffs overlooking the Canadian River (Figures 8 and 9; Gould 1907; Bowers and Reaser 1996). In many places the Alibates Dolomite has been replaced by silica, creating the colorful Alibates agate that was popular among Native American cultures for making tools and jewelry (Figure 10).

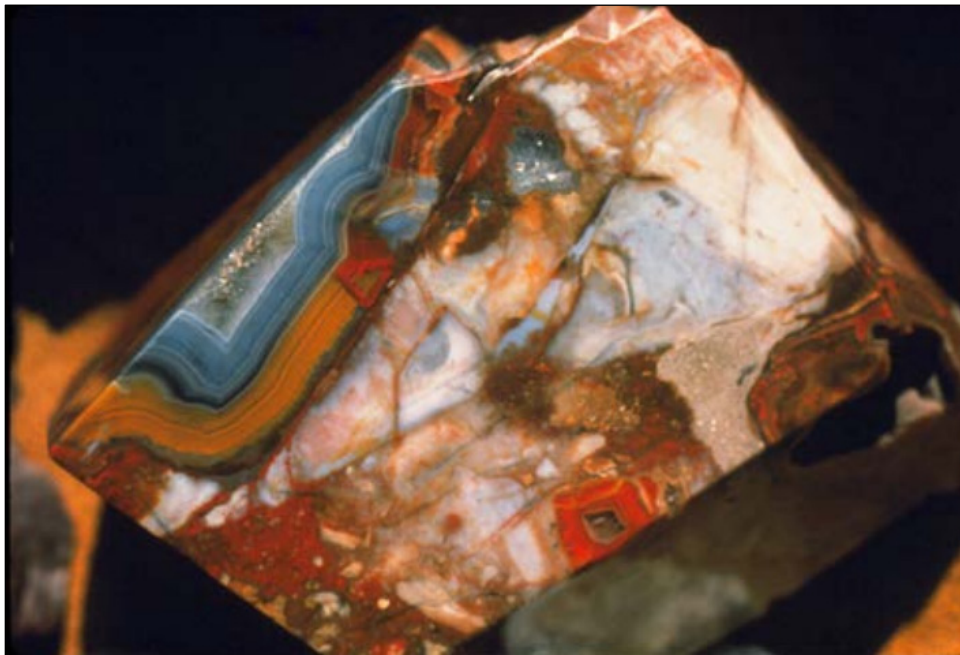


**Figure 8.** View looking southeast at bluff exposures along the Canadian River near the type locality of the Alibates Dolomite. Type locality exposures form a very persistent ledge that caps the steep bluffs in many places (NPS).





**Figure 9.** Exposures of Alibates flint on the bluffs at ALFL (NPS).



**Figure 10.** Photograph of a cut and polished sample of Alibates flint. Alibates flint formed as silica replaced dolomite in a process called chertification, creating colors of red, orange, yellow, blue, and green based on trace elements present within the silica (NPS).



## **Bent's Old Fort National Historic Site (BEOL)**

### **Park Establishment**

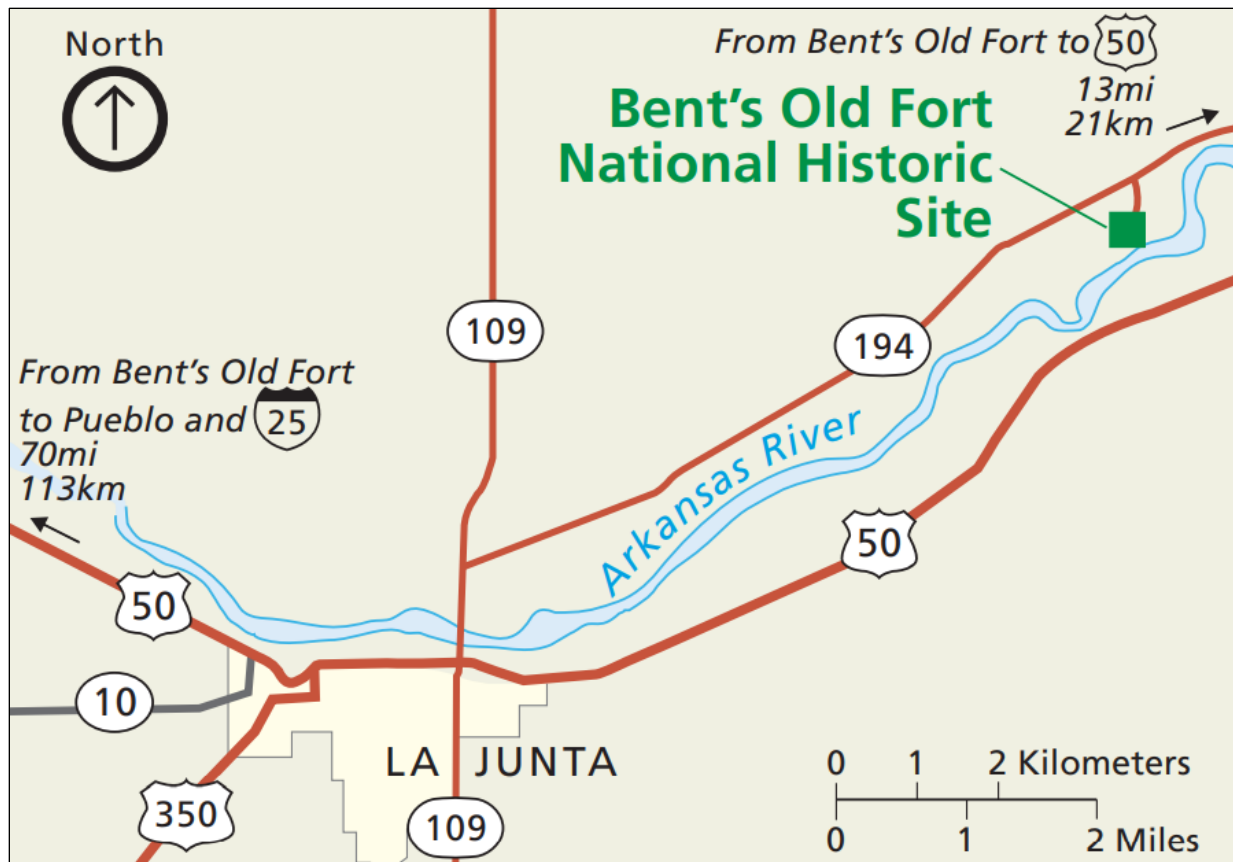
Bent's Old Fort National Historic Site (BEOL) is located on the Arkansas River about 153 km (95 mi) southeast of Colorado Springs in Otero County, southeastern Colorado (Figure 11). Authorized on June 3, 1960, BEOL contains approximately 323 hectares (799 acres) and commemorates the historic Bent's Fort (or Fort William) trading post and the international Santa Fe Trail (itself recognized via the Santa Fe National Historic Trail; SAFE). Between 1833 and 1849, the fort was an important fur trade staging point on the Santa Fe Trail that played a role in the "opening of the West" as U.S. interests expanded into the American Southwest (National Park Service 2016a). As the first permanent trading post established on the Santa Fe Trail, the fort represented a vital trade center where Native American peoples and trappers exchanged furs for other goods. The strategic location of Bent's Fort between Mexico and the Southern Plains tribes, coupled with the trading company's diplomacy and influence, integrated the Southwest into a global economy reaching from the United States to Mexico, Europe, and Asia (National Park Service 2013).

### **Geologic Summary**

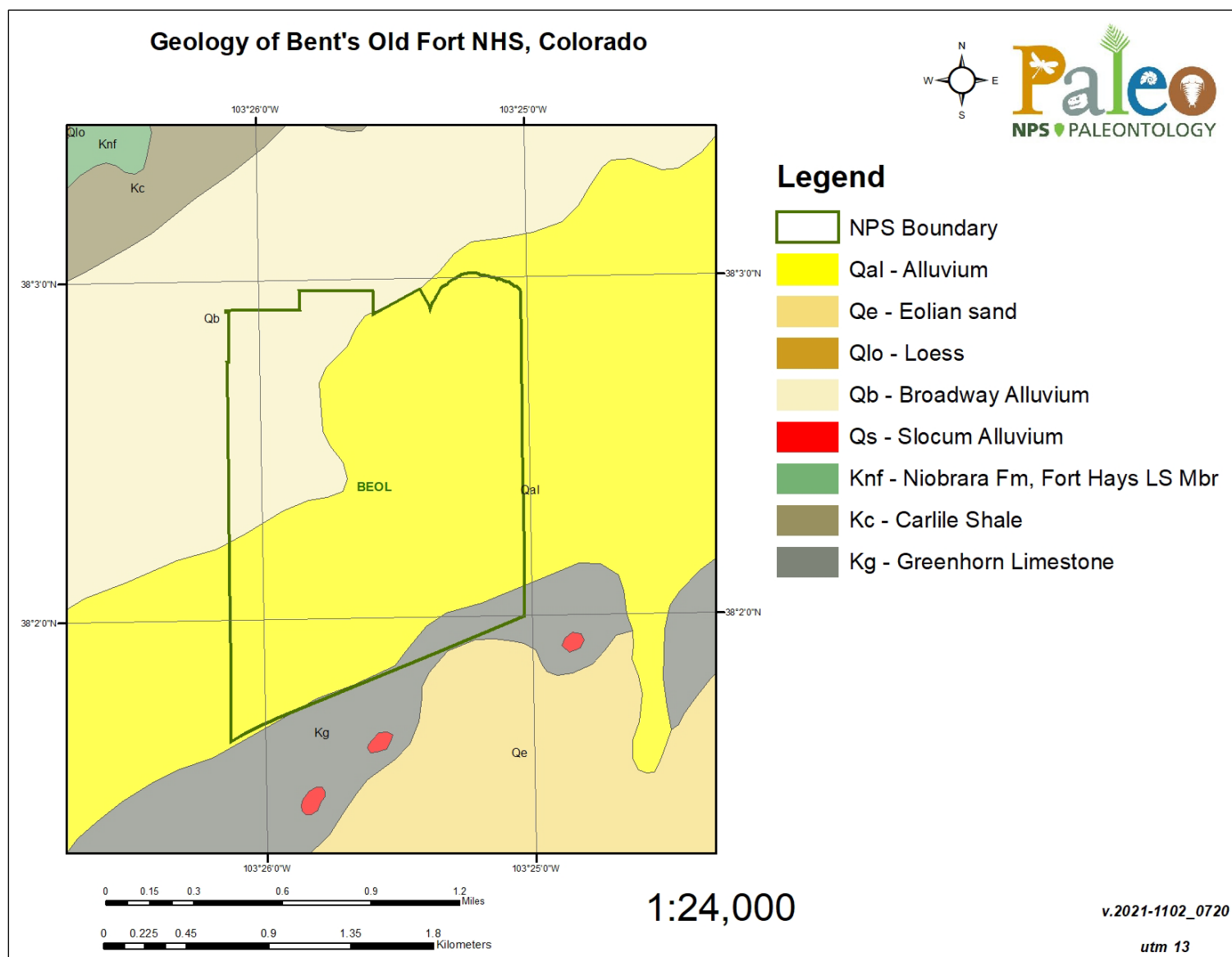
BEOL is situated in the Colorado Piedmont section of the Great Plains physiographic province, a region governed by stream dissection and preferential erosion that formed a landscape of flat to gently rolling surfaces with steep intervening slopes. In general, the Great Plains contains thick layers of rock that formed in marine and fluvial settings. Following deposition, these sedimentary rocks were affected by tectonic movements, carved by streams, dissolved by groundwater, and slowly abraded by winds. All of these geologic processes have played important roles in shaping the landscape of the Great Plains, but streams have been the most influential (KellerLynn 2005). The bedrock geology of BEOL consists of Cretaceous Greenhorn Limestone mapped in the southernmost portion of the historic site, with Quaternary-age Broadway Alluvium underlying the northwestern corner of the historic site. A large portion of BEOL is covered by a veneer of Quaternary alluvium (Figure 12).

### **Stratotypes**

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



**Figure 11.** Regional map of BEOL, Colorado (NPS).



**Figure 12.** Geologic map of BEOL, Colorado. Data modified from BEOL GRI digital geologic map data at <https://irma.nps.gov/DataStore/Reference/Profile/2259369>.



# Capulin Volcano National Monument (CAVO)

## Park Establishment

Capulin Volcano National Monument (CAVO) is located just north of the town of Capulin and about 209 km (130 mi) northeast of Santa Fe in Union County, northeastern New Mexico (Figure 13). Initially proclaimed as Capulin Mountain National Monument on August 9, 1916, the monument was renamed on December 31, 1987. Encompassing about 320 hectares (793 acres), CAVO was established to preserve and interpret the scientific values, geologic integrity, and volcanic features resulting from the creation of Capulin Volcano (National Park Service 2014b). Situated in the dormant Raton-Clayton volcanic field, Capulin Volcano is one of more than 100 volcanic features and represents a geologically young cinder cone that erupted approximately 54,000 years ago (KellerLynn 2015a; Zimmerer 2019). The monument contains the symmetrical namesake cinder cone and associated lava flows that extend beyond the monument boundary and cover an area of about 40 km<sup>2</sup> (16 mi<sup>2</sup>). Capulin Volcano is one of the most accessible extinct volcanoes in the world, with trails leading around the 1.6 km (1 mi) rim that provide unobstructed panoramic views of the volcanic field and the distant Sangre de Cristo Mountains.

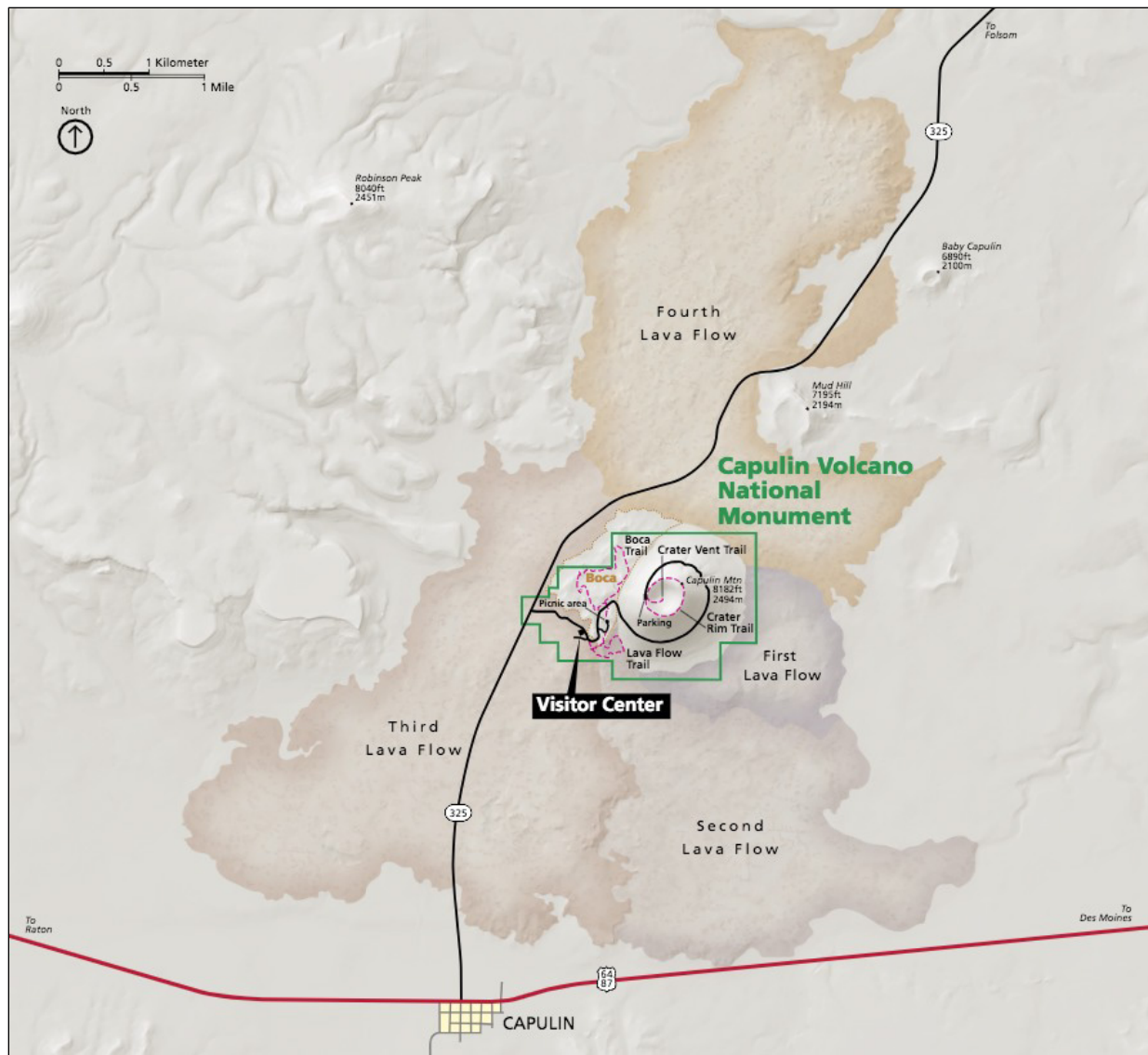
## Geologic Summary

CAVO is situated in the middle of the Raton section of the Great Plains physiographic province, an area dominated by the Raton-Clayton volcanic field. Volcanic rocks of the Raton section form peaks, mesas, and cones that have blanketed older sedimentary rocks and shielded them from the erosion that has cut deeply into the adjoining Colorado Piedmont to the north and Pecos Valley to the south (Trimble 1980). The Raton-Clayton volcanic field was active beginning in the Miocene, with three notable eruptive phases: 1) Raton phase, which had two distinct episodes (9.0–7.3 million years ago and 5.6–3.5 million years ago); 2) Clayton phase (3.0–2.2 million years ago); and 3) Capulin phase (1.69 million–37,000 years ago) (Stroud 1997; Zimmerer 2019). The primary geologic feature at CAVO is Capulin Volcano, one of the tallest and most symmetrical cinder cones in North America standing approximately 2,500 m (8,200 ft) above sea level and nearly 400 m (1,300 ft) above the surrounding plain (KellerLynn 2015a). During the Pleistocene Epoch about 54,000 years ago, Capulin Volcano erupted, producing a series of extensive lava flows and pyroclastic deposits that include cinders, ash, and volcanic bombs (Figures 14 and 15). The bedrock underlying CAVO and the surrounding area is composed entirely of a single formally named igneous unit—the Capulin Basalt.

## Stratotypes

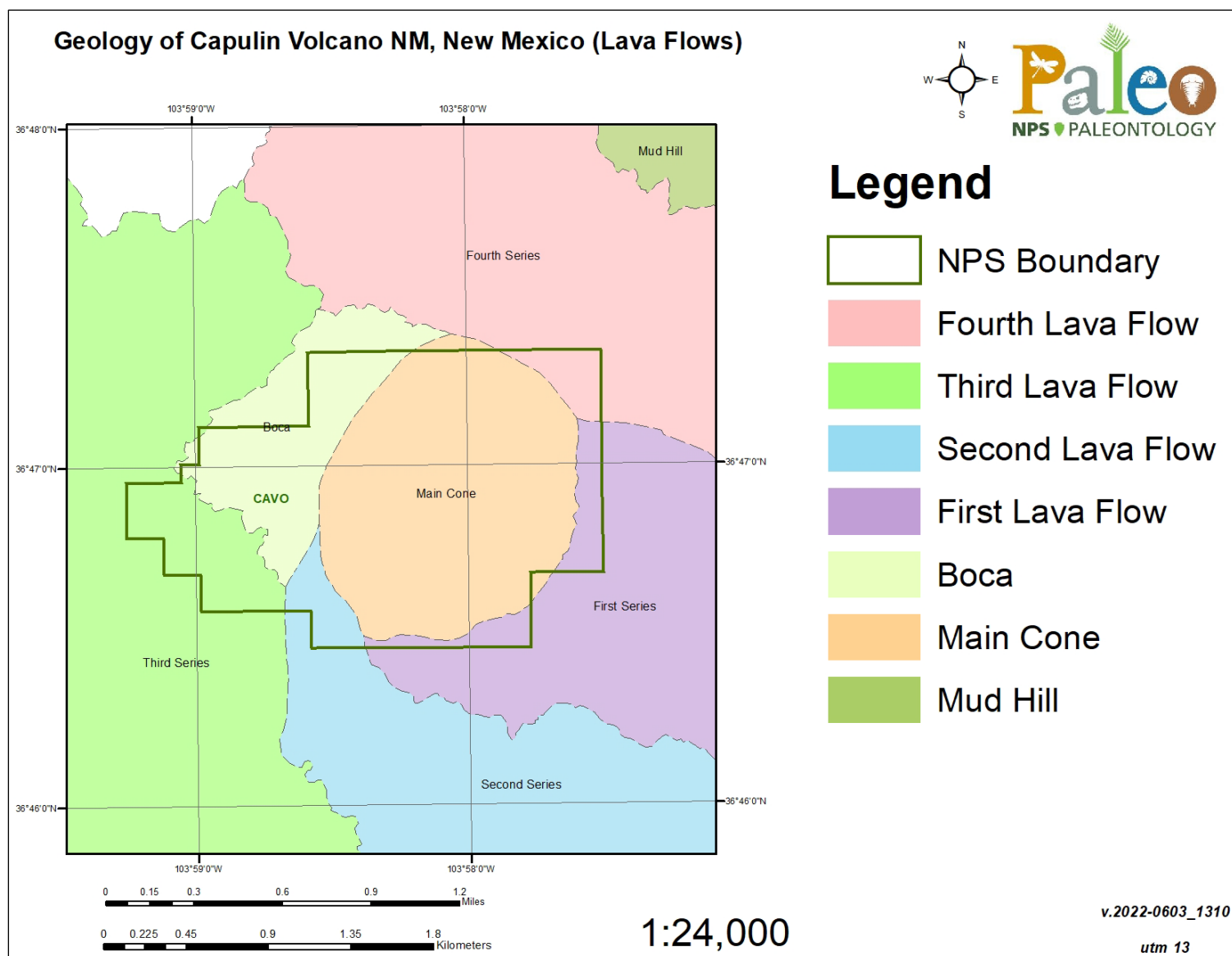
CAVO contains one identified stratotype that represents the Pleistocene Capulin Basalt (Table 3; Figure 16). In addition to the designated stratotype located within CAVO, there are five identified stratotypes located within 48 km (30 mi) of CAVO boundaries that are provided in Appendix C for reference in case of future monument boundary expansion.



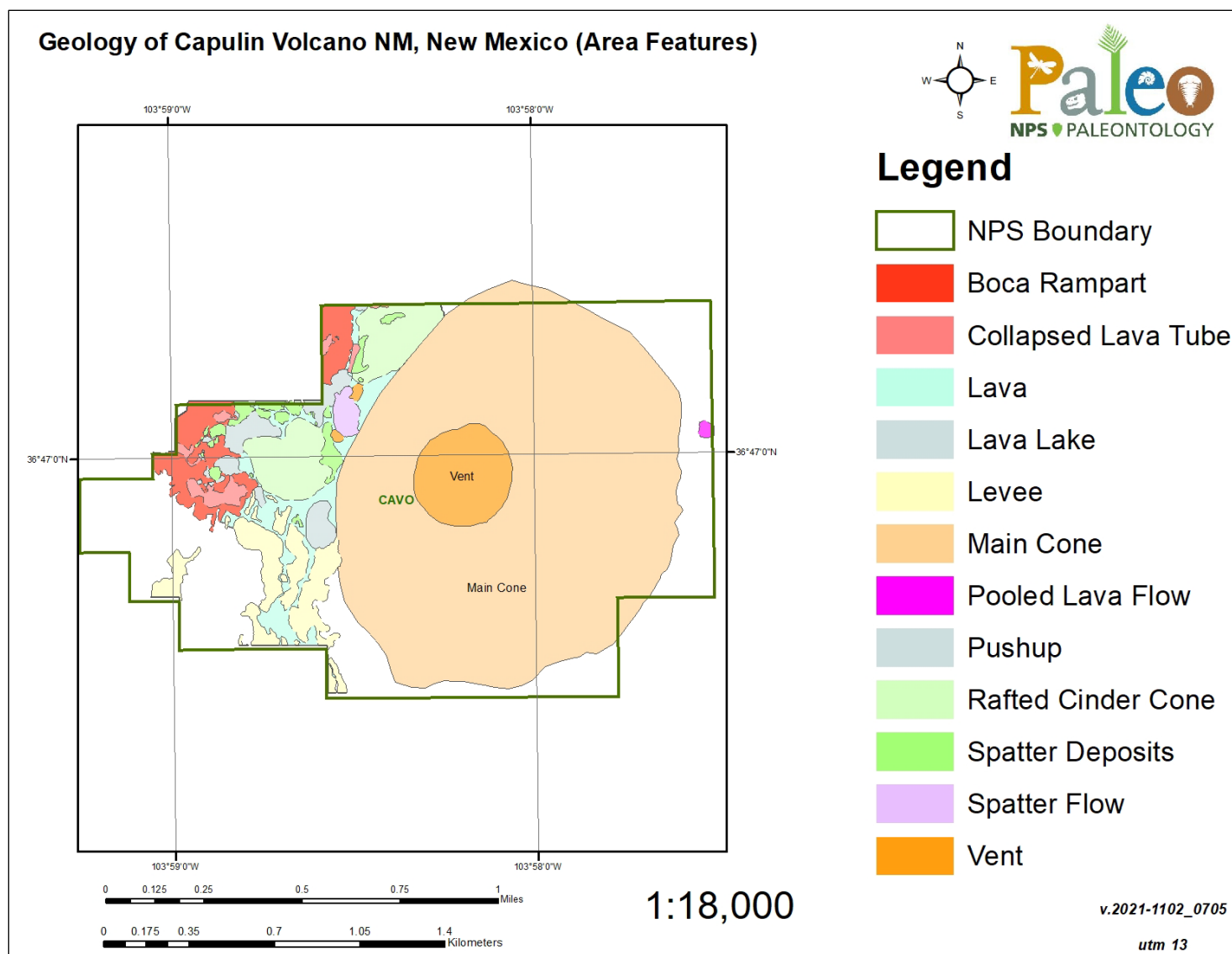


**Figure 13.** Park map of CAVO, New Mexico (NPS).





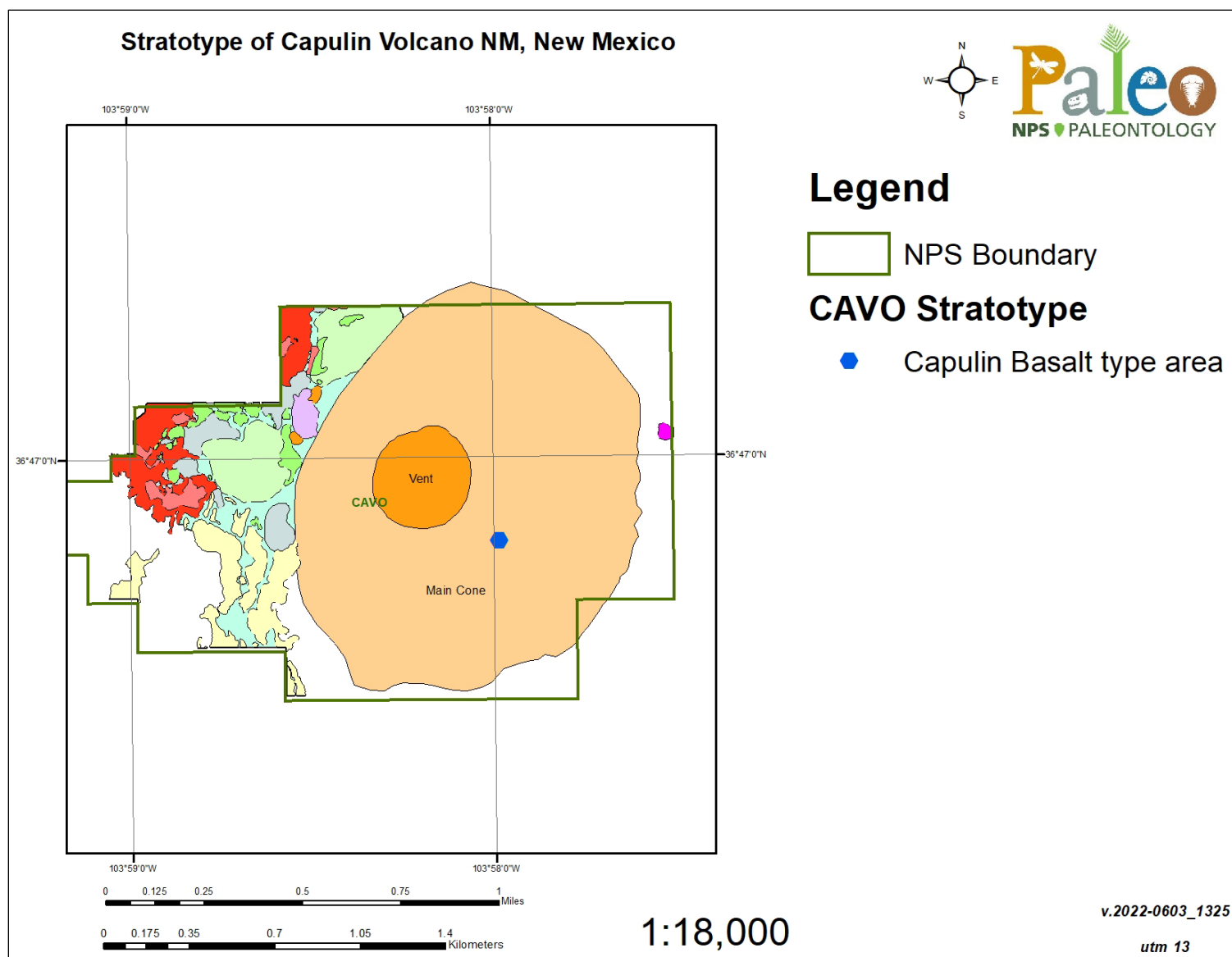
**Figure 14.** Geologic map showing the distribution of lava flow sequences at CAVO, New Mexico. Data modified from CAVO GRI digital geologic lava flow map data at <https://irma.nps.gov/DataStore/Reference/Profile/2164825>.



**Figure 15.** Map showing the distribution of geologic area features of CAVO, New Mexico. Data modified from CAVO GRI digital geologic map data at <https://irma.nps.gov/DataStore/Reference/Profile/2164823>.

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

Unit Name (GRI map symbol)	Reference	Stratotype Location	Age
Capulin Basalt (CZign)	Collins 1949; Scott et al. 1990	Type area: occurs at and near Capulin Volcano in section 4, T. 29 N., R. 28 E. (approximate latitude 36°46'48" N., longitude 103°57'59" W.), Union County, New Mexico. Folsom, New Mexico 7.5' Quadrangle.	Pleistocene



**Figure 16.** Modified geologic map of CAVO showing a stratotype location.

### **Capulin Basalt**

The Pleistocene Capulin Basalt was proposed by Collins (1949) and named after the cone and lava flows of Capulin Volcano in the central part of the Raton-Clayton area, New Mexico. The type area of the formation was designated by Scott et al. (1990) at Capulin Volcano in section 4, T. 29 N., R. 28 E., in Union County, New Mexico (Table 3; Figures 16–18). In the type area, the steep-flanked cinder cone rises several hundred meters or feet above the surrounding landscape and is composed of ash, scoria, volcanic bombs, and blocks (Figures 19 and 20; Scott et al. 1990). The Capulin Basalt is chemically classified as “trachybasalt”, meaning the geologic unit contains more abundant alkali elements, such as sodium and potassium, than true basalt (KellerLynn 2015a). Xenoliths (foreign rock fragments) and xenocrysts (foreign crystals, much smaller than xenoliths) derived from the Cretaceous Dakota Sandstone are a characteristic feature in the Capulin Basalt at CAVO and the surrounding area (Sayre and Ort 1999). Four major lava flow sequences of the Capulin Basalt cover about 40 km<sup>2</sup> (16 mi<sup>2</sup>) and extend well beyond the monument boundary.



**Figure 17.** Type area exposures of the Pleistocene Capulin Basalt that form the namesake Capulin Volcano in CAVO (USGS/R. D. MILLER).





**Figure 18.** Basalt lava flows of the Capulin Basalt cover the landscape of CAVO. The summit of Capulin Volcano appears in the background of the photograph (NPS).



**Figure 19.** Exposures of the Capulin Basalt along Volcano Road showing a cross-section of the alternating cinders and ash that form Capulin Volcano (USGS).



**Figure 20.** Exposures of the Capulin Basalt along Volcano Road showing thin layers of ash alternating with cinders and other pyroclastic material (NPS/ALLY BUCCANERO).





# Chickasaw National Recreation Area (CHIC)

## Park Establishment

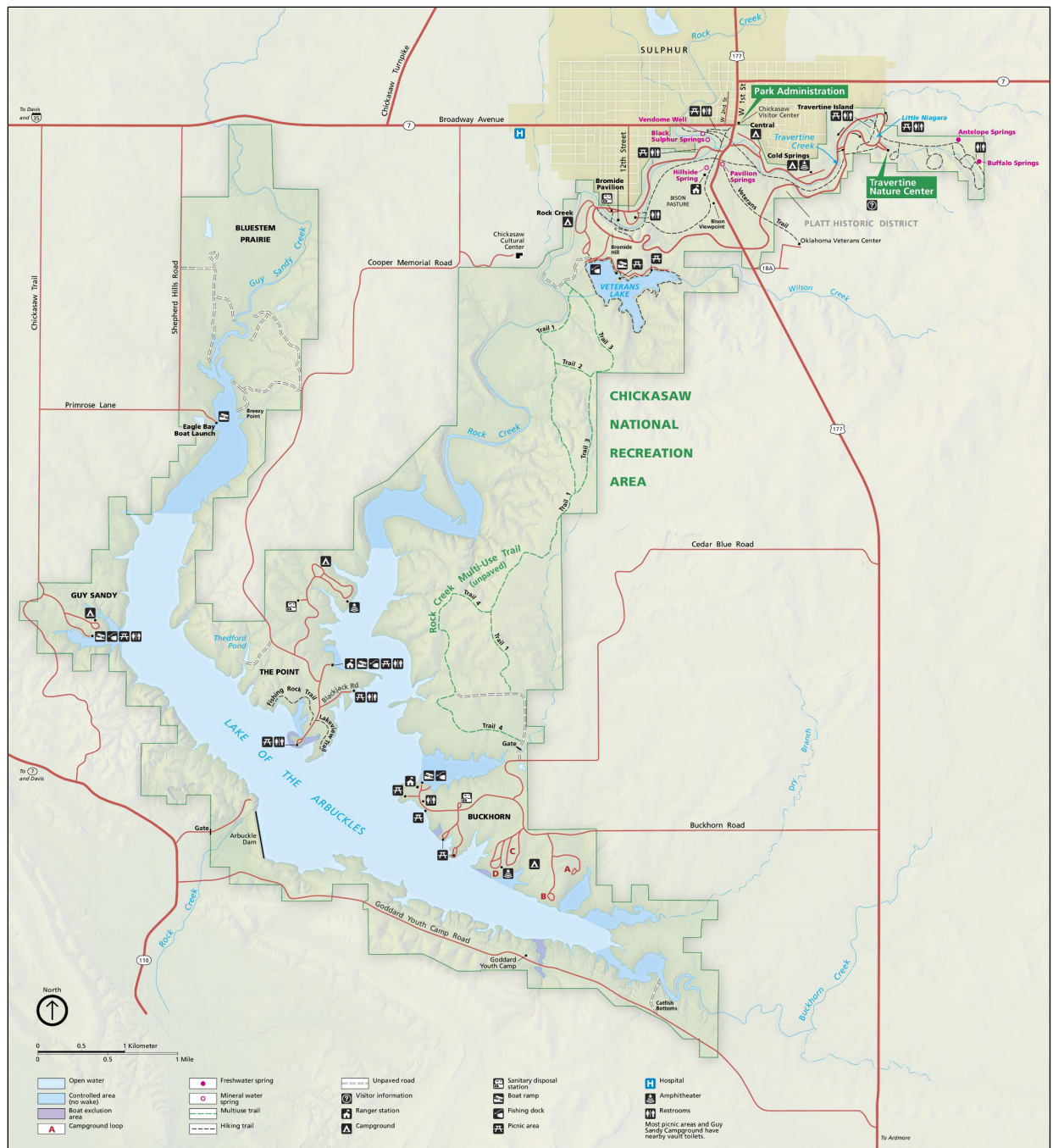
Chickasaw National Recreation Area (CHIC) is located just south of Sulphur and about 120 km (75 mi) southeast of Oklahoma City in Murray County, Oklahoma (Figure 21). Originally authorized as Sulphur Springs Reservation on July 1, 1902, the park unit was renamed and redesignated Platt National Park on June 19, 1906, before it was renamed and redesignated again to Chickasaw National Recreation Area on March 17, 1976 (National Park Service 2016a). Encompassing approximately 4,005 hectares (9,899 acres), CHIC is named in honor of the Chickasaw Nation and protects a collection of freshwater mineral springs, streams, and lakes that provide outdoor recreational activities such as swimming, boating, fishing, camping, and hiking. The unique concentration of mineral springs and creeks in CHIC originate from the highly deformed rocks of the Arbuckle–Simpson aquifer and have a long history of recreational and medicinal use (National Park Service 2017a). Chickasaw National Recreation Area also preserves historic park structures and infrastructure constructed by the Civilian Conservation Corps in the 1930s, as well as the extensive Lake of the Arbuckles (Graham 2015).

## Geologic Summary

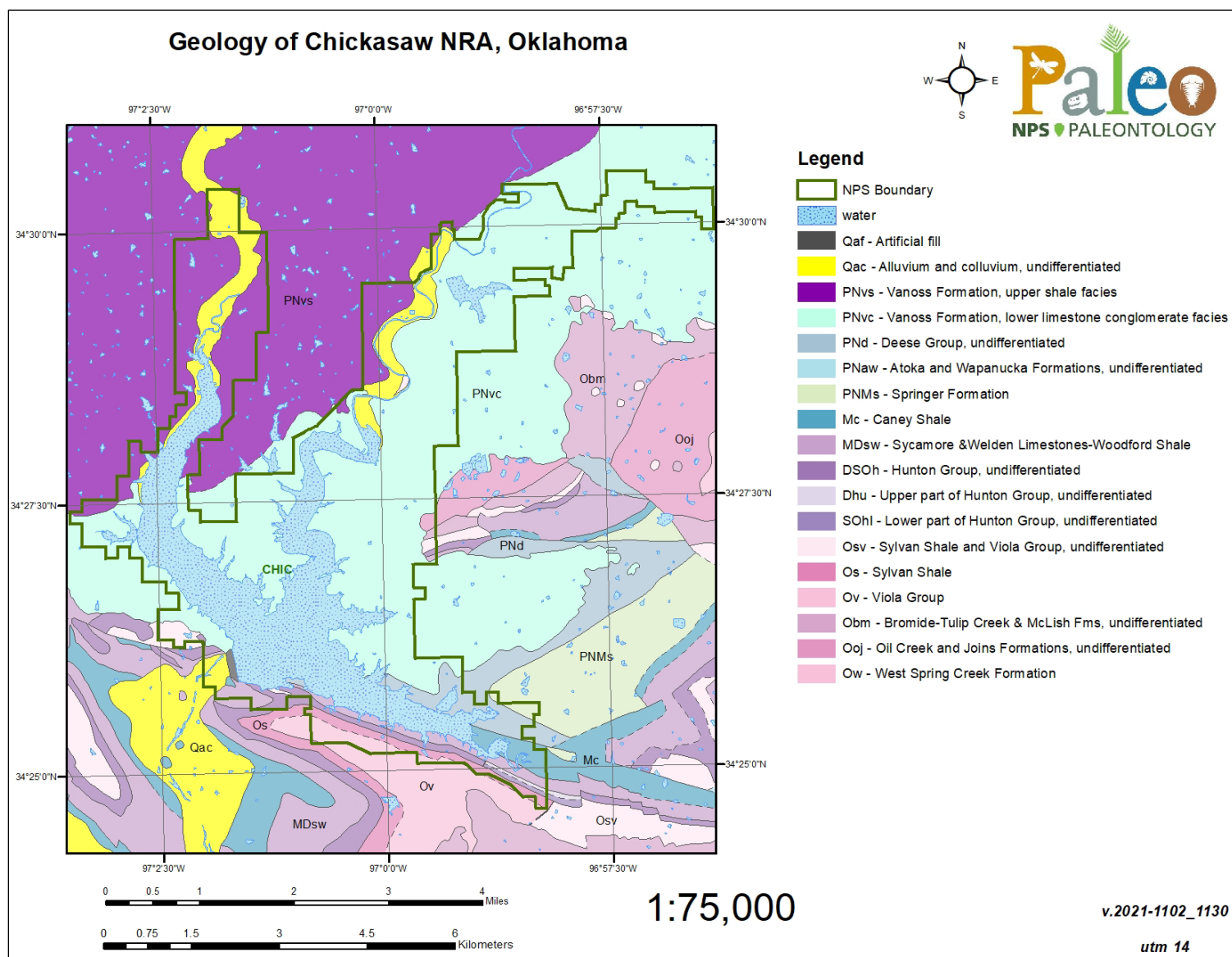
CHIC is situated within the Arbuckle Uplift, a geologic province of Oklahoma that contains some of the thickest accumulations of Paleozoic-age sedimentary rock in the central United States. The landscape of CHIC is defined by gently rolling hills and stream-cut ravines that represent the erosional remnants of the Arbuckle Mountains. The evolution of the Arbuckle Mountains involves four major geological events: 1) rifting of ancestral North America in the Cambrian Period; 2) shallow marine deposition from the Cambrian to the Mississippian; 3) uplift and deformation during the Pennsylvanian–Permian; and 4) major erosion (Graham 2015) since original deposition. The bedrock underlying CHIC consists of Paleozoic-age strata spanning the Ordovician through the Pennsylvanian (Figure 22). Widely mapped throughout the northern portion of the recreation area is the Pennsylvanian Vanoss Formation, which is subdivided into an upper shale facies (a distinct sedimentary unit, with characteristics reflecting specific factors from the time of deposition) and lower limestone conglomerate facies. Rocks older than the Vanoss Formation are mapped south of the Lake of the Arbuckles in the Tishomingo anticline (Blome et al. 2013). The core of the anticline consists of limestones of the Viola Group, with younger rocks exposed on the flanks of the fold that include the Ordovician Sylvan Shale, Silurian–Devonian Hunton Group, Devonian Woodford Shale, Mississippian Sycamore Limestone, and others.

## Stratotypes

There are no designated stratotypes identified within the boundaries of CHIC. There are 43 identified stratotypes located within 48 km (30 mi) of CHIC boundaries that are provided in Appendix C for reference in case of future recreation area boundary expansion.



**Figure 21.** Park map of CHIC, Oklahoma (NPS).



**Figure 22.** Geologic map of CHIC, Oklahoma. Data modified from CHIC GRI digital geologic map data at <https://irma.nps.gov/DataStore/Reference/Profile/2165116>.



## **Fort Larned National Historic Site (FOLS)**

### **Park Establishment**

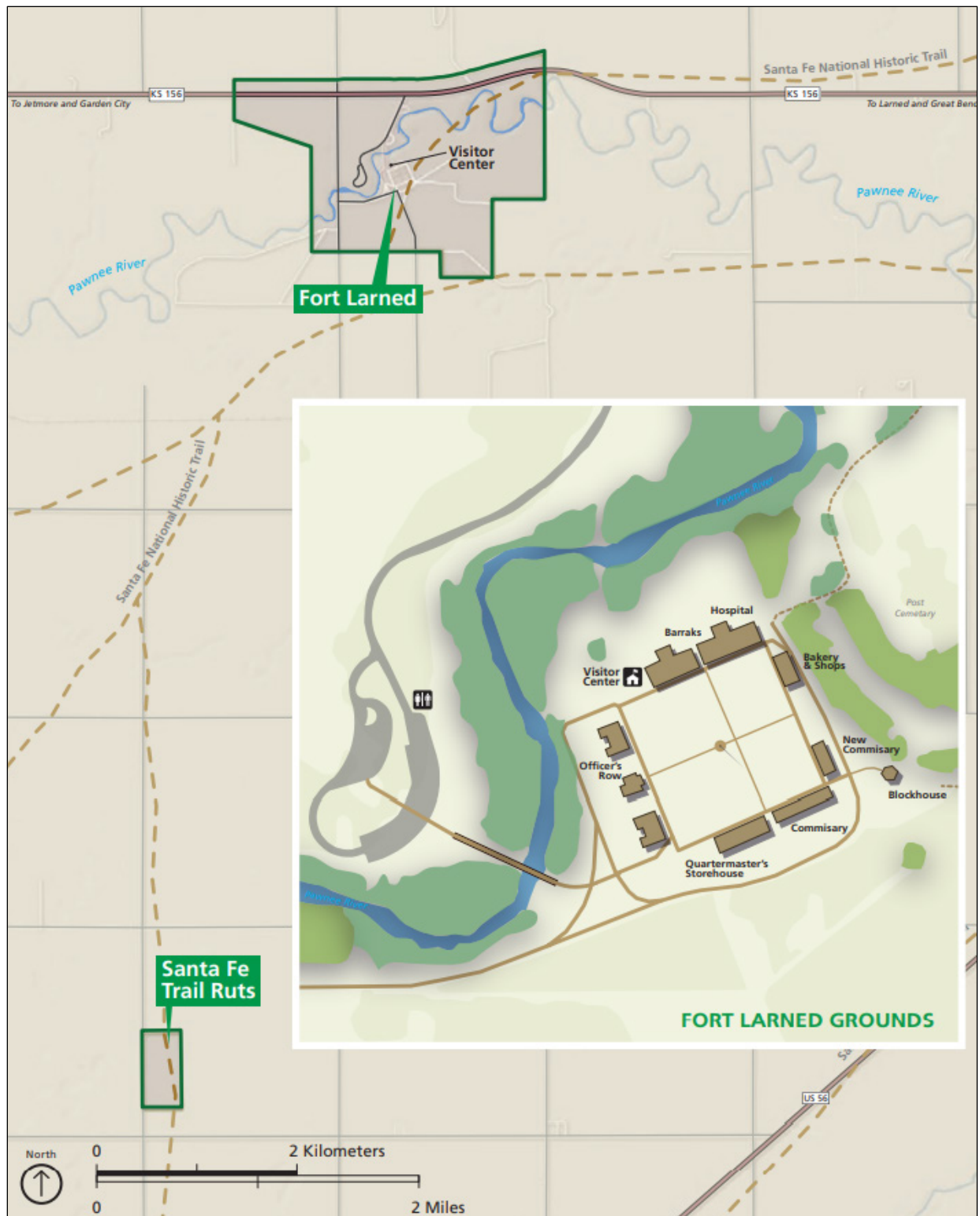
Fort Larned National Historic Site (FOLS) is located 10 km (6 mi) west of Larned and 80 km (50 mi) northeast of Dodge City in Pawnee County, Kansas (Figure 23). Established on August 31, 1964, FOLS contains approximately 290 hectares (718 acres) and preserves the original structures and landscape of Fort Larned, as well as the remains of the historic Santa Fe Trail (Santa Fe National Historic Trail; SAFE) that helped play a significant role in opening the American West. Fort Larned was constructed along the Santa Fe Trail in 1859 and served as an important military post where troops escorted mail coaches, protected wagon trains, and patrolled the region. During its history, the fort also served as an Agency for the Indian Bureau and was a key military base during the Indian War of 1867–1869 (National Park Service 2016a). The original historic fort buildings and furnishings comprise one of the most complete military posts remaining along the Santa Fe Trail and provide an authentic experience of a typical western frontier fort protecting U.S. interests (National Park Service 2017b).

### **Geologic Summary**

FOLS is situated within the Plains Border section of the Great Plains physiographic province, a region characterized by numerous, dissected, east-trending river valleys and interstream divides that include the Republican, Solomon, Saline, Smoky Hill, Arkansas, Medicine Lodge, Cimarron, Pawnee, and North Canadian Rivers (Trimble 1980). Similar to the Missouri Plateau, Colorado Piedmont, and Pecos Valley sections of the Great Plains, the landscape of the Plains Border section and FOLS is primarily governed by stream dissection and preferential erosion. Located on the floodplain of the Pawnee River, the geology of FOLS predominantly consists of young surficial deposits representing Quaternary-age terrace valley fill and loess. A narrow meandering belt of Holocene-age alluvium is mapped in association with the Pawnee River, which transects the historic site (Figure 24).

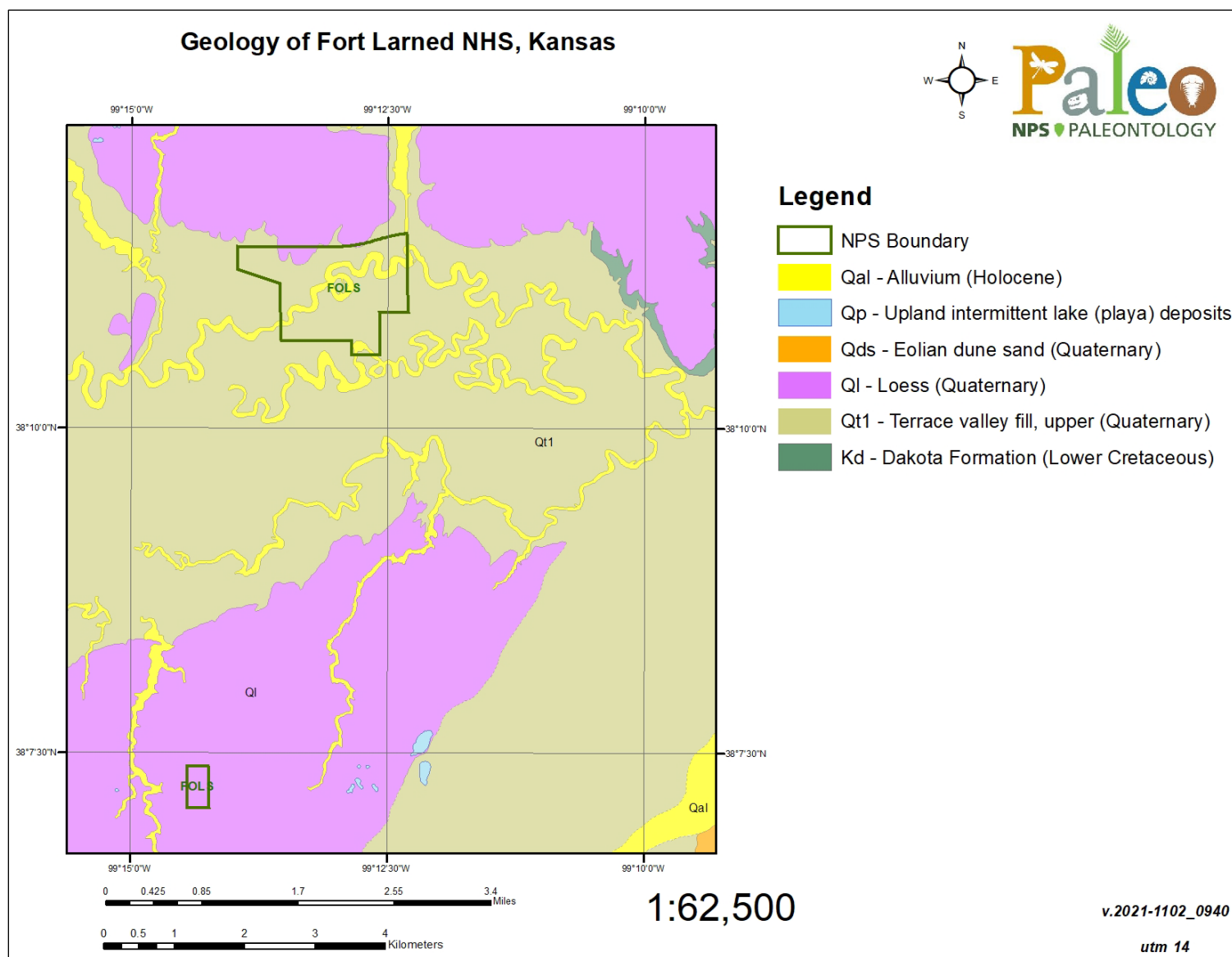
### **Stratotypes**

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



**Figure 23.** Park map of FOLS, Kansas (NPS).





**Figure 24.** Geologic map of FOLS, Kansas. Data modified from FOLS GRI digital geologic map data at <https://irma.nps.gov/DataStore/Reference/Profile/2222922>.





# **Fort Union National Monument (FOUN)**

## **Park Establishment**

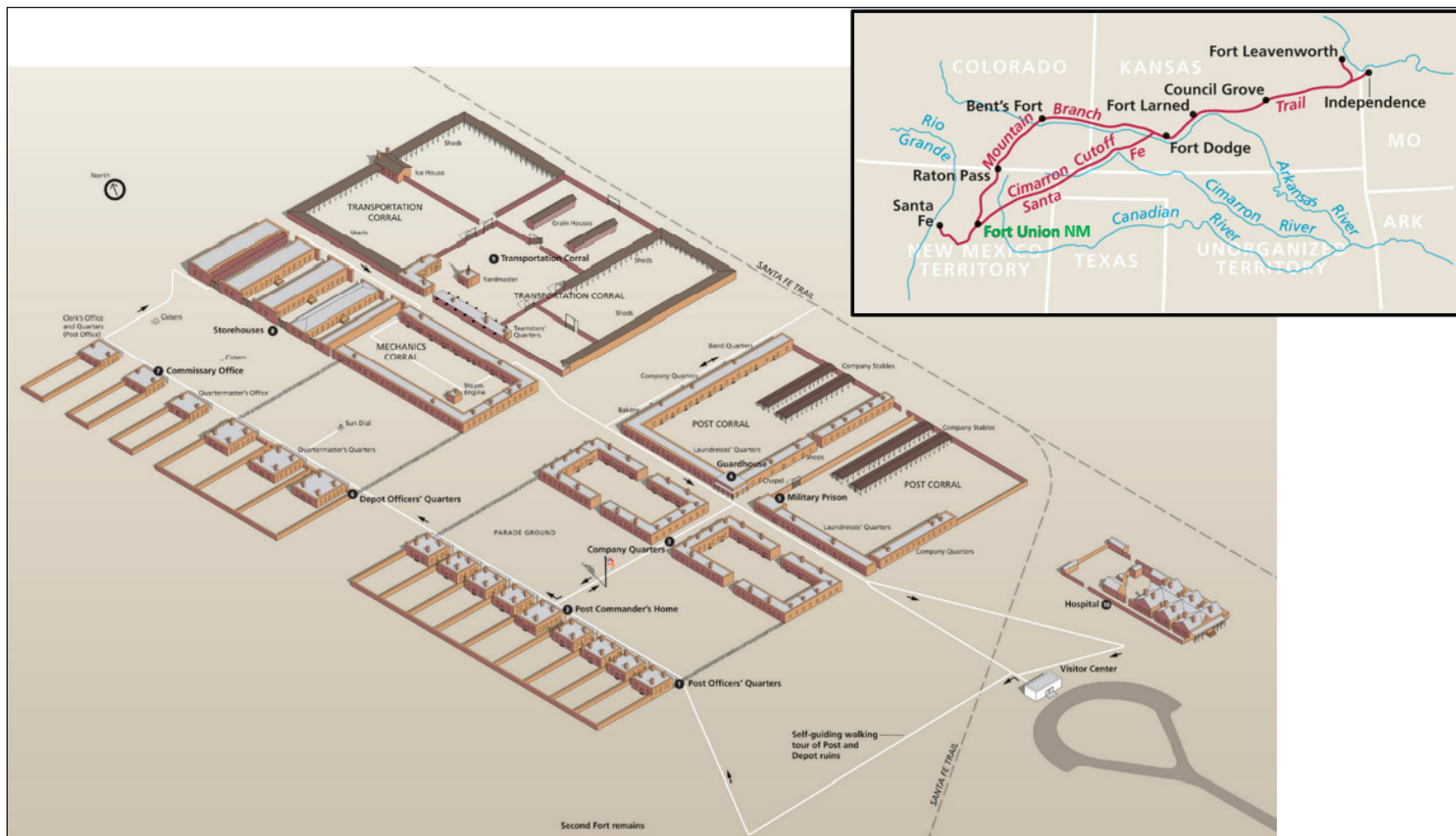
Fort Union National Monument (FOUN) is located 13 km (8 mi) northwest of Interstate 25 and Watrous, and about 153 km (95 mi) northeast of Santa Fe in Mora County, New Mexico (Figure 25). Established on June 28, 1954, FOUN contains approximately 291 hectares (721 acres) and protects the historic remains of Fort Union and a portion of the associated historic Santa Fe Trail (Santa Fe National Historic Trail; SAFE). The monument contains remnants of the Southwest's largest frontier fort, including earthworks, archeological resources, and stabilized adobe ruins (National Park Service 2014c). Built in 1851, Fort Union served as a hub along the Santa Fe Trail for the delivery of supplies and equipment to other military posts throughout the Southwest and played a key role in the Indian Wars as well as the Confederate defeat at Glorieta Pass (National Park Service 2016a). FOUN is separated into two units encompassing the sites of the three Fort Unions. The smaller unit is located west of Wolf Creek and preserves the stone foundations of the original Fort Union (operational from 1851–1861), and the stabilized ruins of the third Fort Union's arsenal. The main unit of FOUN is located east of Wolf Creek and contains the Star Fort earthworks of the second Fort Union (operational from 1861–1862) and the stabilized adobe ruins of the third Fort Union.

## **Geologic Summary**

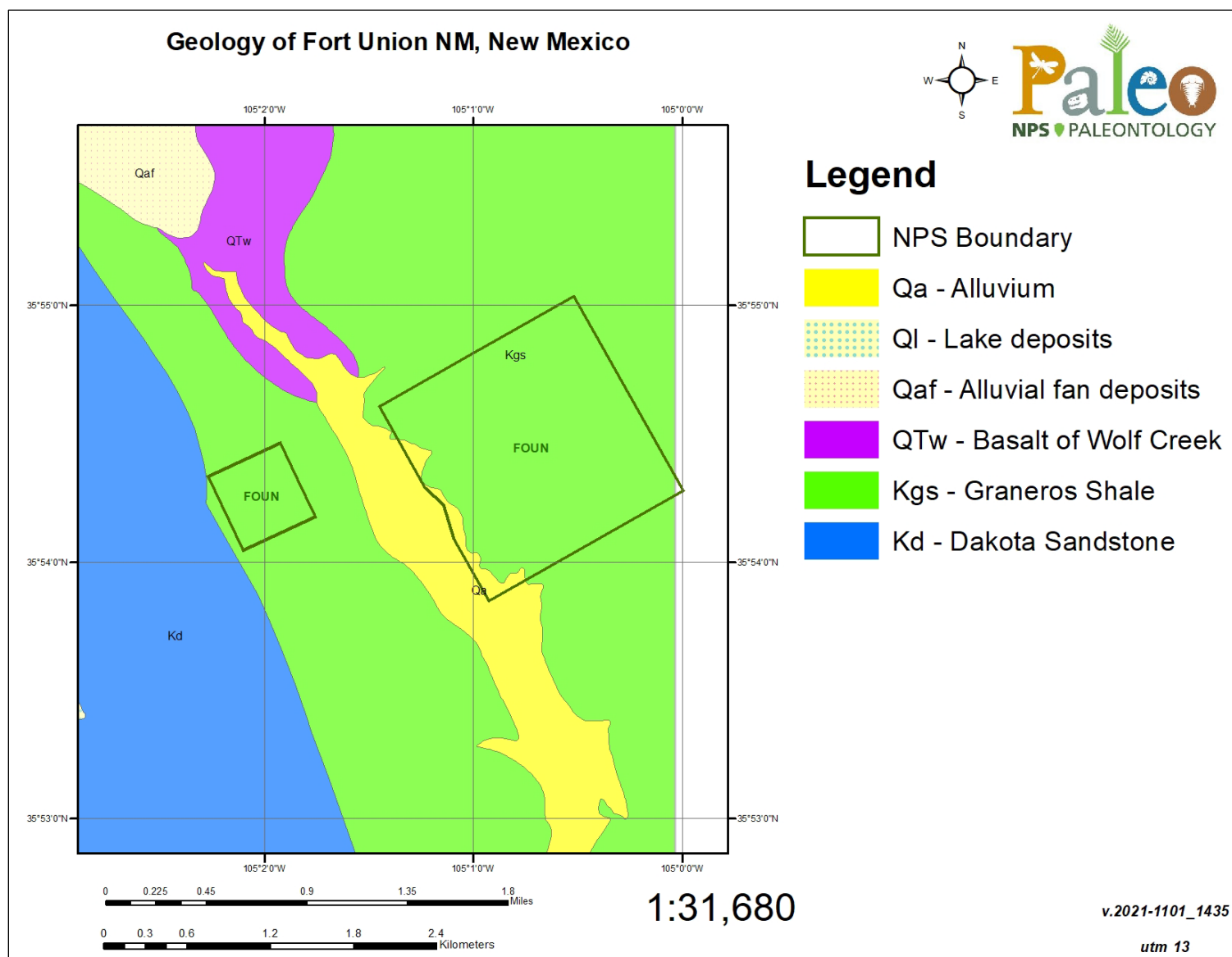
FOUN is situated in the southwestern Raton section of the Great Plains physiographic province, a region characterized by volcanism that has buried and shielded older underlying sedimentary rocks from erosion that has deeply incised the adjacent Colorado Piedmont and Pecos Valley sections (Trimble 1980). The landscape of FOUN developed over the last 100 million years, during a time when a large inland sea (Western Interior Seaway) inundated the west-central part of North America extending from the Arctic to the Tropics. Rocks deposited in the Western Interior Seaway include the Cretaceous Dakota Sandstone and Graneros Shale. Although not mapped inside FOUN, the Dakota Sandstone provided the necessary building material for fort construction. The Graneros Shale forms the predominant bedrock underlying the monument and was historically used to yield clay to produce adobe used at the frontier fort (Figure 26; KellerLynn 2012). Mapped along the western edge of the main unit of FOUN is young Quaternary-age alluvium that coincides with Wolf Creek.

## **Stratotypes**

There are no designated stratotypes identified within the boundaries of FOUN. There are four identified stratotypes located within 48 km (30 mi) of FOUN boundaries that are provided in Appendix C for reference in case of future monument boundary expansion.



**Figure 25.** Park map of FOUN, New Mexico. Inset map shows the geographic location of FOUN along the 1,450 km (900 mi)-long Santa Fe Trail (NPS).



**Figure 26.** Geologic map of FOUN, New Mexico. Data modified from FOUN GRI digital geologic map data at <https://irma.nps.gov/DataStore/Reference/Profile/1040284>.



# Lake Meredith National Recreation Area (LAMR)

## Park Establishment

Lake Meredith National Recreation Area (LAMR) is situated adjacent to Alibates Flint Quarries National Monument (ALFL) approximately 64 km (40 mi) north of Amarillo in the Canadian River valley of Hutchison, Moore, and Potter Counties, Texas (Figure 27). Initially authorized as Sanford National Recreation Area on March 15, 1965, the recreation area was renamed on October 16, 1972 (National Park Service 2016a). Encompassing about 18,201 hectares (44,978 acres), LAMR is the largest area of public lands in the Texas panhandle and provides access to diverse, outdoor land- and water-based recreation activities such as boating, fishing, watersports, and hiking. Exposed geologic features known as the Canadian River Breaks are a dominant landscape feature in LAMR that reveal active geologic processes that are easily visible to an extent that is not seen elsewhere in the region. The topography of the Canadian River Breaks creates a divergence from the surrounding landscape and formed as the Canadian River carved a narrow, steep-walled canyon approximately 60–90 m (200–300 ft) deep and up to 3.2 km (2 mi) wide. LAMR features abundant natural resources including aquatic, wetland, and riparian habitats that support a diverse biological community.

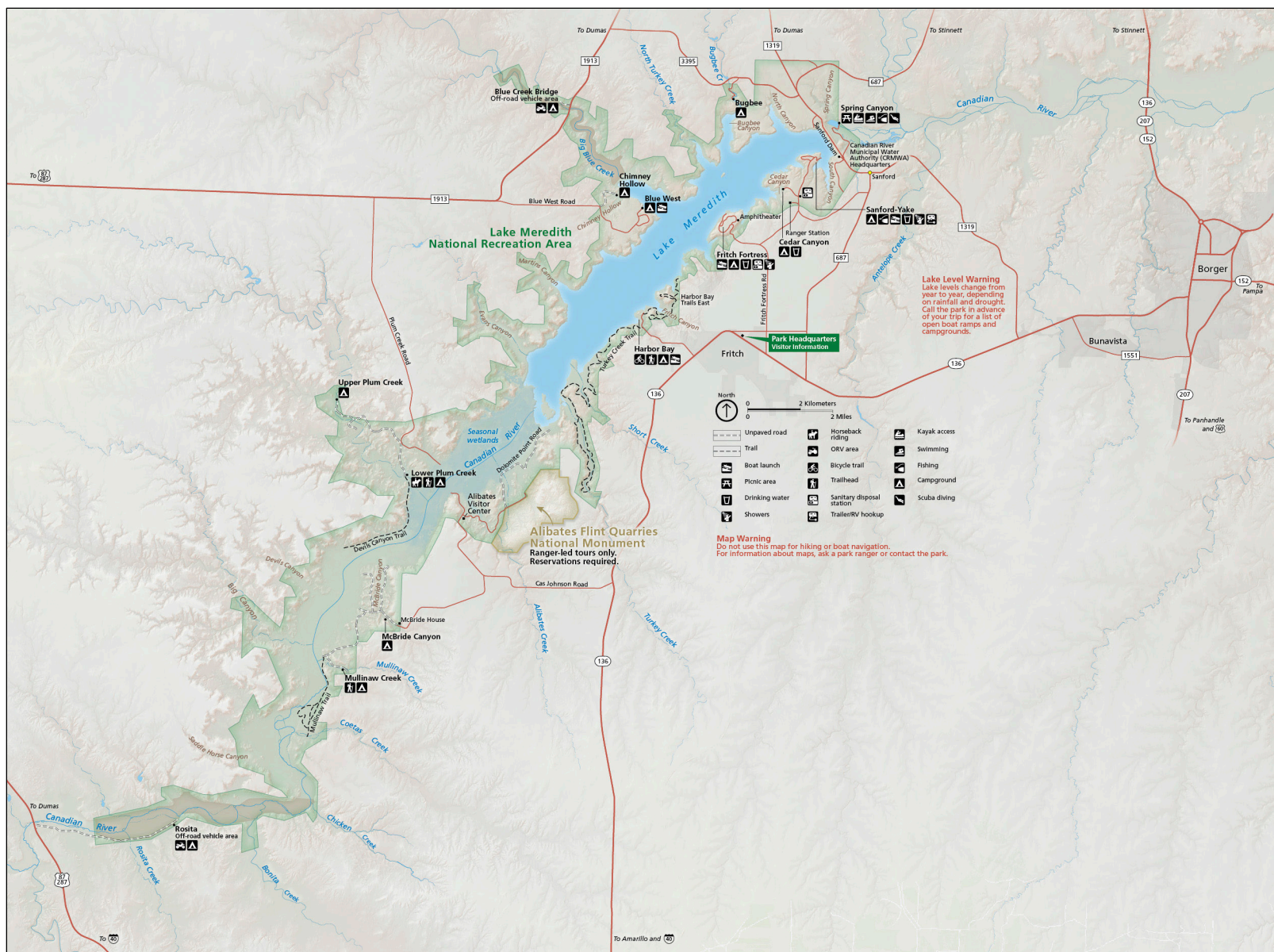
## Geologic Summary

LAMR is situated in the High Plains section of the Great Plains physiographic province, a region characterized by upland hills, ridges, and canyons. The primary geologic structure of the recreation area is the Amarillo Uplift, a feature that formed during the Pennsylvanian (~300 million years ago) and imposed regional controls on deposition and erosion. The bedrock underlying LAMR predominantly consists of Permian-age red beds of the Quartermaster Formation, which records depositional conditions in a vast ocean approximately 260 million years ago (Figure 28; KellerLynn 2015b). The Permian Alibates Dolomite also occurs relatively frequently within LAMR and adjacent AFLF along the Canadian River Valley. Units of Triassic-age are located in the southern region of LAMR and include the Tecovas and Trujillo Formations, while the Neogene Ogallala Formation forms the rim of the Canadian River Breaks throughout most of the recreation area. Young surficial units mapped in the recreation area include Quaternary-age alluvium, eolian sand, and fluvial terrace deposits.

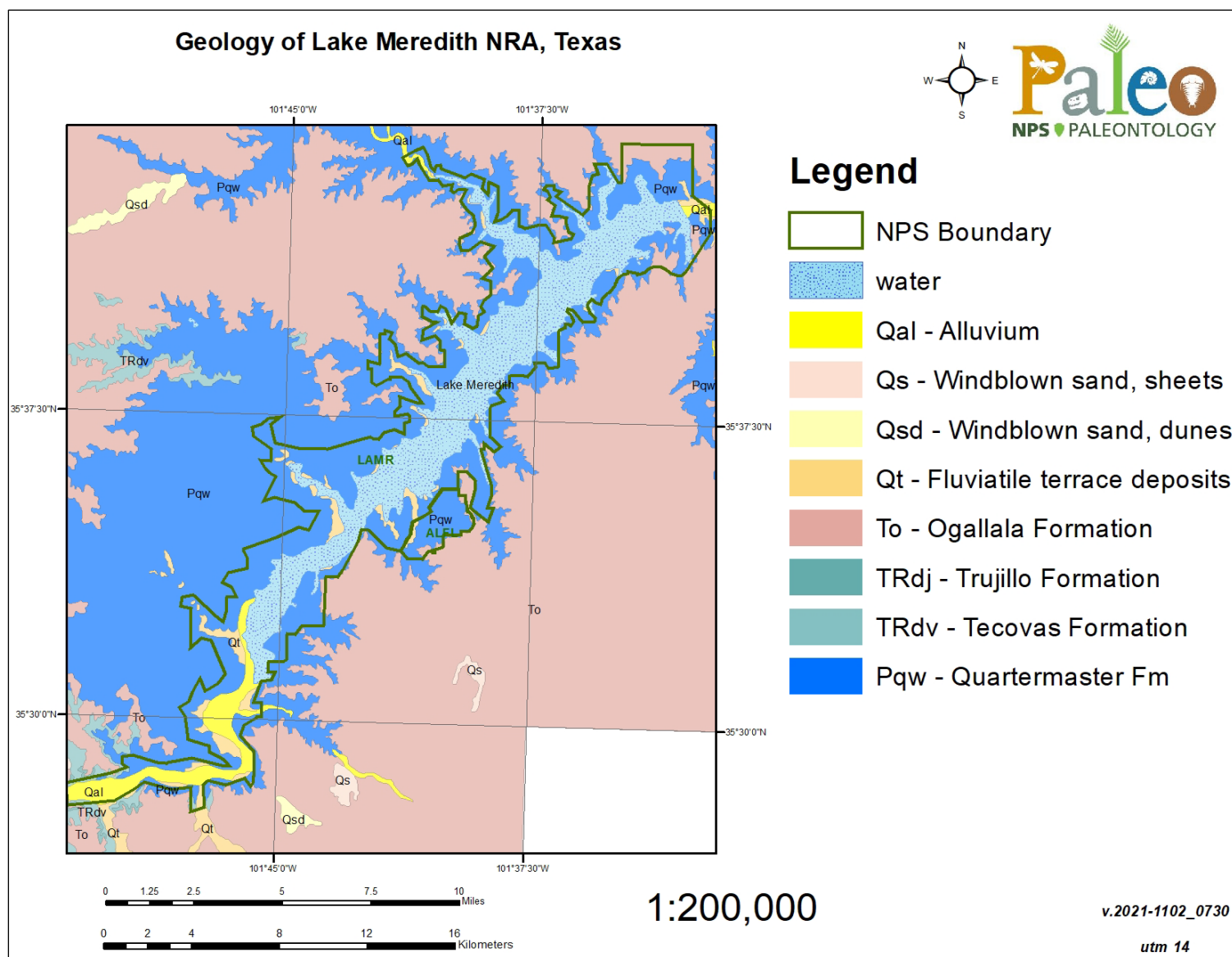
## Stratotypes

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





**Figure 27.** Park map of LAMR and ALFL, Texas (NPS).



**Figure 28.** Geologic map of LAMR and adjacent ALFL, Texas. Data modified from LAMR GRI digital geologic map data at <https://irma.nps.gov/DataStore/Reference/Profile/2176370>.





# **Lyndon B. Johnson National Historical Park (LYJO)**

## **Park Establishment**

Lyndon B. Johnson National Historical Park (LYJO) consists of two separate districts (Johnson City and LBJ Ranch Districts) located in and near Johnson City in Blanco and Gillespie Counties, Texas (Figure 29). Originally authorized as a national historic site on December 2, 1969, the park unit was redesignated a national historical park on December 28, 1980 (National Park Service 2016a).

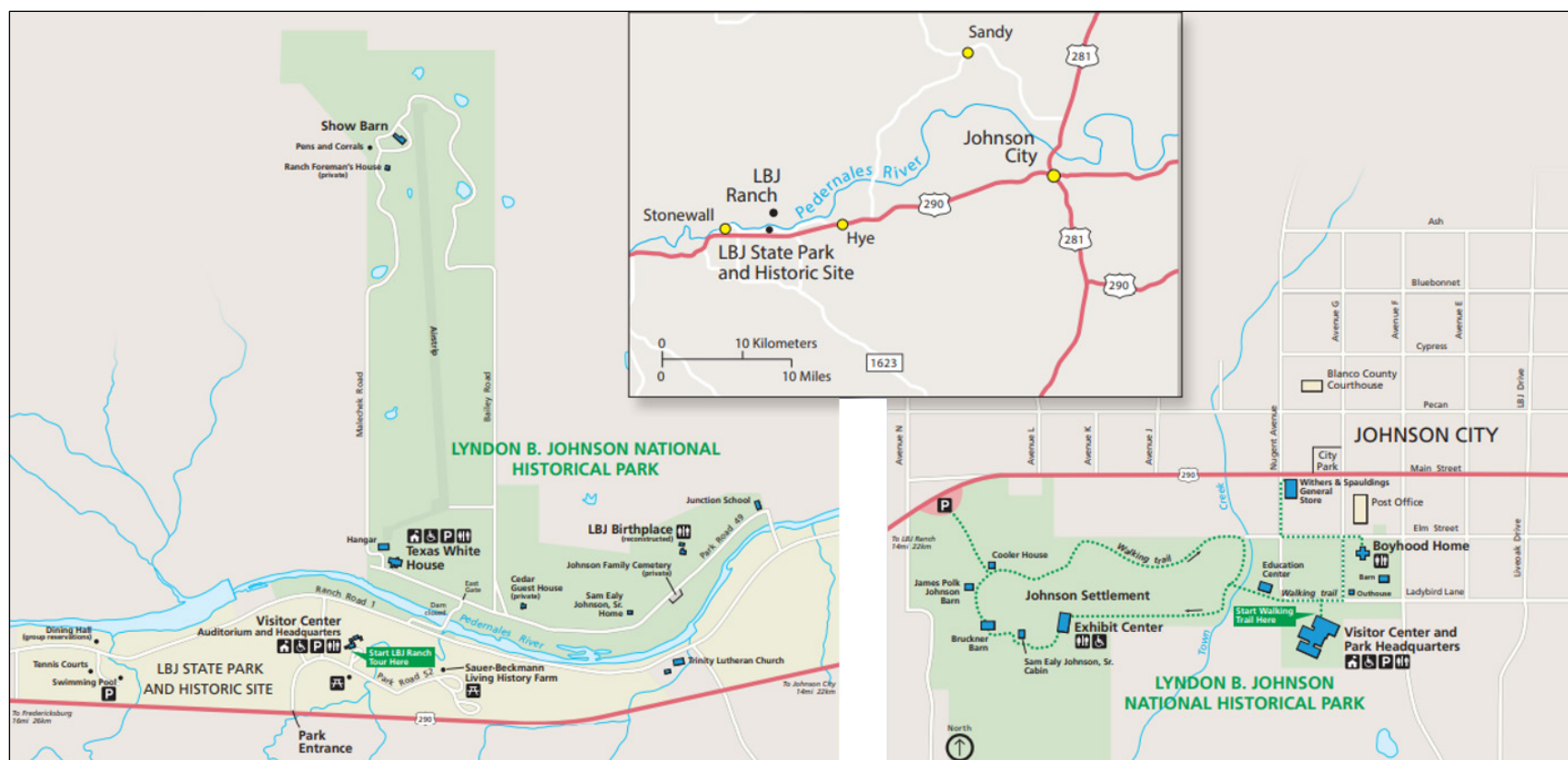
Encompassing approximately 635 hectares (1,570 acres), LYJO was established to protect the historic structures and Texas Hill Country landscapes associated with the ancestry, life, and legacy of Lyndon Baines Johnson, the 36<sup>th</sup> president of the United States (National Park Service 2014d). The LBJ Ranch District provides one of the most complete pictures of the Johnson family, conserving historic properties including the Texas White House as well as the Johnson Family Cemetery and surrounding ranch landscape, complete with outbuildings and a heritage herd of Hereford cattle. The Texas White House was the Johnson family home and ranch, providing refuge from the stress and frenetic activity of political life in Washington, D.C. The smaller Johnson City District includes the Boyhood Home area where the family moved in 1913 and the Johnson Settlement area where Johnson's grandparents first settled.

## **Geologic Summary**

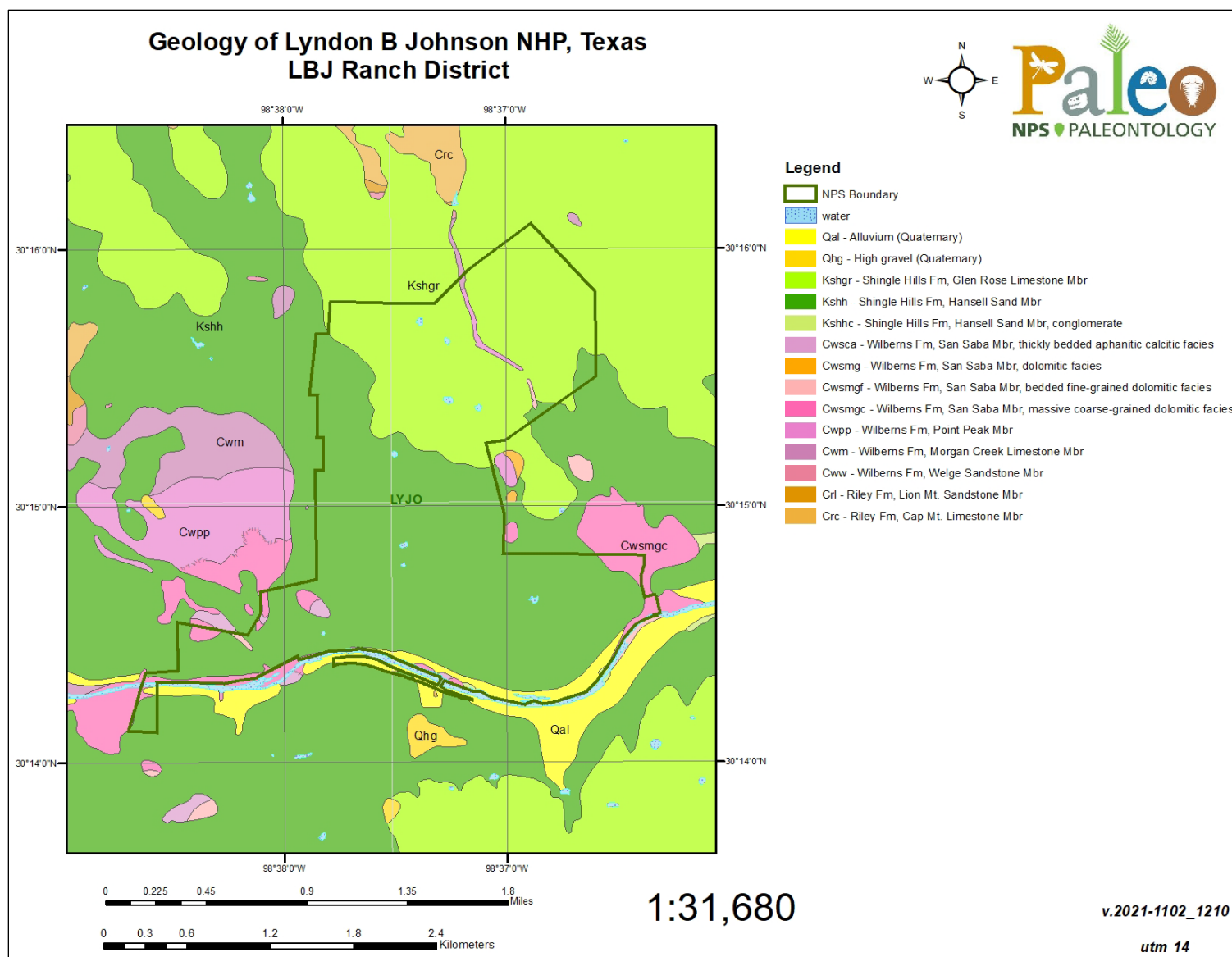
LYJO is situated along the Pedernales River in an area of central Texas known as the Llano Uplift, which has the metamorphic core of an ancient mountain range, Paleozoic and Mesozoic-age sedimentary rocks, and recent alluvial, terrace, and colluvial deposits (Thornberry-Ehrlich 2008). The formation of the Llano Uplift occurred during the Precambrian and represents part of an ancient collisional orogenic (mountain building event) belt. The oldest bedrock underlying the historical park is represented by sedimentary rocks of the Cambrian Wilberns Formation in the LBJ Ranch district (Figure 30). The Cretaceous-age Shingle Hills Formation is widely mapped in both districts of LYJO and is subdivided into the Hansell Sand and Glen Rose Limestone Members (Figures 30 and 31). The Shingle Hills Formation tends to form sharp bluffs where exposures rim the Llano Uplift. Young, Quaternary-age surficial deposits of unconsolidated alluvium are located along the Pedernales River (LBJ Ranch District) and Town Creek (Johnson City District).

## **Stratotypes**

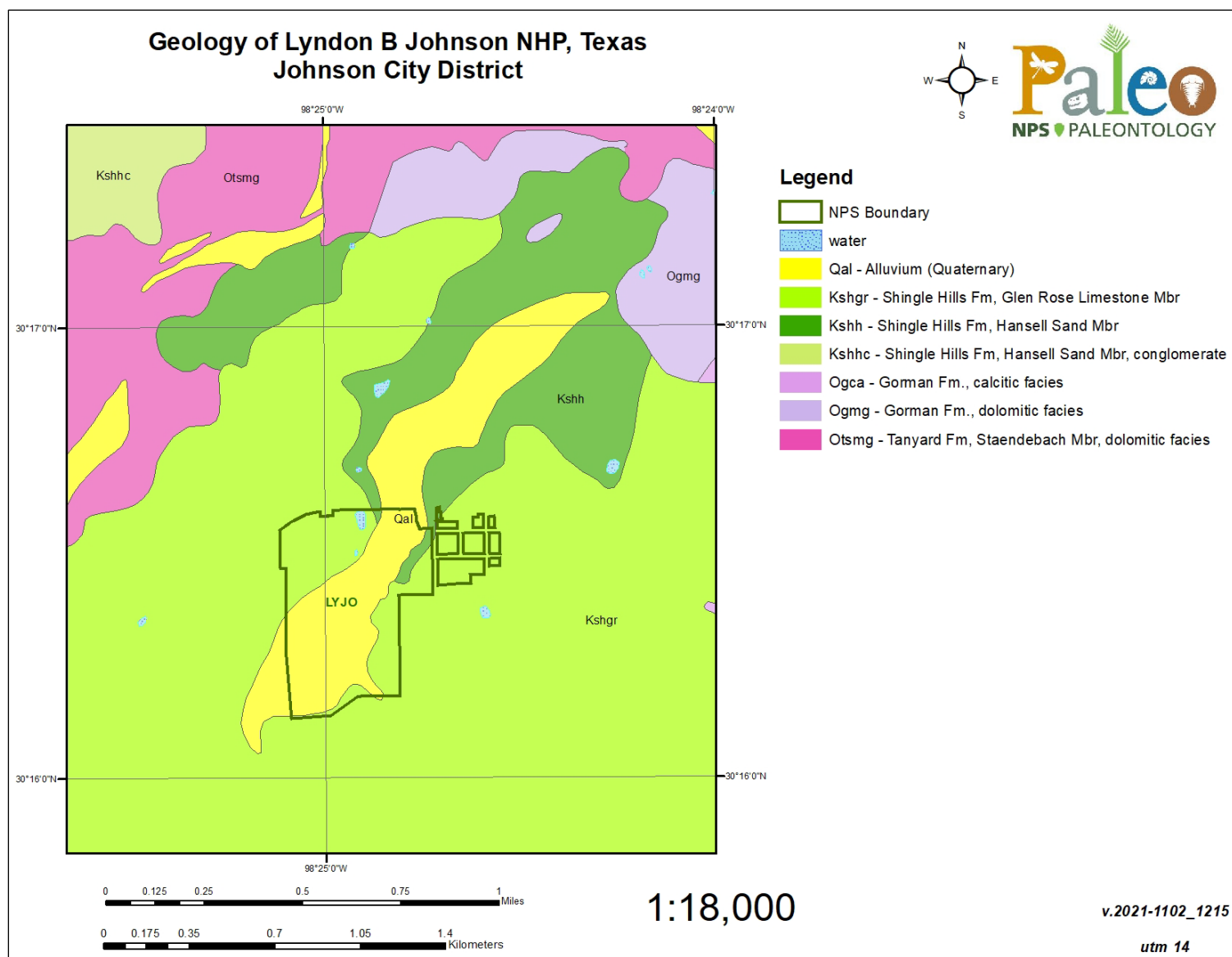
There are no designated stratotypes identified within the boundaries of LYJO. There are five identified stratotypes located within 48 km (30 mi) of LYJO boundaries that are provided in Appendix C for reference in case of future park boundary expansion.



**Figure 29.** Park map of the LBJ Ranch District (left) and Johnson City District (right) of LYJO, Texas. Inset map shows the regional distribution of the two park unit districts (NPS).



**Figure 30.** Geologic map of LYJO (LBJ Ranch District), Texas. Data modified from LYJO GRI digital geologic map data at <https://irma.nps.gov/DataStore/Reference/Profile/2254848>.



**Figure 31.** Geologic map of LYJO (Johnson City District), Texas. Data modified from LYJO GRI digital geologic map data at <https://irma.nps.gov/DataStore/Reference/Profile/2254848>.

# **Pecos National Historical Park (PECO)**

## **Park Establishment**

Pecos National Historical Park (PECO) consists of two units (Pecos and Glorieta Units) located in the upper Pecos River Valley about 45 km (28 mi) southeast of Santa Fe in San Miguel and Santa Fe Counties, New Mexico (Figure 32). Initially authorized as a national monument on June 28, 1965, the park unit was expanded and redesignated a national historical park on June 27, 1990.

Encompassing approximately 2,708 hectares (6,694 acres), PECO preserves 12,000 years of human history, including natural and cultural resources of the Pecos Pueblo, Spanish colonial missions, Santa Fe Trail (Santa Fe National Historic Trail; SAFE), Glorieta Battlefield of the Civil War, and a 1900s Pueblo Revival-style ranch (National Park Service 2016a). At this site strategically located along the trade path between pueblo farmers of the Rio Grande and hunting tribes of the buffalo plains, the Pecos people build a fortress-like pueblo during the 15<sup>th</sup> century that would later become a regional trade center. The Pecos Unit contains the ruins of the pueblo and Spanish missions, as well as the Forked Lightning Ranch that was first owned and developed by Tex Austin, the individual who introduced the concept of dude ranching into the Pecos Valley. The Glorieta Unit contains Pigeon's Ranch and Cañoncito, the location of the 1862 Civil War Battle of Glorieta Pass that halted Confederate advancement into the West.

## **Geologic Summary**

PECO is situated in the northern Pecos Valley section of the Great Plains physiographic province, a region where the Pecos River has carved a broad valley from the Sangre de Cristo Mountains southward to the Rio Grande (Trimble 1980). The Sangre de Cristo Mountains terminate in the foothills at PECO and were uplifted during the Laramide Orogeny that occurred between 70 million to 40 million years ago. Much of the Pecos River Valley is carved into older marine sedimentary rocks, with much of the underlying rock consisting of upper Paleozoic limestones. The geology of PECO can be subdivided into three main groups of rocks: 1) Quaternary and older Cenozoic-age surficial units that include terrace deposits, gravel deposits, valley fill, alluvium, and colluvium; 2) Pennsylvanian through Triassic sedimentary rocks approximately 320 to 200 million years old; and 3) Precambrian igneous and metamorphic rocks more than 1.4 billion years old (Figures 33–35; Port 2015). The oldest bedrock underlying PECO is located in the Glorieta Unit (Cañoncito subunit) and consists of Paleoproterozoic granite to granitic gneiss. Diverse Pennsylvanian through Triassic units are mapped in the park, including the Pennsylvanian Alamitos Formation; Pennsylvanian–Permian Sangre de Cristo Formation; Permian Yeso Formation, Glorieta Sandstone, San Andres Formation, and Artesia Formation; and Triassic Moenkopi, Santa Rosa, and Chinle Formations.

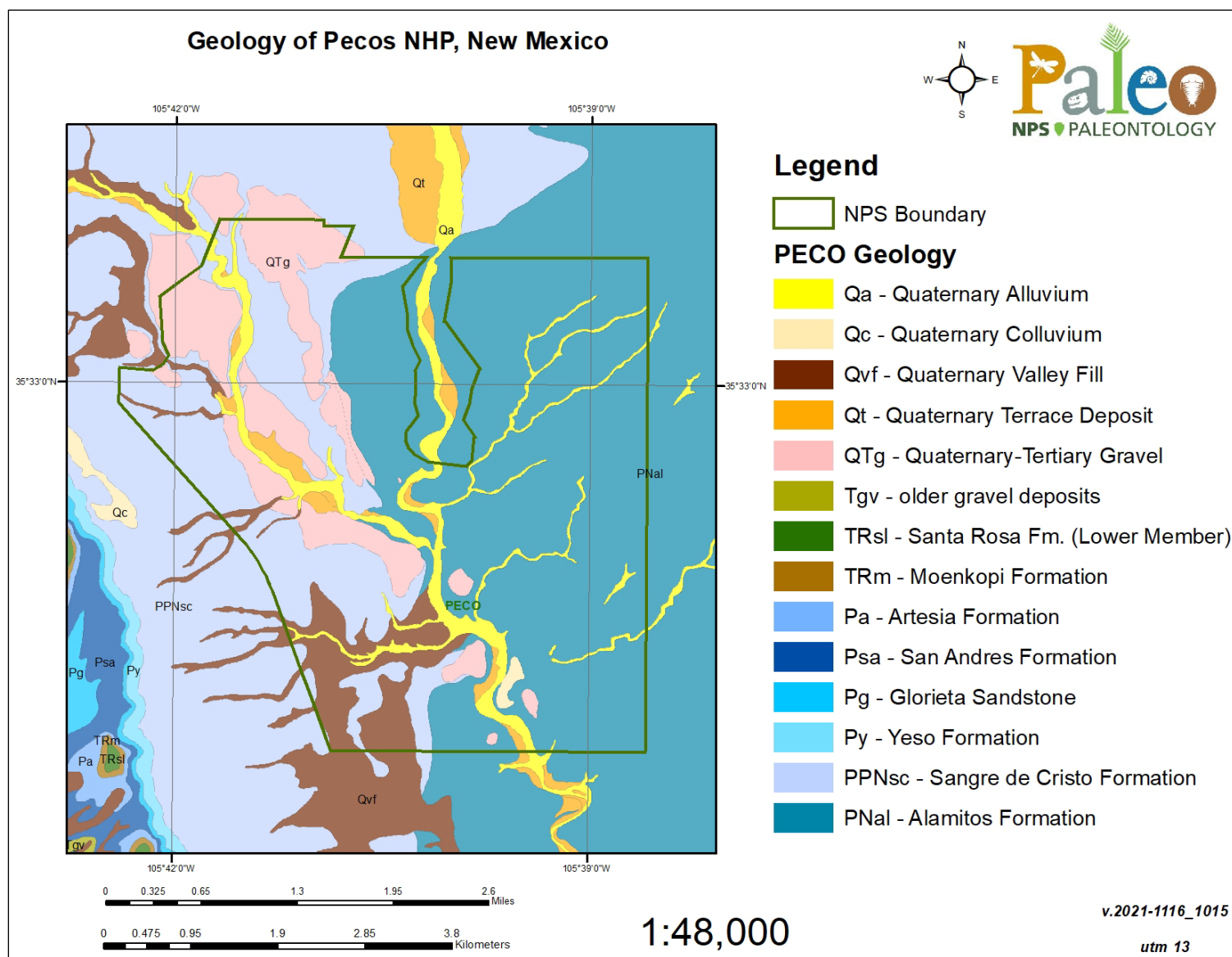
## **Stratotypes**

There are no designated stratotypes identified within the boundaries of PECO. There are 21 identified stratotypes located within 48 km (30 mi) of PECO boundaries that are provided in Appendix C for reference in case of future park boundary expansion.

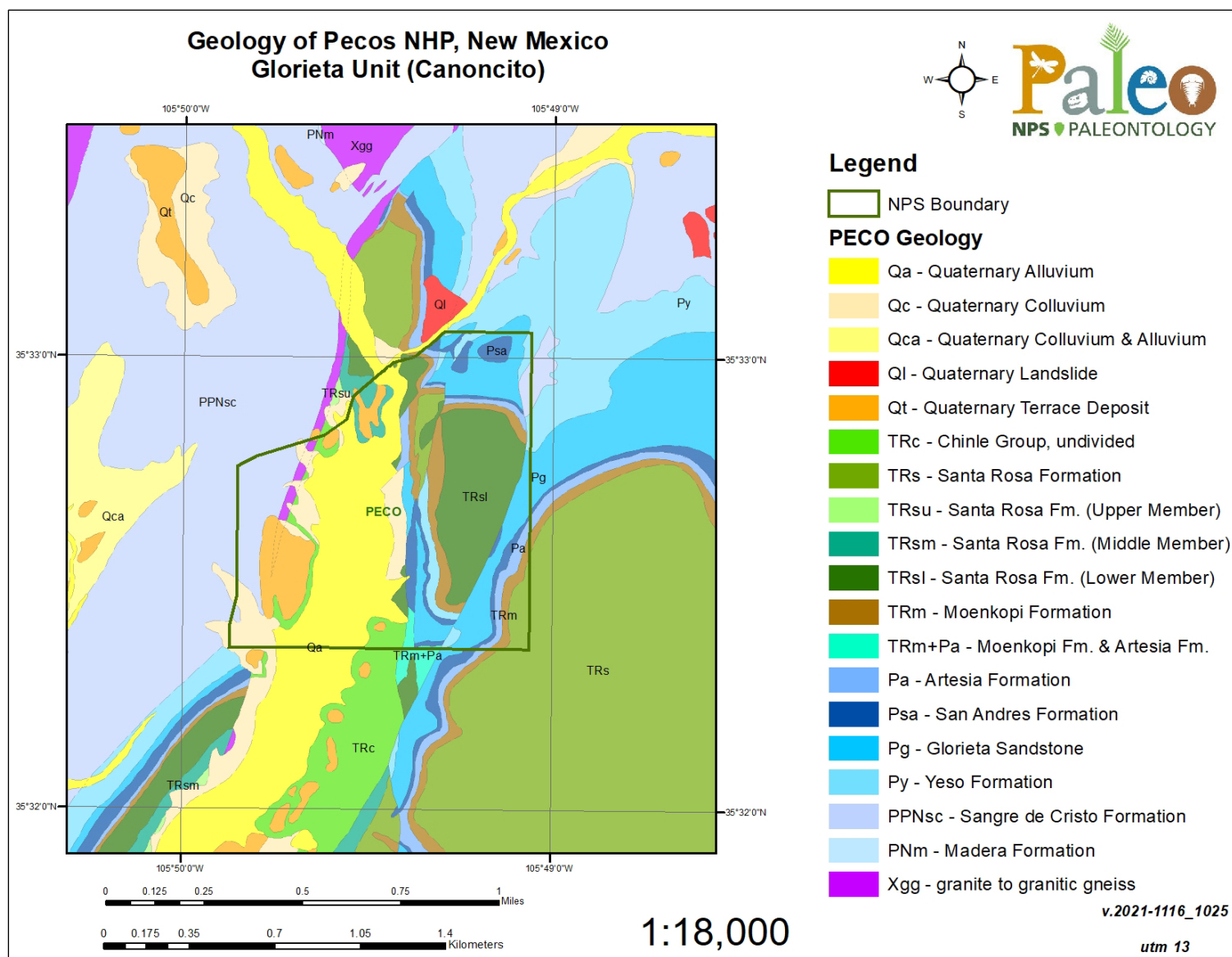


Figure 32. Park map of PECO, New Mexico (NPS).



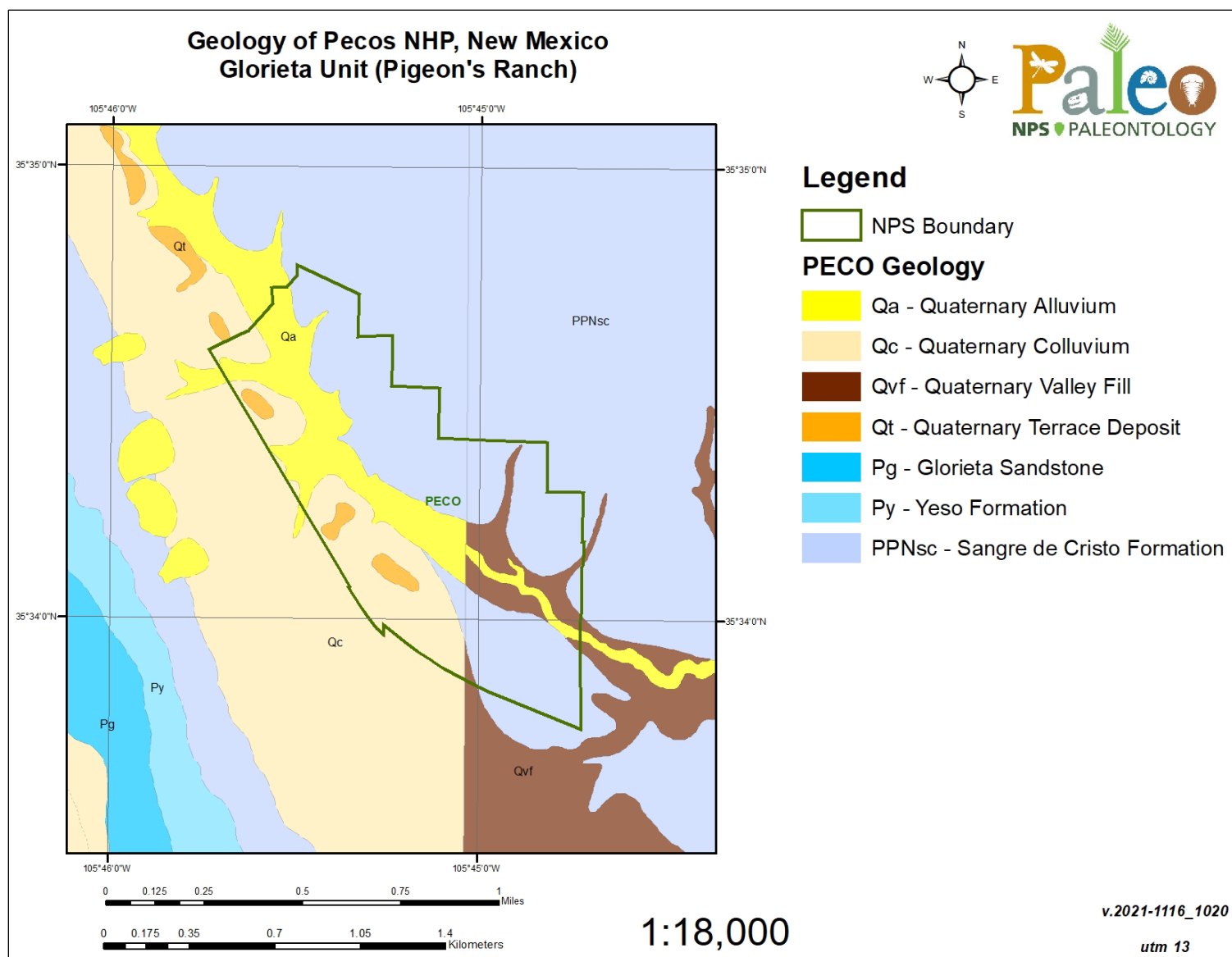


**Figure 33.** Geologic map of PECO, New Mexico. Data modified from PECO GRI digital geologic map data at <https://irma.nps.gov/DataStore/Reference/Profile/1047622>.



**Figure 34.** Geologic map of PECO (Glorieta Unit, Cañoncito subunit), New Mexico. Data modified from PECO GRI digital geologic map data at <https://irma.nps.gov/DataStore/Reference/Profile/1047622>.





**Figure 35.** Geologic map of PECO (Glorieta Unit, Pigeon's Ranch subunit), New Mexico. Data modified from PECO GRI digital geologic map data at <https://irma.nps.gov/DataStore/Reference/Profile/1047622>.



# **Sand Creek Massacre National Historic Site (SAND)**

## **Park Establishment**

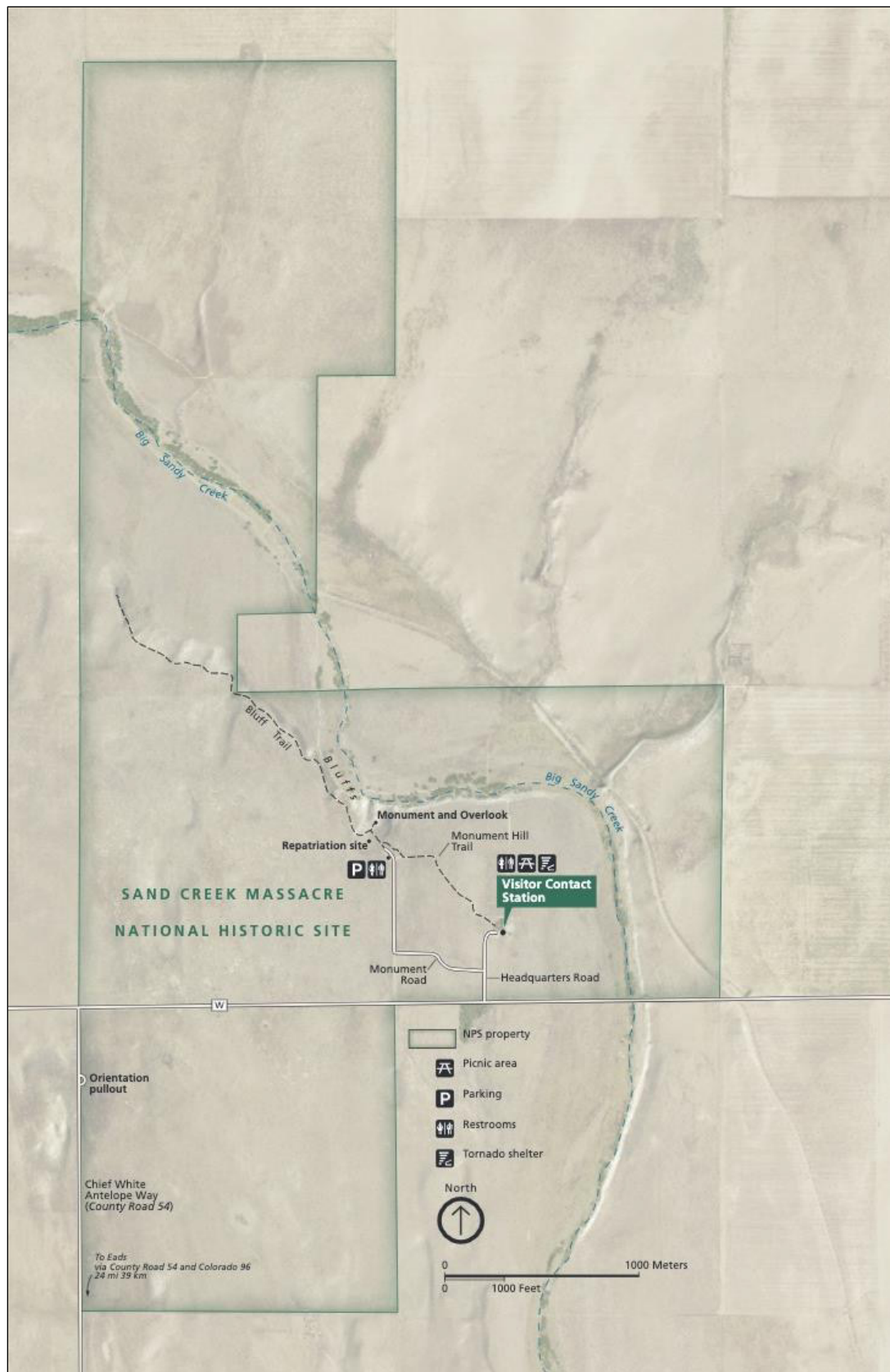
Sand Creek Massacre National Historic Site (SAND) is located along Big Sandy Creek approximately 274 km (170 mi) southeast of Denver in Kiowa County, Colorado (Figure 36). Authorized on November 7, 2000, SAND contains about 5,092 hectares (12,583 acres). It commemorates the November 29, 1864 U.S. Army attack on a peaceful village encampment of Southern Cheyenne and Arapaho people along Big Sandy Creek, in which more than 230 of them were killed in what is now known as the Sand Creek Massacre. The Sand Creek Massacre profoundly influenced relations between the U.S. and Native American nations and changed Cheyenne and Arapaho history, society, and culture (National Park Service 2016a). The Sand Creek Massacre is a symbol of the struggles of Native American peoples to maintain their ancestral ways of life, and ultimately hardened resistance to white expansion resulting in escalated warfare between the U.S. military and the Cheyenne, Arapaho, and Sioux tribes (National Park Service 2017c). For more than 150 years, the Sand Creek Massacre has remained one of the most emotionally charged and controversial events in U.S. history, the origins of which lay in the irresistible momentum of Manifest Destiny—the belief that American settlers were destined to establish dominance over the western lands of the United States between the Mississippi River and the Pacific coast.

## **Geologic Summary**

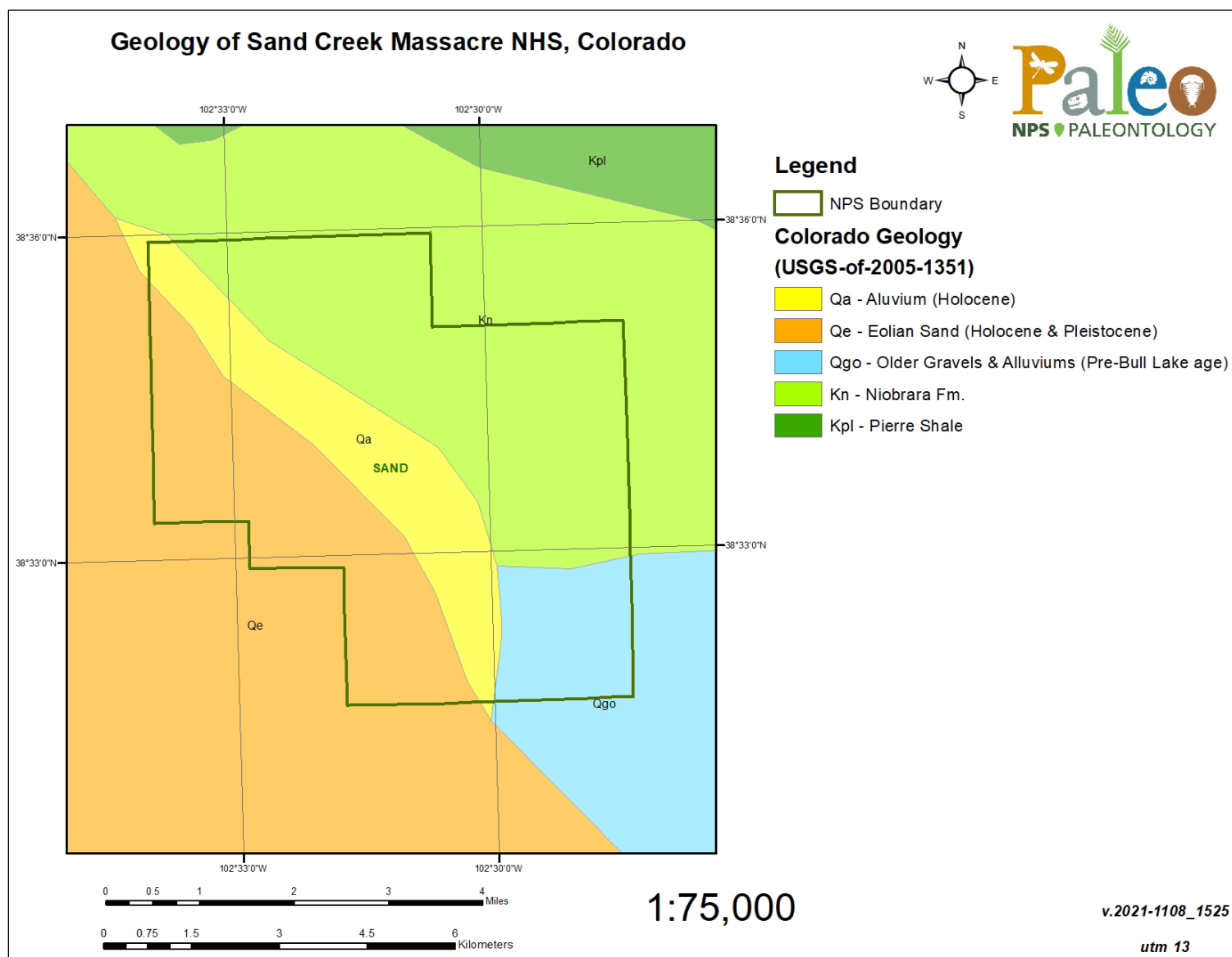
SAND is situated at the boundary of the Colorado Piedmont and High Plains sections of the Great Plains physiographic province, areas defined by regional uplifts, stream modification, and widespread eolian (wind-blown) sand and silt deposits (Trimble 1980). The bedrock underlying SAND is composed entirely of the Cretaceous-age Niobrara Formation located in the northeastern half of the park unit. Younger Quaternary-age surficial deposits cover the rest of the historic site and include eolian sand deposits, as well as older gravels and alluvium of pre-Bull Lake age. The youngest unit mapped in SAND consists of Holocene-age alluvium that occurs as a narrow NW–SE trending band coinciding with Big Sandy Creek (Figure 37).

## **Stratotypes**

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



**Figure 36.** Park map of SAND, Colorado (NPS property only) (NPS).



**Figure 37.** Geologic map of SAND, Colorado. Data modified from USGS digital geologic map data at <https://pubs.usgs.gov/of/2005/1351/>.



# **Waco Mammoth National Monument (WACO)**

## **Park Establishment**

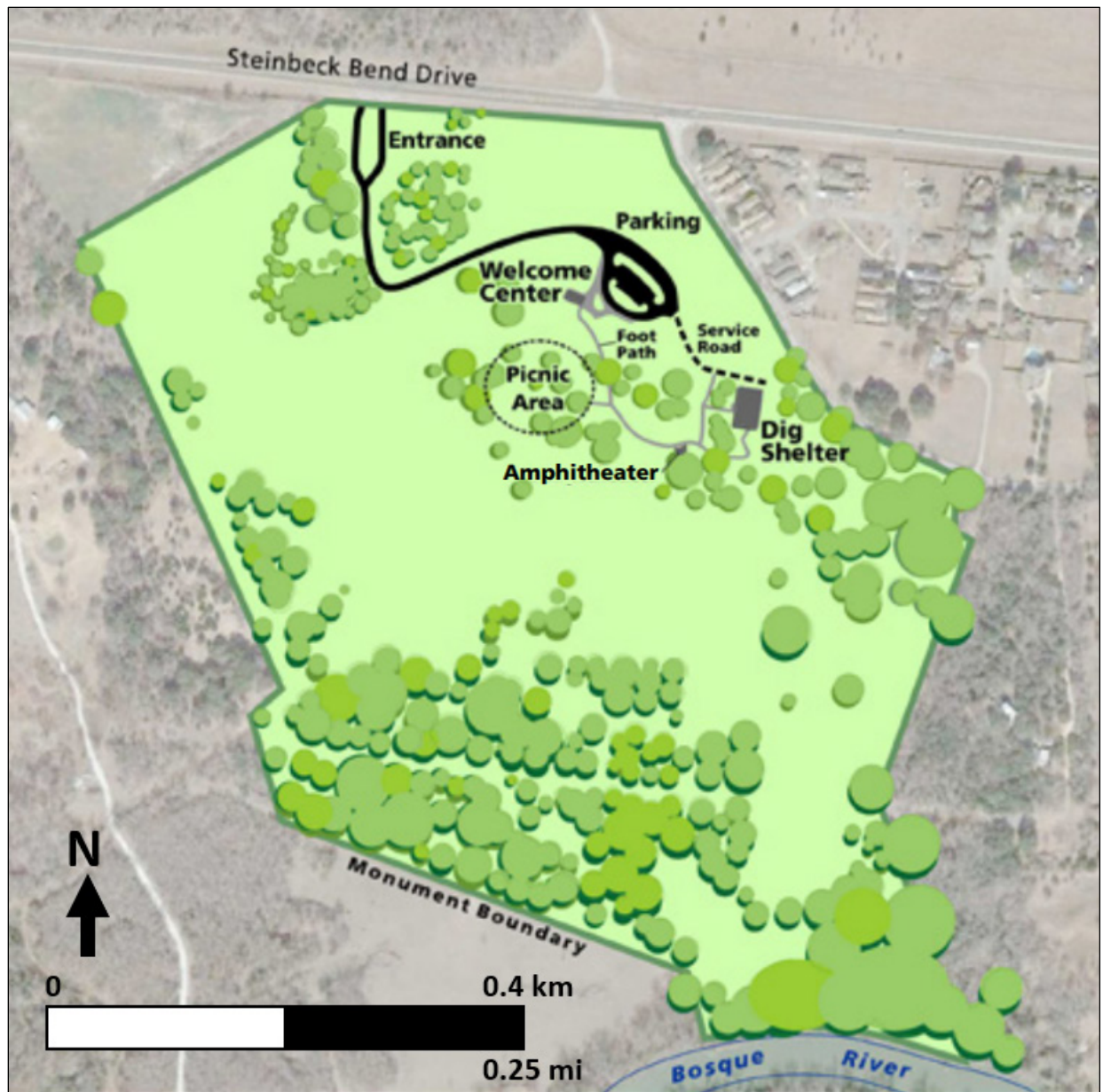
Waco Mammoth National Monument (WACO) is located within the city limits of Waco, near the confluence of the Brazos and Bosque Rivers in McLennan County, Texas (Figure 38). Designated a national park unit on July 10, 2015, WACO encompasses approximately 43 hectares (107 acres) and protects the only nursery herd of Pleistocene-age Columbian mammoths known to exist in the United States. The first mammoth fossils at WACO were discovered in 1978 by two Waco residents who noticed a bone protruding from the sidewall of a ravine while taking a hike. To date 23 mammoths, one sabertoothed cat, a camel, and other Ice Age animals have been found here (National Park Service 2016a). The paleontological resources at WACO are unique and scientifically notable, preserving a large number of nearly intact mammoths that include both adult female and juvenile specimens. The excavated and in situ fossil collection at WACO provides an exceptional opportunity to study and interpret the behavior and herd structure of the extinct Columbian mammoth, but also helps scientists construct an important snapshot of the rich diversity of life that existed along the interface of the Great Plains and the Gulf Coastal Plains during the late Pleistocene (National Park Service 2016b).

## **Geologic Summary**

The geologic landscape at WACO dates back thousands of years and preserves Texas Ice Age environments that encapsulate a rich assemblage of Pleistocene fauna. Mammoths migrated across the Bering Land Bridge from northeastern Siberia into North America approximately 1.7 million years ago. The Columbian mammoth evolved from its ancestral mammoth species about 126,000 years ago and was the largest North American mammoth species. Standing more than 4 m (14 ft) tall and weighing up to 20,000 pounds, the Columbian mammoth was bigger than modern-day elephants and roamed over much of North America, with a range that included most of the contiguous United States and extended south into Costa Rica (National Park Service 2016b). Geologic units in WACO are relatively young, Quaternary-age surficial deposits predominantly consisting of terrace deposits and unconsolidated alluvium (Figure 39). The monument's paleontological dig shelter is situated in the northern portion of the monument where terrace deposits have exceptionally preserved the Ice Age faunal specimens.

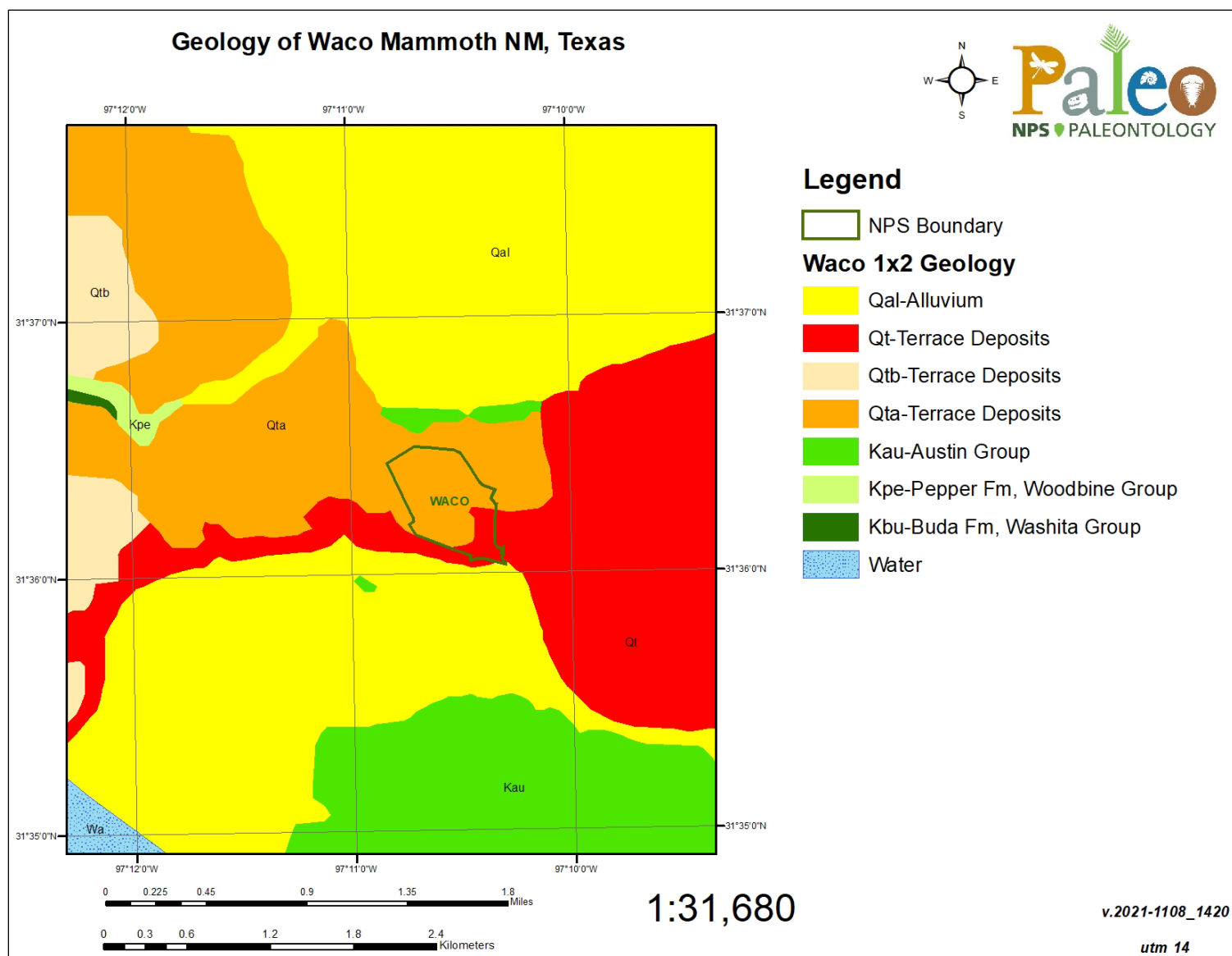
## **Stratotypes**

There are no designated stratotypes identified within the boundaries of WACO. There are two identified stratotypes located within 48 km (30 mi) of WACO boundaries that are provided in Appendix C for reference in case of future monument boundary expansion.



**Figure 38.** Park map of WACO, Texas (NPS).





**Figure 39.** Geologic map of WACO, Texas. Data modified from PDF file at [https://store.beg.utexas.edu/geologic-atlas-of-texas/2111-ga0037.html?search\\_query=waco&results=12](https://store.beg.utexas.edu/geologic-atlas-of-texas/2111-ga0037.html?search_query=waco&results=12).



# **Washita Battlefield National Historic Site (WABA)**

## **Park Establishment**

Washita Battlefield National Historic Site (WABA) is located just outside of Cheyenne and approximately 201 km (125 mi) west of Oklahoma City in Roger Mills County, Oklahoma (Figure 40). Authorized on November 12, 1996, WABA contains about 127 hectares (315 acres) and was established to preserve, protect, and commemorate the site of the controversial “Battle of the Washita”. Described as both a battle and a massacre, the November 27, 1868 attack of the 7<sup>th</sup> U.S. Cavalry under Lieutenant Colonel George A. Custer destroyed Peace Chief Black Kettle’s Cheyenne village and resulted in more than 100 Cheyenne captured or killed (National Park Service 2016a). The attack on the Cheyenne encampment along the Washita River was the first implementation of a new strategy adopted by the U.S. Army to strike tribal settlements during the winter, when they were most vulnerable. The confrontation at Washita established Custer’s reputation as an aggressive “Indian fighter” and represented a pivotal point for the Cheyenne and other Southern Great Plains tribes, symbolizing their struggle to maintain their traditional way of life (National Park Service 2016c).

## **Geologic Summary**

WABA is situated in the Anadarko Basin, a deep sedimentary basin containing a thick accumulation of Cambrian through Permian-age strata that is renowned for its rich hydrocarbon resources. Formation of the Anadarko Basin can be traced to the Late Mississippian–Early Pennsylvanian Wichita Orogeny, which occurred during the tectonic collision that created the supercontinent Pangea (Perry 1989). The bedrock underlying WABA consists entirely of the Permian Doxey Formation and Cloud Chief Formation, which are generally covered by surficial deposits except for small areas of the eastern half of the historic site. The landscape of WABA is dominated by Quaternary-age surficial deposits that are largely associated with the Washita River Valley (Figure 41). The northern portion of WABA consists of floodplain deposits and paleodunes while the southern area of the historic site contains fluvial terrace deposits.

## **Stratotypes**

There are no designated stratotypes identified within the boundaries of WABA. There are four identified stratotypes located within 48 km (30 mi) of WABA boundaries that are provided in Appendix C for reference in case of future historic site boundary expansion.

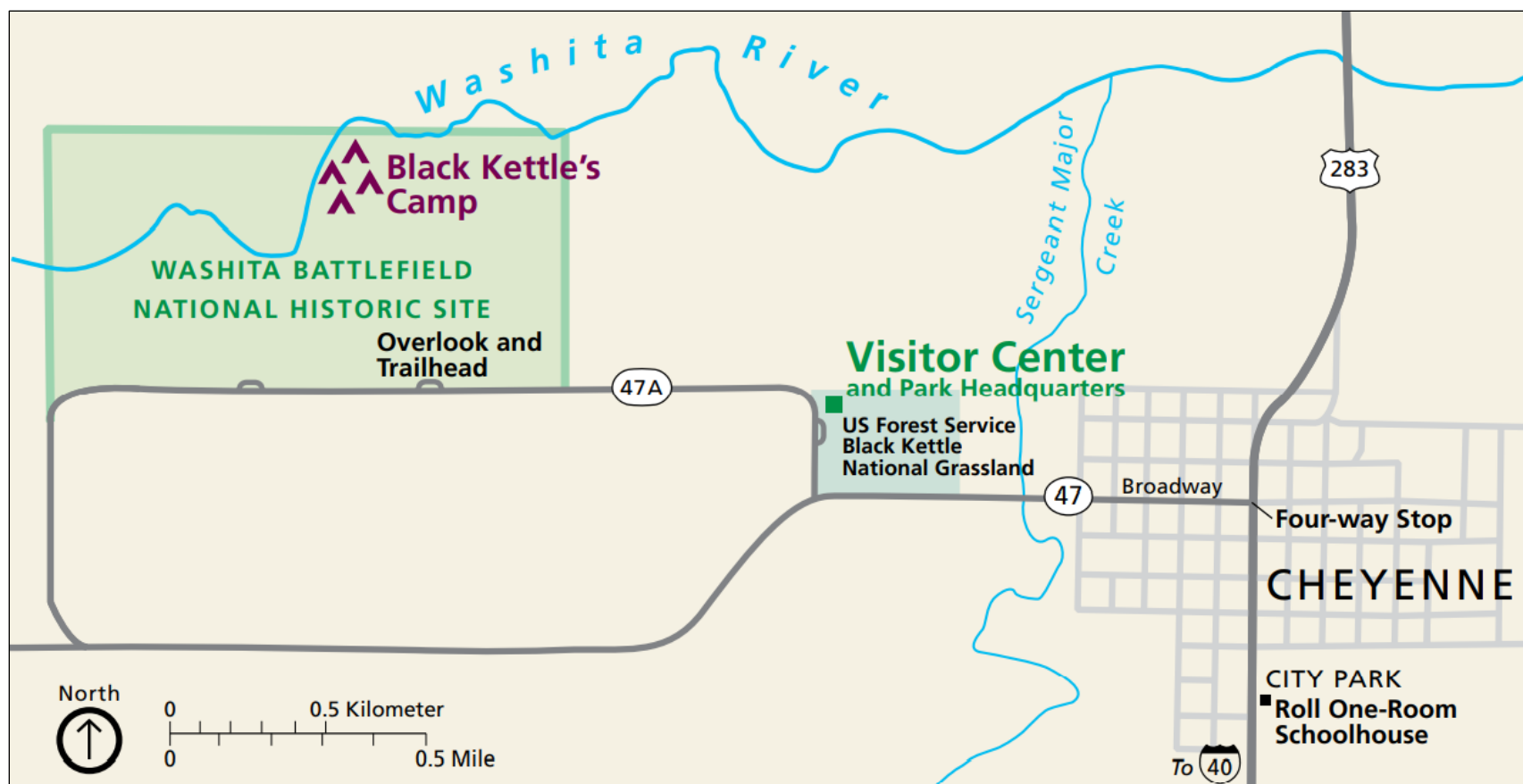
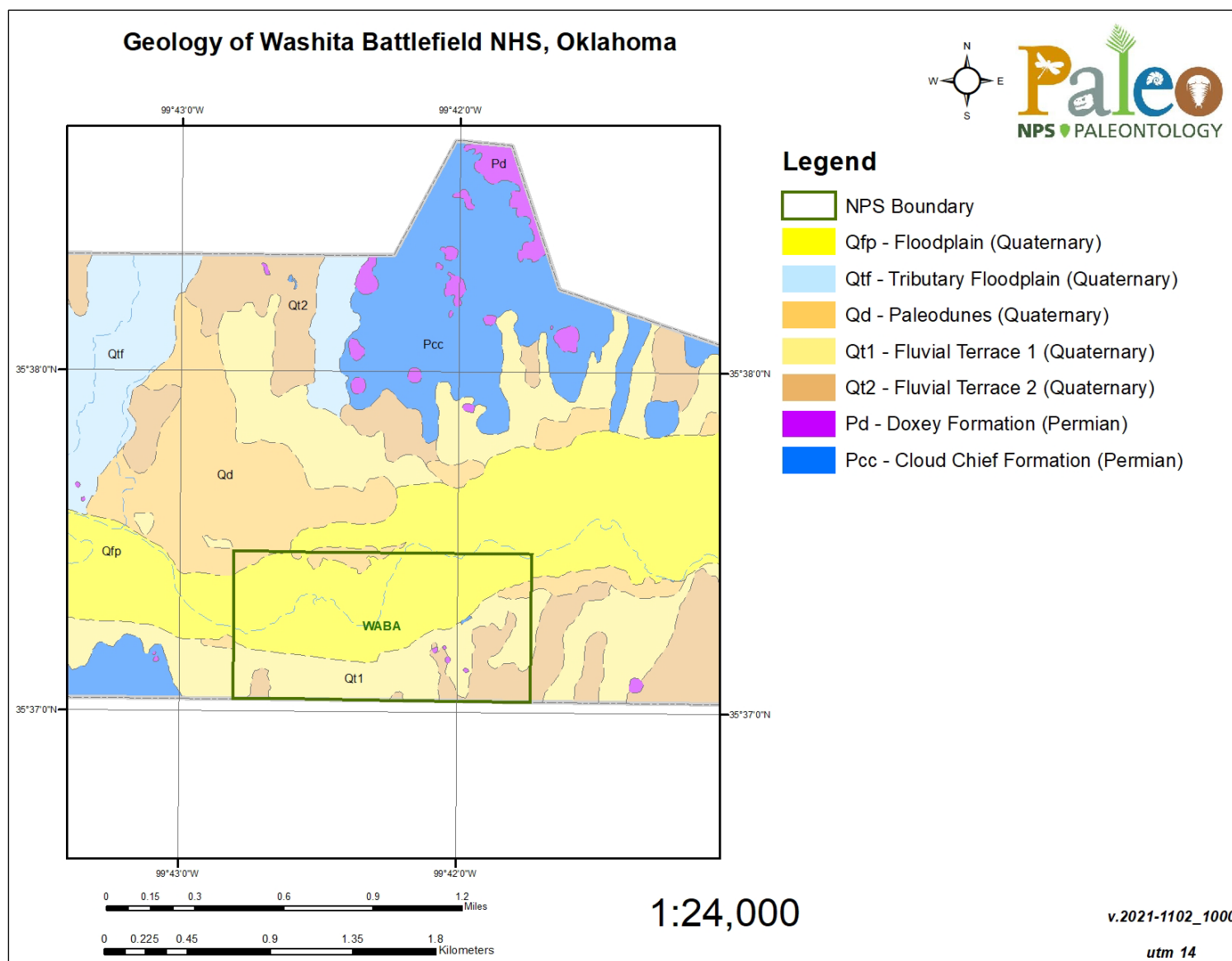


Figure 40. Park map of WABA, Oklahoma (NPS).



**Figure 41.** Geologic map of WABA, Oklahoma. Data modified from WABA GRI digital geologic map data at <https://irma.nps.gov/DataStore/Reference/Profile/2194280>.



## 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 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 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 stratotypes designated external to an NPS area that may face destruction, alteration, or other significant impacts, the NPS Geologic Resources Division can work with park staff to potentially set up a reference section within an NPS area, which affords a baseline level of protection.
4. The NPS Geologic Resources Division should work with park 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).
5. From the assessment in (4), 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).

6. The NPS Geologic Resources Division should work with park 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, queryable 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. A paper by Crofts et al. (2020) provides additional details on potential threats. Brocx et al. (2019) include examples of destroyed stratotypes and suggest protocols for conservation in Australia. Criteria to assess 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. Photographs of each stratotype are rare and thus obtaining photographs of NPS stratotypes is a first step for resource management. 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)
- Tectonism and volcanism

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

Potential human activities that 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 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 SOPN 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>.

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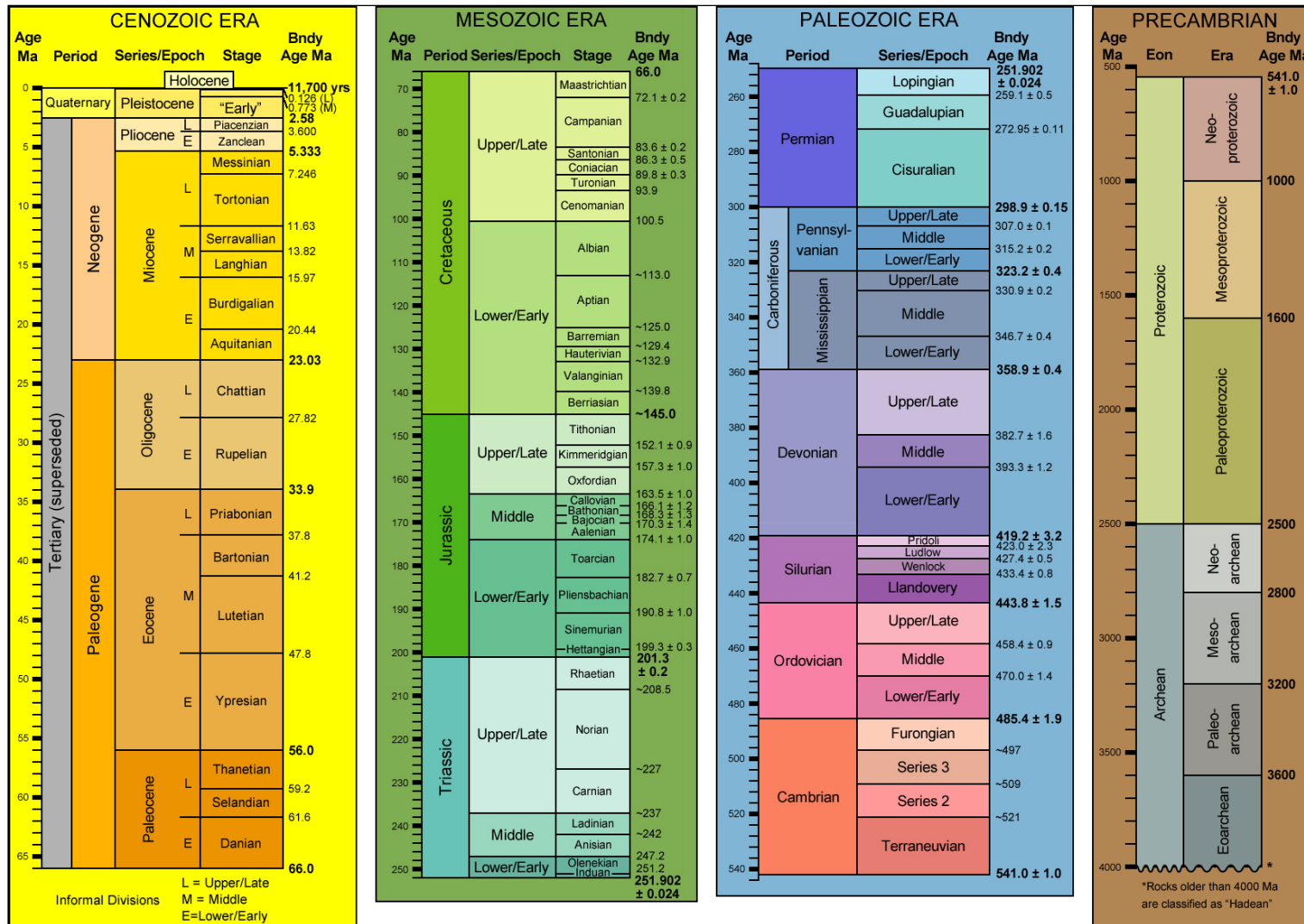
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## Appendix B: Geologic Time Scale



**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 SOPN Parks**

### **CAVO**

- Oligocene
  - Slagle Trachyte (type area)
- Oligocene–Miocene
  - Chico Phonolite (type area)
- Miocene
  - Red Mountain Rhyodacite (type locality)
- Pliocene
  - Raton Basalt (type area)
- Pliocene–Pleistocene
  - Clayton Basalt (type area)

### **CHIC**

- Ordovician
  - Oil Creek Formation (type locality)
  - Oil Creek Formation, Pruitt Ranch Limestone Member (type section)
  - Bromide Formation (type section)
  - Bromide Formation, Mountain Lake Member (type section)
  - Bromide Formation, Pooleville Member (type section)
  - Joins Formation (type locality)
  - West Spring Creek Formation (type section)
  - Tulip Creek Formation (type section)
  - Chimneyhill Limestone, Ideal Quarry Member (type section)
  - Chimneyhill Limestone, Keel Member (type locality)
  - Corbin Ranch Formation (type section)
  - McLish Formation (type locality)
  - Viola Springs Formation (type section)
- Ordovician–Silurian
  - Chimneyhill Limestone (type locality)
- Silurian
  - Cochran Formation (type section)

- Henryhouse Formation (type section)
- Clarita Formation (type locality)
- Clarita Formation, Fitzhugh Member (type locality)
- Clarita Formation, Price Falls Member (type section)
- Devonian
  - Haragan Shale (type area)
  - Frisco Limestone (type section)
  - Bois d'Arc Formation (type section and type locality)
  - Bois d'Arc Formation, Cravatt Member (type locality)
  - Bois d'Arc Formation, Fittstown Member (type locality)
- Mississippian
  - Goddard Formation (type section and type locality)
  - Goddard Formation, Redoak Hollow Member (type locality)
  - Goddard Formation, Tiff Member (type section)
  - Welden Limestone (type locality)
  - Caney Shale (type section)
  - Caney Shale, Delaware Creek Member (type section)
  - Sycamore Limestone (type area)
  - Sycamore Limestone, Cornell Ranch Member (type section)
  - Sycamore Limestone, Worthey Member (type section)
- Mississippian–Pennsylvanian
  - Springer Formation (type area)
- Pennsylvanian
  - Deese Group (type locality)
  - Deese Formation/Group, Natsy Member (type locality)
  - West Arm Formation (type locality)
  - Springer Formation, Academy Church Shale Member (type locality)
  - Lake Ardmore Sandstone (type locality)
  - Atoka Formation, Barnett Hill Member (type locality)
  - Wapanucka Formation (type locality)

## FOUN

- Mississippian
  - Tererro Formation, Manuelitas Member (type section)

- Tererro Formation, Turquillo Member (type section)
- Pennsylvanian
  - Alamitos Formation (reference section)
  - Sandia Formation (principal reference section)

## **LYJO**

- Ordovician
  - Honeycut Limestone (type section)
- Devonian
  - Stribling Formation (type section)
- Devonian–Mississippian
  - Houy Formation (type section)
  - Houy Formation, Doublehorn Shale Member (type section)
- Pennsylvanian
  - Marble Falls Limestone (type locality)

## **PECO**

- Mississippian
  - Tererro Formation (type locality)
  - Tererro Formation, Cowles Member (type section)
  - Tererro Formation, Macho Member (type section)
  - Tererro Formation, Manuelitas Member (type section)
  - Espiritu Santo Formation (type locality)
  - Espiritu Santo Formation, Del Padre Sandstone Member (type locality)
- Pennsylvanian
  - Alamitos Formation (composite type section)
  - La Pasada Formation (type locality)
- Permian
  - Glorieta Sandstone (type section)
- Cretaceous
  - Mancos Shale, Juana Lopez Member (type section)
- Paleocene–Eocene
  - Galisteo Formation (type section)
- Oligocene–Pliocene



- Santa Fe Group (type area)
- Miocene
  - Tesuque Formation (type section)
  - Tesuque Formation Bishops Lodge Member (type section)
  - Tesuque Formation Nambe Member (type section)
  - Tesuque Formation, Pojoaque Member (type section)
  - Tesuque Formation, Skull Ridge Member (type section)
- Pliocene
  - Puye Conglomerate (type section)
  - Puye Conglomerate, Totavi Lentil (type locality)
- Pliocene–Pleistocene
  - Ancha Formation (type section)
- Pleistocene
  - Bandelier Tuff, Otowi Member (type area)

## **WABA**

- Permian
  - Elk City Sandstone (type section)
  - Doxey Formation (type section)
  - Cloud Chief Formation (type section)
  - Cloud Chief Formation, Big Basin Member (type section)

## **WACO**

- Cretaceous
  - Atco Formation (type locality)
  - Bruceville Formation (type locality)

The Department of the Interior protects and manages the nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its special responsibilities to American Indians, Alaska Natives, and affiliated Island Communities.

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National Park Service  
U.S. Department of the Interior



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**[Natural Resource Stewardship and Science](#)**

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