National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

National Park Service Geologic Type Section Inventory

Chihuahuan Desert Inventory & Monitoring Network

Natural Resource Report NPS/CHDN/NRR—2021/2249

ON THE COVER

Exposures of the Chisos Formation and its members at Goat Mountain, BIBE. Goat Mountain is the type locality for the Wasp Spring Flow Breccia Member of the Chisos Formation (USGS).

National Park Service Geologic Type Section Inventory

Chihuahuan Desert Inventory & Monitoring Network

Natural Resource Report NPS/CHDN/NRR—2021/2249

Tim Henderson,[1] Vincent L. Santucci[1], Tim Connors[2], and Justin S. Tweet[3]

[1]National Park Service
Geologic Resources Division
1849 "C" Street, NW
Washington, D.C. 20240

[2]National Park Service
Geologic Resources Division
Post Office Box 25287
Denver, Colorado 80225

[3]National Park Service
9149 79th Street S.
Cottage Grove, Minnesota 55016

April 2021

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

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

The Natural Resource Report Series is used to disseminate comprehensive information and analysis about natural resources and related topics concerning lands managed by the National Park Service. The series supports the advancement of science, informed decision-making, and the achievement of the National Park Service mission. The series also provides a forum for presenting more lengthy results that may not be accepted by publications with page limitations.

All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner.

This report received informal peer review by subject-matter experts who were not directly involved in the collection, analysis, or reporting of the data.

This report is available in digital format from the Chihuahuan Desert Inventory and Monitoring Network and Natural Resource Publications Management websites. If you have difficulty accessing information in this publication, particularly if using assistive technology, please email irma@nps.gov.

Please cite this publication as:

Henderson, T., V. L. Santucci, T. Connors, and J. S. Tweet. 2021. National Park Service geologic type section inventory: Chihuahuan Desert Inventory & Monitoring Network. Natural Resource Report NPS/CHDN/NRR—2021/2249. National Park Service, Fort Collins, Colorado. https://doi.org/10.36967/nrr-2285306.

NPS 960/175233, April 2021

Contents

Contents (continued)

Figures

Page

Figures (continued)

Page

Tables

Page

Photographs

Page

Executive Summary

A fundamental responsibility of the National Park Service is to ensure that park resources are preserved, protected, and managed in consideration of the resources themselves and for the benefit and enjoyment by the public. Through the inventory, monitoring, and study of park resources, we gain a greater understanding of the scope, significance, distribution, and management issues associated with these resources and their use. This baseline of natural resource information is available to inform park managers, scientists, stakeholders, and the public about the conditions of these resources and the factors or activities which may threaten or influence their stability.

There are several different categories of geologic or stratigraphic units (supergroup, group, formation, member, bed) which represent a hierarchical system of classification. The mapping of stratigraphic units involves the evaluation of lithologies, bedding properties, thickness, geographic distribution, and other factors. If a new mappable geologic unit is identified, it 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 2005). 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 of the unit is designated as the type section or type locality (see Definitions). The type section is an important reference section for a named geologic unit which presents a relatively complete and representative profile for this unit. The type or reference section is important both historically and scientifically, and should be recorded such that other researchers may evaluate it in the future. Therefore, this inventory of geologic type sections in NPS areas is an important effort in documenting these locations in order that NPS staff recognize and protect these areas for future studies.

The documentation of all geologic type sections throughout the 423 units of the NPS is an ambitious undertaking. The strategy for this project is to select a subset of parks to begin research for the occurrence of geologic type sections within particular parks. The focus adopted for completing the baseline inventories throughout the NPS was centered on the 32 inventory and monitoring networks (I&M) established during the late 1990s. The I&M networks are clusters of parks within a defined geographic area based on the ecoregions of North America (Fenneman 1946; Bailey 1976; Omernik 1987). These networks share similar physical resources (geology, hydrology, climate), biological resources (flora, fauna), and ecological characteristics. Specialists familiar with the resources and ecological parameters of the network, and associated parks, work with park staff to support network level activities (inventory, monitoring, research, data management).

Adopting a network-based approach to inventories worked well when the NPS undertook paleontological resource inventories for the 32 I&M networks. The network approach is also being applied to the inventory for the geologic type sections in the NPS. The planning team from the NPS Geologic Resources Division who proposed and designed this inventory selected the Greater Yellowstone Inventory and Monitoring Network (GRYN) as the pilot network for initiating this project. Through the research undertaken to identify the geologic type sections within the parks of the GRYN, methodologies for data mining and reporting on these resources was established.

Methodologies and reporting adopted for the GRYN have been used in the development of this type section inventory for the Chihuahuan Desert Inventory & Monitoring Network.

The goal of this project is to consolidate information pertaining to geologic type sections which 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 landmarks and geologic heritage resources. The review of stratotype occurrences for the CHDN shows there are currently no designated stratotypes for AMIS, CAVE, FODA, RIGR, or WHSA; BIBE contains 31 stratotypes that are subdivided into ten type sections, seventeen type localities, and four reference sections; and GUMO contains 24 stratotypes that are subdivided into a Global Stratotype Section and Point (GSSP) with three component stages, ten type sections, five type localities, and six reference sections.

This report concludes with 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.

Acknowledgments

Many individuals were consulted in the preparation of this report on the geologic type sections for the national parks of the Chihuahuan Desert Inventory and Monitoring Network. We first want to extend our sincere appreciation to Randy Orndorff, David Soller, and Nancy Stamm (U.S. Geological Survey [USGS]) for their assistance with this geologic type section inventory and other important NPS projects. Randy, Nancy and David manage the National Geologic Map Database for the United States (NGMDB, https://ngmdb.usgs.gov/ngm-bin/ngm_compsearch.pl?glx=1) and the U.S. Geologic Names Lexicon ("GEOLEX", https://ngmdb.usgs.gov/Geolex/search), critical sources of geologic map information for science, industry and the American public. We also extend our appreciation to Don Parker (Baylor University), Chris Henry (Nevada Bureau of Mines & Geology; University of Nevada), and Kevin Urbanczyk (Sul Ross State University) for providing information or assistance with the review of this document.

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. A special thanks to Jason Suarez (The University of Texas Bureau of Economic Geology) for the permission to use figures in this publication. 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 Chihuahuan Desert Inventory and Monitoring Network and various network parks, including: Andy Hubbard, Cheryl McIntyre, Mark Isley, and Allyson Mathis (CHDN), Don Corrick (BIBE), Rod Horrocks (CAVE), Jonena Hearst (GUMO), and David Bustos (WHSA). Additional thanks to Michael Bozek and Don Weeks for continued support for this and other important geology projects in the Intermountain Region of the NPS.

This project is possible through the support from research associates and staff in the National Park Service Geologic Resources Division and we extend our thanks to Hal Pranger, Julia Brunner, Jason Kenworthy, and Jim Wood. We especially appreciate the dedicated assistance from Lima Soto, the past Geoscientists-in-the-Parks Program (GIP) Coordinator, to ensure a highly qualified geology intern was hired for this project.

Dedication

This Chihuahuan Desert Inventory and Monitoring Network Geologic Type Section Inventory is dedicated to Big Bend National Park Geologist Don Corrick. Don's more than two decades of professional and scientific contributions at the park have significantly advanced the management, protection, study, and interpretation of the geological resources of Big Bend National Park. In 2017, Don's long-term dream to renovate the old paleontology exhibit at the park was realized with the dedication of the Fossil Discovery Exhibit. We are grateful for his continuous support to geologic issues in Big Bend National Park and throughout the National Park System, and dedicate this report to him.

Don Corrick, Geologist at Big Bend National Park, during the dedication of the park's new Fossil Discovery Exhibit (January 2017) (NPS).

Introduction

The NPS Geologic Type Section Inventory Project ("Stratotype Inventory Project") is a continuation of and complements the work performed by the Geologic Resources Inventory (GRI). The GRI is funded by the NPS Inventory and Monitoring Program and administered by the Geologic Resources Division (GRD). The GRI is designed to compile and present baseline geologic resource information available to park managers, and advance science-informed management of natural resources in the national parks. The goals of the GRI team are to increase understanding and appreciation of the geologic features and processes in parks and provide robust geologic information for use in park planning, decision making, public education, and resource stewardship.

Documentation of stratotypes (i.e., type sections/type localities/type areas) that occur within national park boundaries represents a significant component of a geologic resource inventory, as these designations serve as the standard for defining and recognizing geologic units (North American Commission on Stratigraphic Nomenclature 2005). The importance of stratotypes lies in the fact that they store information, represent important comparative sites where knowledge can be built up or reexamined, and can serve as teaching sites for students (Brocx et al. 2019). The geoheritage significance of stratotypes is analogous to that of libraries and museums, in that they are natural reservoirs of Earth history spanning ~4.5 billion years and record the prodigious forces and evolving life forms that define our planet and our understanding as a contributing species.

The goals of this project are to: (1) systematically report the assigned stratotypes that occur within national park boundaries; (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. Additionally, numerous stratotypes are located geographically outside of national park boundaries, but only those within 48 km (30 mi) of park boundaries will be presented in this report.

This geologic type section inventory for the parks of the Chihuahuan Desert Inventory & Monitoring Network (CHDN) follows standard practices, methodologies, and organization of information introduced in the Greater Yellowstone I&M Network type section inventory (Henderson et al. 2020). All network-specific reports are prepared, peer-reviewed, and submitted to the Natural Resources Stewardship and Science Publications Office for finalization. A small team of geologists and paleontologists from the NPS Geologic Resources Division and the NPS Paleontology Program have stepped up to undertake this important inventory for the NPS.

This inventory fills a current void in basic geologic information not currently compiled by the NPS either at most parks and at the servicewide level. This inventory requires some intensive and strategic data mining activities to determine instances where geologic type sections occur within NPS areas. Sometimes the lack of specific locality or other data presents limitations in determining if a particular type section is geographically located within or outside NPS administered boundaries. Below are the primary considerations warranting this inventory of NPS geologic type sections.

- Geologic type sections are a part of our national geologic heritage and are a cornerstone of the scientific value used to define the societal significance of geoheritage sites (https://www.nps.gov/articles/scientific-value.htm);
- Geologic type sections are important geologic landmarks and reference locations which define important scientific information associated with geologic strata. Geologic formations are commonly named after geologic features and landmarks that are recognizable to park staff;
- Geologic type sections are both historically and scientifically important components of earth sciences and mapping;
- Understanding and interpretation of the geologic record is largely dependent upon the stratigraphic occurrences of mappable lithologic units (formations, members). These geologic units are the foundational attributes of geologic maps;
- Geologic maps are important tools for science, resource management, land use planning, and other areas and disciplines;
- Geologic type sections are similar in nature to type specimens in biology and paleontology, serving as a "gold standard" which help to define characteristics used in classification;
- The documentation of geologic type sections in NPS areas has not been previously inventoried and there is a general absence of baseline information for this geologic resource category.
- In general, NPS staff in parks are not aware of the concept of geologic type sections and therefore may not understand the significance or occurrence of these natural landmarks in parks;
- Given the importance of geologic type sections as geologic landmarks and geologic heritage resources, these locations should be afforded some level of preservation or protection when they occur within NPS areas;
- If NPS staff are unaware of geologic type sections within parks, the NPS would not proactively monitor the stability, condition, or potential impacts to these locations during normal park operations or planning. The lack of baseline information pertaining to the geologic type sections in parks would limit the protection of these localities from activities which may involve ground disturbance or construction. Therefore, considerations need to be addressed about how the NPS may preserve geologic type sections and better inform NPS staff about their existence in the park.
- There may be an important conversation that needs to be addressed regarding whether or not geologic type sections 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 type sections which are established on NPS administered lands. Through this inventory, the associated report, and close communication with park and I&M Network staff, the hope is 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 type sections are preserved and available for future study.

Geology and Stratigraphy of the Chihuahuan Desert I&M Network Parks

The Chihuahuan Desert Inventory & Monitoring Network (CHDN) consists of seven national park units in the desert and mountain landscapes of southeastern New Mexico and west Texas (Figure 1). The Chihuahuan Desert is an expansive ecoregion covering nearly 647,500 km^2 (250,000 mi^2) of the southwestern United States and northern Mexico and represents one of the most biologically diverse deserts in the Western Hemisphere. The Chihuahuan Desert is geographically isolated and distinct ecologically from adjacent arid desert regions by two mountain ranges, the Sierra Madre Occidental to the west and the Sierra Madre Oriental to the east. Within the United States, the Chihuahuan Desert spans the Trans-Pecos region of Texas, along the Rio Grande River, into southern New Mexico.

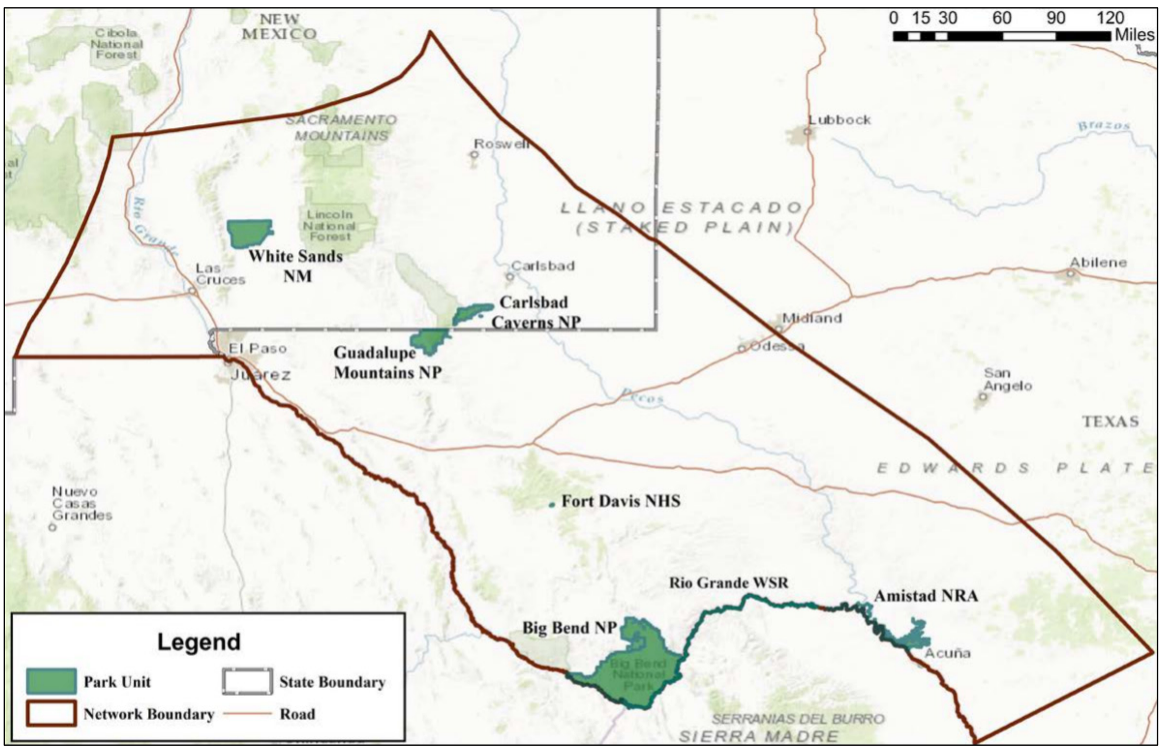


Figure 1. Map of Chihuahuan Desert Network parks, including: Amistad National Recreation Area (AMIS), Big Bend National Park (BIBE), Carlsbad Caverns National Park (CAVE), Fort Davis National Historic Site (FODA), Guadalupe Mountains National Park (GUMO), Rio Grande Wild and Scenic River (RIGR), and White Sands National Park (WHSA; previously a National Monument) (NPS).

The Chihuahuan Desert consists of a basin and range topography with broad desert valleys bordered by fault-block mountains. The topography forms closed basins which support playa lakes and dune field development. This ecoregion lies within the Pecos and Rio Grande drainage systems in the U.S. The Permian or Capitan reef system is represented in the Guadalupe and Glass Mountains in southern

New Mexico and west Texas, supporting extensive cave and karst resources including Carlsbad Caverns National Park, which is a UNESCO World Heritage Site.

Precambrian

The CHDN parks do not include any exposed or mapped Precambrian rocks within the park boundaries (see Appendix B for a geologic time scale).

Paleozoic

The Paleozoic geology of the CHDN is represented at BIBE, CAVE, and GUMO. BIBE preserves a series of Paleozoic units which range from Ordovician to Early Pennsylvanian in age. During the Paleozoic the Big Bend area was situated within a northeasterly trending trough called the Ouachita Trough. The trough was submerged by marine seas and was a depositional center for continental sediments. Maxwell et al. (1967) refers to the Paleozoic sequences at Persimmon Gap as undifferentiated limestones, chert, novaculite, and shale from the Maravillas, Caballos, and Tesnus formations. The Tesnus Formation is Late Mississippian to Early Pennsylvanian in age with marine and non-marine units (Fan and Shaw 1956; Noble 1992). The lower unit of the Tesnus Formation consists of massive and interbedded marine sandstone turbidites and siliceous shales. The upper unit is predominantly non-marine and consists of fine-grained clastic sediments.

Permian strata are well-exposed at GUMO and CAVE in the Guadalupe Mountains of west Texas and southern New Mexico. A large normal fault defines the western flank of the Guadalupe Mountains, while the eastern edge is marked by the Capitan Reef escarpment. The reef escarpment preserves the Permian depositional profile of the Delaware Basin. The Capitan Reef is exposed in both GUMO and CAVE. At GUMO the reef consists of an uplifted block forming a prominent mountain range. At CAVE the reef is exposed in the same uplifted block but is at lower elevation due to a regional dip.

Three areas in GUMO have been designated by the International Union of Geological Sciences (IUGS) as Global Stratotype Sections for the middle Permian Guadalupian Series of the geologic time scale along with their component Roadian, Wordian, and Capitanian Stages (Henderson et al. 2012). The middle Permian is known worldwide as the Guadalupian Series.

The middle Permian Artesia Group (Tansill, Yates, Seven Rivers, Queen and Grayburg formations) and the Capitan Limestone are the primary geologic units exposed in both CAVE and GUMO. Older units representing the early and middle Permian are mapped at GUMO and include the Bone Spring Limestone, Victorio Peak Formation, Cutoff Formation, Brushy Canyon Formation, Cherry Canyon Formation, Goat Seep Dolomite, and Bell Canyon Formation.

Mesozoic

The Mesozoic geology of the CHDN is represented by Cretaceous units within AMIS, BIBE, and RIGR. The Cretaceous geology exposed within AMIS includes the Salmon Peak Limestone, Devils River Limestone, Del Rio Clay, Buda Limestone, and the Boquillas Formation. The grand cliffs that bound the Pecos River in the vicinity of AMIS are composed of Lower Cretaceous Devils River

Limestone which represents some of the most complete exposures of Lower Cretaceous rock in North America (Kerans et al. 1995).

BIBE's Mesozoic section is dominated by marine and terrestrial deposits from the Cretaceous. The thick Cretaceous sequence includes the terminal Cretaceous–Paleogene transition. The Cretaceous sequence in stratigraphic order includes: Glen Rose Limestone, Telephone Canyon Formation, Del Carmen Limestone, Sue Peaks Formation, Santa Elena Limestone, Devils River Limestone, Del Rio Clay, Buda Limestone, Boquillas Formation, Pen Formation, Aguja Formation, Javelina Formation, and Black Peaks Formation. Most of this sequence, from the Glen Rose Limestone to the Pen Formation, is also exposed within RIGR.

Cenozoic

An extensive Cenozoic history is preserved at BIBE including rocks representing all Paleogene and Neogene epochs spanning from the Paleocene through the Pleistocene. Volcanic flows, talus slopes, pediments and graded plains extend from these mountain highlands. The Chisos Mountains are surrounded by huge fan-like aprons of sediments. Dikes and sills are exposed in and around the pediments. From oldest to youngest, the Cenozoic stratigraphy of BIBE includes the Hannold Hill Formation (early Eocene), Canoe Formation (middle Eocene), Chisos Formation (middle Eocene–early Oligocene), South Rim Formation (early Oligocene), other Oligocene volcanics, Delaho Formation (late Oligocene–middle Miocene), Banta Shut-in Formation (late Miocene) and Pliocene–Pleistocene alluvium.

FODA is located in the Davis Mountains of west Texas and the geology is dominated by thick Cenozoic volcanics documented in three concordant volcanic units of late Eocene age (Everett 1967).

WHSA, in the Tularosa Basin, has no exposures of lithified bedrock, instead being covered by a variety of unlithified sediments pertaining to the Quaternary Lake Otero system (KellerLynn 2012).

National Park Service Geologic Resource Inventory

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 in more than 270 natural resource parks throughout the National Park System. The GRI is one of 12 inventories funded by the National Park Service (NPS) Inventory and Monitoring Program. The Geologic Resources Division (GRD) of the NPS Natural Resource Stewardship and Science Directorate administers the GRI. The GRI team consists of a partnership between the GRD and the Colorado State University Department of Geosciences to produce GRI products.

GRI Products

The GRI team undertakes three tasks for each park in the Inventory and Monitoring program: (1) conduct a scoping meeting and provide a summary document, (2) provide digital geologic map data in a geographic information system (GIS) format, and (3) provide a GRI report. These products are designed and written for non-geoscientists.

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 sessions were held on the following dates for the CHDN parks: CAVE and GUMO on March 6–8, 2001; BIBE on January 15–17, 2002; WHSA on November 14, 2007; FODA on April 15, 2008; and AMIS on April 23, 2008 (no scoping has been held for RIGR).

Following the scoping meeting, the GRI map team converts the geologic maps identified in the mapping plan to GIS data in accordance with the GRI data model. After the map is completed, the GRI report team uses these data, as well as the scoping summary and additional research, to prepare the GRI report. As of 2020, GRI reports have been completed for CAVE, GUMO, and WHIS. The GRI team conducts no new field work in association with their products.

The compilation and use of natural resource information by park managers is called for in the 1998 National Parks Omnibus Management Act (§ 204), 2006 National Park Service Management Policies, and the Natural Resources Inventory and Monitoring Guideline (NPS-75). Additional information regarding the GRI, including contact information, is available at https://www.nps.gov/subjects/geology/gri.htm.

Geologic Map Data

A geologic map in GIS format is the principal deliverable of the GRI program. GRI GIS data produced for the CHDN parks follows the selected source maps and includes components such as: faults, mine area features, mine point features, geologic contacts, geologic units (bedrock, surficial, glacial), geologic line features, structure contours, and so forth. These are commonly acceptable geologic features to include in a geologic map.

Posters display the data over imagery of the park and surrounding area. Complete GIS data are available at the GRI publications website: https://www.nps.gov/subjects/geology/geologic-resources-inventory-products.htm.

Geologic Maps

A geologic map is the fundamental tool for depicting the geology of an area. Geologic maps are two-dimensional representations of the three-dimensional geometry of rock and sediment at, or beneath the land surface (Evans 2016). Colors and symbols on geologic maps correspond to geologic map units. The unit symbols consist of an uppercase letter indicating the geologic age and lowercase letters indicating the formation's name. Other symbols depict structures such as faults or folds, locations of past geologic hazards that may be susceptible to future activity, and other geologic features. Anthropogenic features such as mines or quarries, as well as observation or collection locations, may be indicated on geologic maps. The American Geosciences Institute website (https://www.americangeosciences.org/environment/publications/mapping) provides more information about geologic maps and their uses.

Geologic maps are typically one of two types: surficial or bedrock. Surficial geologic maps typically encompass deposits that are unconsolidated and which formed during the past 2.6 million years (the Quaternary Period). Surficial map units are differentiated by geologic process or depositional environment. Bedrock geologic maps encompass older, typically more consolidated sedimentary, metamorphic, and/or igneous rocks. Bedrock map units are differentiated based on age and/or rock type. GRI has produced various maps for the CHDN parks.

Source Maps

The GRI team does not conduct original geologic mapping. The team digitizes paper maps and compiles and converts digital data to conform to the GRI GIS data model. The GRI GIS dataset includes essential elements of the source maps such as map unit descriptions, a correlation chart of units, a map legend, map notes, cross sections, figures, and references. These items are typically included in a master geology document (PDF) for a specific park. The GRI team uses a unique "GMAP ID" value for each geologic source map, and all sources used to produce the GRI GIS datasets for the CHDN parks can be found in Appendix A.

GRI GIS Data

The GRI team standardizes map deliverables by using a data model. The most recent GRI GIS data for AMIS, BIBE, FODA and WHSA was compiled using data model version 2.1, which is available at https://www.nps.gov/articles/gri-geodatabase-model.htm; the CAVE and GUMO data are based on older data models and need to be upgraded to the most recent version. This data model dictates GIS data structure, including layer architecture, feature attribution, and relationships within ESRI ArcGIS software. The GRI website (https://www.nps.gov/subjects/geology/gri.htm) provides more information about the program's products.

GRI GIS data are available on the GRI publications website (https://www.nps.gov/subjects/geology/geologic-resources-inventory-products.htm) and through the NPS Integrated Resource Management Applications (IRMA) Data Store portal (https://irma.nps.gov/DataStore/Search/Quick). Enter "GRI" as the search text and select AMIS, BIBE, CAVE, FOBU, GUMO, RIGR, or WHSA from the unit list.

The following components are part of the data set:

- A GIS readme file that describes the GRI data formats, naming conventions, extraction instructions, use constraints, and contact information;
- Data in ESRI geodatabase GIS format;
- Layer files with feature symbology;
- Federal Geographic Data Committee (FGDC)-compliant metadata;
- An ancillary map information document that contains information captured from source maps such as map unit descriptions, geologic unit correlation tables, legends, cross-sections, and figures;
- ESRI map documents that display the GRI GIS data; and
- A version of the data viewable in Google Earth (.kml / .kmz file)

GRI Map Posters

Posters of the GRI GIS draped over shaded relief images of the park and surrounding area are included in GRI reports. Not all GIS feature classes are included on the posters. Geographic information and selected park features have been added to the posters. Digital elevation data and added geographic information are not included in the GRI GIS data, but are available online from a variety of sources. Contact GRI for assistance locating these data.

Use Constraints

Graphic and written information provided in this report is not a substitute for site-specific investigations. Ground-disturbing activities should neither be permitted nor denied based upon the information provided. Please contact GRI with any questions.

Minor inaccuracies may exist regarding the locations of geologic features relative to other geologic or geographic features on the posters. Based on the source map scales (1:100,000, 1:62,500, and 1:24,000) and US National Map Accuracy Standards, geologic features represented in the geologic map data are expected to be horizontally within 51 m (167 ft), 32 m (104 ft), and 12 m (40 ft), respectively, of their true locations.

Methods

This section of the report presents the methods employed and definitions adopted during this inventory of geologic type sections located within the administrative boundaries of the parks in the CHDN. This report is part of a more extensive inventory of geologic type sections throughout the National Park System. Therefore, the methods, definitions, and challenges identified here pertain not only to the parks of the CHDN, but also to other inventory and monitoring networks and parks.

There are a number of considerations to be addressed throughout this inventory. The most up-to-date information available is necessary, either found online or in published articles and maps. Occasionally, there is a lack of specific information that limits the information contained in 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 are sometimes identified by different names in each of the states where the units are mapped. An example would be the Triassic Chugwater Formation in Wyoming, which is equivalent to the Spearfish Formation in the Black Hills of South 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.

Finally, it is worth noting that this inventory report is intended for a wide audience, including NPS staff who might not have a background in geology. Therefore, this document has been developed as a reference document that supports science, resource management, and a historic framework for geologic information associated with NPS areas.

Methodology

The process of determining whether a specific stratotype occurs in an NPS area involves multiple steps. The process begins with an evaluation of the existing park-specific GRI map to prepare a full list of recognized map units (Figure 2).

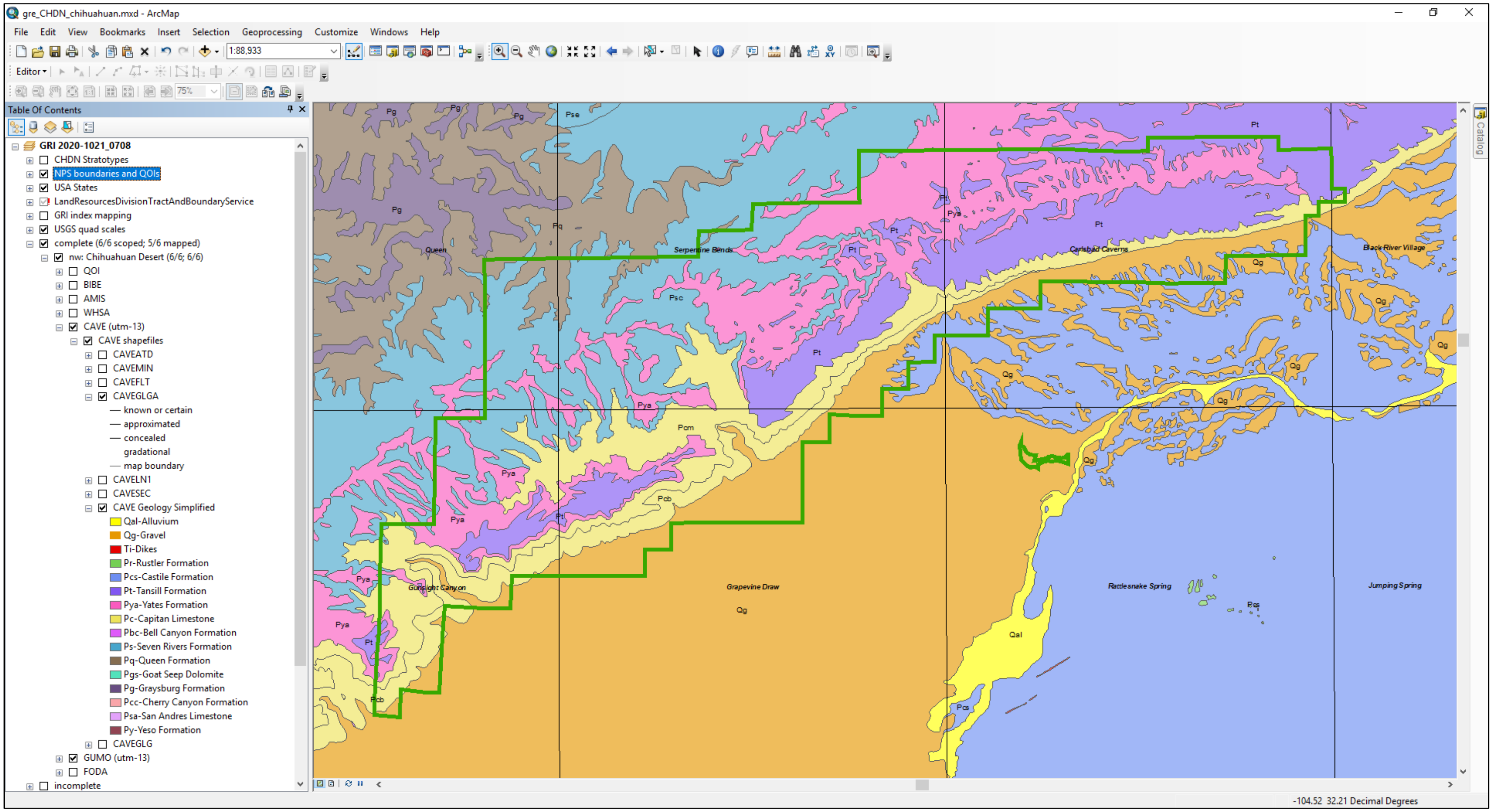


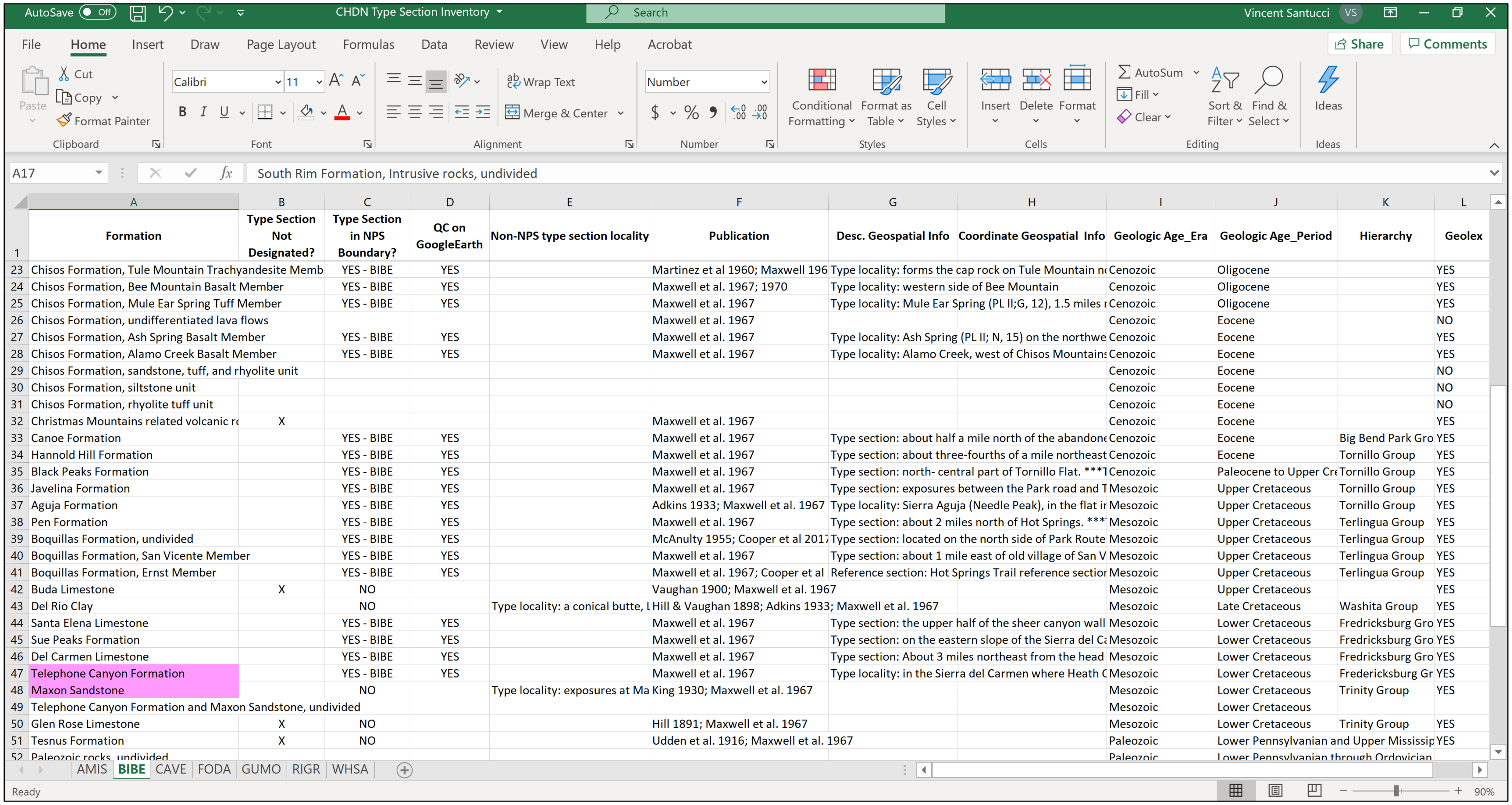
Figure 2. Screenshot of digital geologic map of Carlsbad Caverns National Park showing mapped units.

Each map unit name is then queried in the U.S. 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 3 below is taken from a search on the Javelina Formation.

Figure 3. GEOLEX search result for the Javelina Formation.

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 on subdivisions of a single 93.2 km^2 (36 mi^2) township into 36 individual 2.59 km^2 (1 mi^2) sections, and were converted into Google Earth (.kmz file) locations using Earth Point (https://www.earthpoint.us/TownshipsSearchByDescription.aspx). The most accurate GEOLEX descriptions using TRS coordinates can help locate features within 0.1618 km^2 (0.0625 mi^2). Once stratotype locality information provided for a given unit is geolocated using Google Earth, a GRI digital geologic map of the national park is draped over it. This step serves two functions: to improve accuracy in locating the stratotype, and validating the geologic polygon for agreement with GEOLEX nomenclature. Geolocations in Google Earth are then converted into an ArcGIS format using a "KML to Layer" conversion tool in ArcMap.

After this, 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) is a stratotype officially designated; (2) is the stratotype on NPS land; (3) has it 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) was the geologic unit found in GEOLEX; and (10) a generic notes field (Figure 4).



	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	Hierarchy	Geolex
23	Chisos Formation, Tule Mountain Trachyandesite Memb		YES - BIBE	YES		Martinez et al 1960; Maxwell 196	Type locality: forms the cap rock on Tule Mountain no		Cenozoic	Oligocene		YES
24	Chisos Formation, Bee Mountain Basalt Member		YES - BIBE	YES		Maxwell et al. 1967; 1970	Type locality: western side of Bee Mountain		Cenozoic	Oligocene		YES
25	Chisos Formation, Mule Ear Spring Tuff Member		YES - BIBE	YES		Maxwell et al. 1967	Type locality: Mule Ear Spring (PL II;G, 12), 1.5 miles r		Cenozoic	Oligocene		YES
26	Chisos Formation, undifferentiated lava flows					Maxwell et al. 1967			Cenozoic	Eocene		NO
27	Chisos Formation, Ash Spring Basalt Member		YES - BIBE	YES		Maxwell et al. 1967	Type locality: Ash Spring (PL II; N, 15) on the northwe		Cenozoic	Eocene		YES
28	Chisos Formation, Alamo Creek Basalt Member		YES - BIBE	YES		Maxwell et al. 1967	Type locality: Alamo Creek, west of Chisos Mountains		Cenozoic	Eocene		YES
29	Chisos Formation, sandstone, tuff, and rhyolite unit								Cenozoic	Eocene		NO
30	Chisos Formation, siltstone unit								Cenozoic	Eocene		NO
31	Chisos Formation, rhyolite tuff unit								Cenozoic	Eocene		NO
32	Christmas Mountains related volcanic ro	X				Maxwell et al. 1967			Cenozoic	Eocene		YES
33	Canoe Formation		YES - BIBE	YES		Maxwell et al. 1967	Type section: about half a mile north of the abandone		Cenozoic	Eocene	Big Bend Park Gro	YES
34	Hannold Hill Formation		YES - BIBE	YES		Maxwell et al. 1967	Type section: about three-fourths of a mile northeast		Cenozoic	Eocene	Tornillo Group	YES
35	Black Peaks Formation		YES - BIBE	YES		Maxwell et al. 1967	Type section: north- central part of Tornillo Flat. ***T		Cenozoic	Paleocene to Upper Cre	Tornillo Group	YES
36	Javelina Formation		YES - BIBE	YES		Maxwell et al. 1967	Type section: exposures between the Park road and T		Mesozoic	Upper Cretaceous	Tornillo Group	YES
37	Aguja Formation		YES - BIBE	YES		Adkins 1933; Maxwell et al. 1967	Type locality: Sierra Aguja (Needle Peak), in the flat ir		Mesozoic	Upper Cretaceous	Tornillo Group	YES
38	Pen Formation		YES - BIBE	YES		Maxwell et al. 1967	Type section: about 2 miles north of Hot Springs. ***		Mesozoic	Upper Cretaceous	Terlingua Group	YES
39	Boquillas Formation, undivided		YES - BIBE	YES		McAnulty 1955; Cooper et al 2017	Type section: located on the north side of Park Route		Mesozoic	Upper Cretaceous	Terlingua Group	YES
40	Boquillas Formation, San Vicente Member		YES - BIBE	YES		Maxwell et al. 1967	Type section: about 1 mile east of old village of San V		Mesozoic	Upper Cretaceous	Terlingua Group	YES
41	Boquillas Formation, Ernst Member		YES - BIBE	YES		Maxwell et al. 1967; Cooper et al	Reference section: Hot Springs Trail reference sectior		Mesozoic	Upper Cretaceous	Terlingua Group	YES
42	Buda Limestone	X	NO			Vaughan 1900; Maxwell et al. 1967			Mesozoic	Upper Cretaceous		YES
43	Del Rio Clay		NO		Type locality: a conical butte, l	Hill & Vaughan 1898; Adkins 1933; Maxwell et al. 1967			Mesozoic	Late Cretaceous	Washita Group	YES
44	Santa Elena Limestone		YES - BIBE	YES		Maxwell et al. 1967	Type section: the upper half of the sheer canyon wall		Mesozoic	Lower Cretaceous	Fredricksburg Gro	YES
45	Sue Peaks Formation		YES - BIBE	YES		Maxwell et al. 1967	Type section: on the eastern slope of the Sierra del Ca		Mesozoic	Lower Cretaceous	Fredricksburg Gro	YES
46	Del Carmen Limestone		YES - BIBE	YES		Maxwell et al. 1967	Type section: About 3 miles northeast from the head		Mesozoic	Lower Cretaceous	Fredricksburg Gro	YES
47	Telephone Canyon Formation		YES - BIBE	YES		Maxwell et al. 1967	Type locality: in the Sierra del Carmen where Heath C		Mesozoic	Lower Cretaceous	Fredericksburg Gr	YES
48	Maxon Sandstone		NO		Type locality: exposures at Ma	King 1930; Maxwell et al. 1967			Mesozoic	Lower Cretaceous	Trinity Group	YES
49	Telephone Canyon Formation and Maxon Sandstone, undivided								Mesozoic	Lower Cretaceous		
50	Glen Rose Limestone	X	NO			Hill 1891; Maxwell et al. 1967			Mesozoic	Lower Cretaceous	Trinity Group	YES
51	Tesnus Formation	X	NO			Udden et al. 1916; Maxwell et al. 1967			Paleozoic	Lower Pennsylvanian and Upper Mississip		YES
52	Paleozoic rocks, undivided								Paleozoic	Lower Pennsylvanian through Ordovician		

Figure 4. Stratotype inventory spreadsheet of the CHDN displaying attributes appropriate for geolocation assessment. Purple highlighted cells represent geologic units supplemented to the GRI map unit listing.

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 seeks to describe 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 (original or subsequently designated) for a named geologic unit or boundary and constitutes the basis for definition or recognition of that unit or boundary (North American Commission on Stratigraphic Nomenclature 2005). 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 2005). Once a unit stratotype is assigned, it is never changed. 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 2005).

(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 2005). 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 2005).

(4) **Lithodeme**: the term “lithodeme” is defined as a mappable unit of plutonic, highly metamorphosed, or pervasively deformed rock and is a term equivalent in rank to “formation” among stratified rocks (North American Commission on Stratigraphic Nomenclature 2005). 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.

Amistad National Recreation Area

An oasis in the desert, Amistad National Recreation Area (AMIS) consists of the US portion of the International Amistad Reservoir located in Val Verde County, southwestern Texas (Figure 5). The recreation area was authorized on November 28, 1990 and encompasses 23,674 hectares (58,500 acres) (Anderson 2017). Derived from the Spanish word meaning "friendship," Amistad is best known for its excellent aquatic recreation (boating, canoeing, kayaking), camping, hiking, rock art viewing, fishing, hunting, and scuba diving. AMIS is home to a diverse array of plant and animal life above and below the water, including amphibians, birds, fish, insects, reptiles, cacti, ferns, freshwater plants, grasses, trees, and wildflowers.

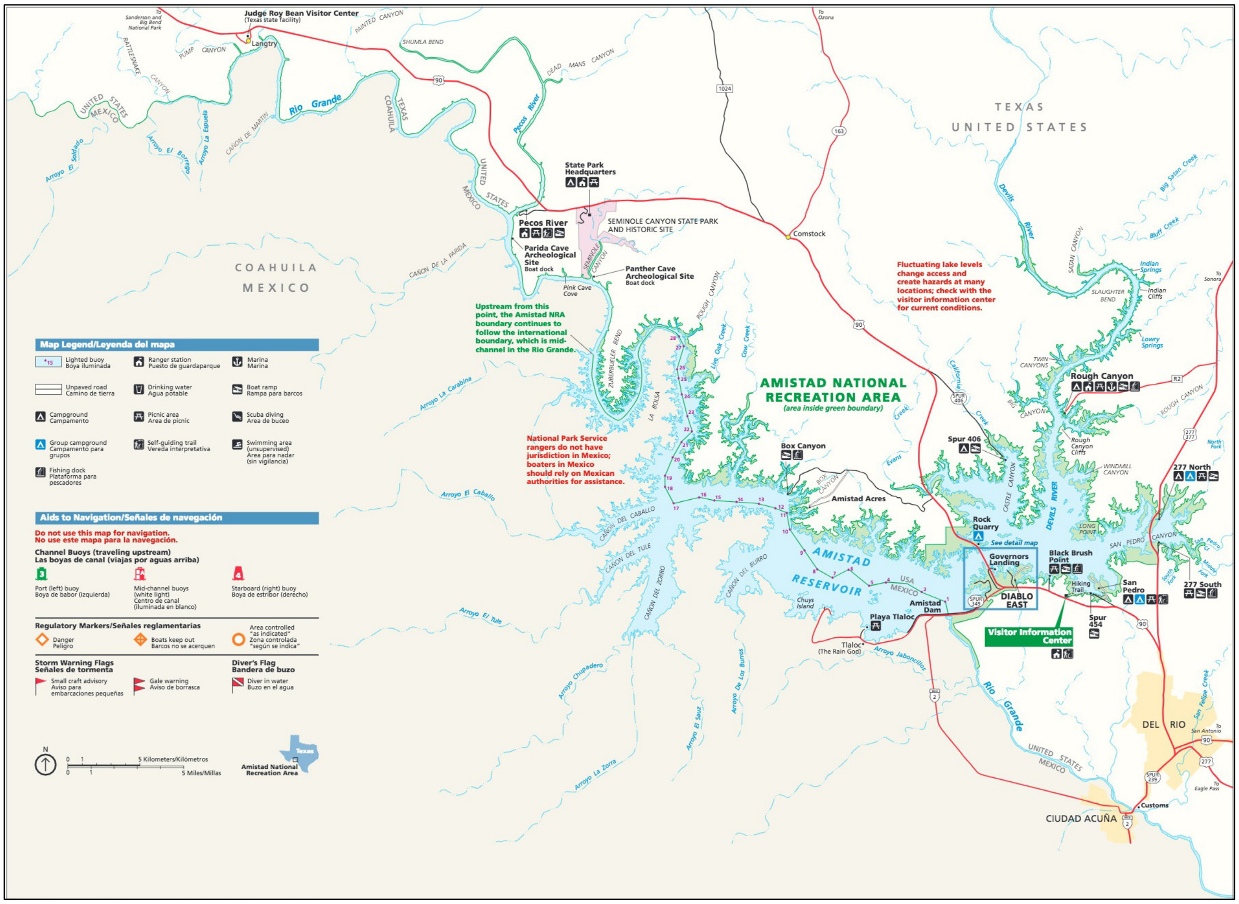


Figure 5. Park map of AMIS, Texas (NPS).

The geology of AMIS is underlain by Cretaceous-age (100–66 million years ago) limestone (Figure 6). A number of Cretaceous formations make up the strata of the area, including the Salmon Peak, Devils River, and Georgetown Limestones, as well as the Del Rio, Buda, Boquillas, and Eagle Ford Formations, the Eagle Ford Group, and the Austin Group. A number of these formations are known to contain a wide variety of marine fossils and form karst landscape (carbonate dissolution features such as caves and sinkholes) that is common in the area.

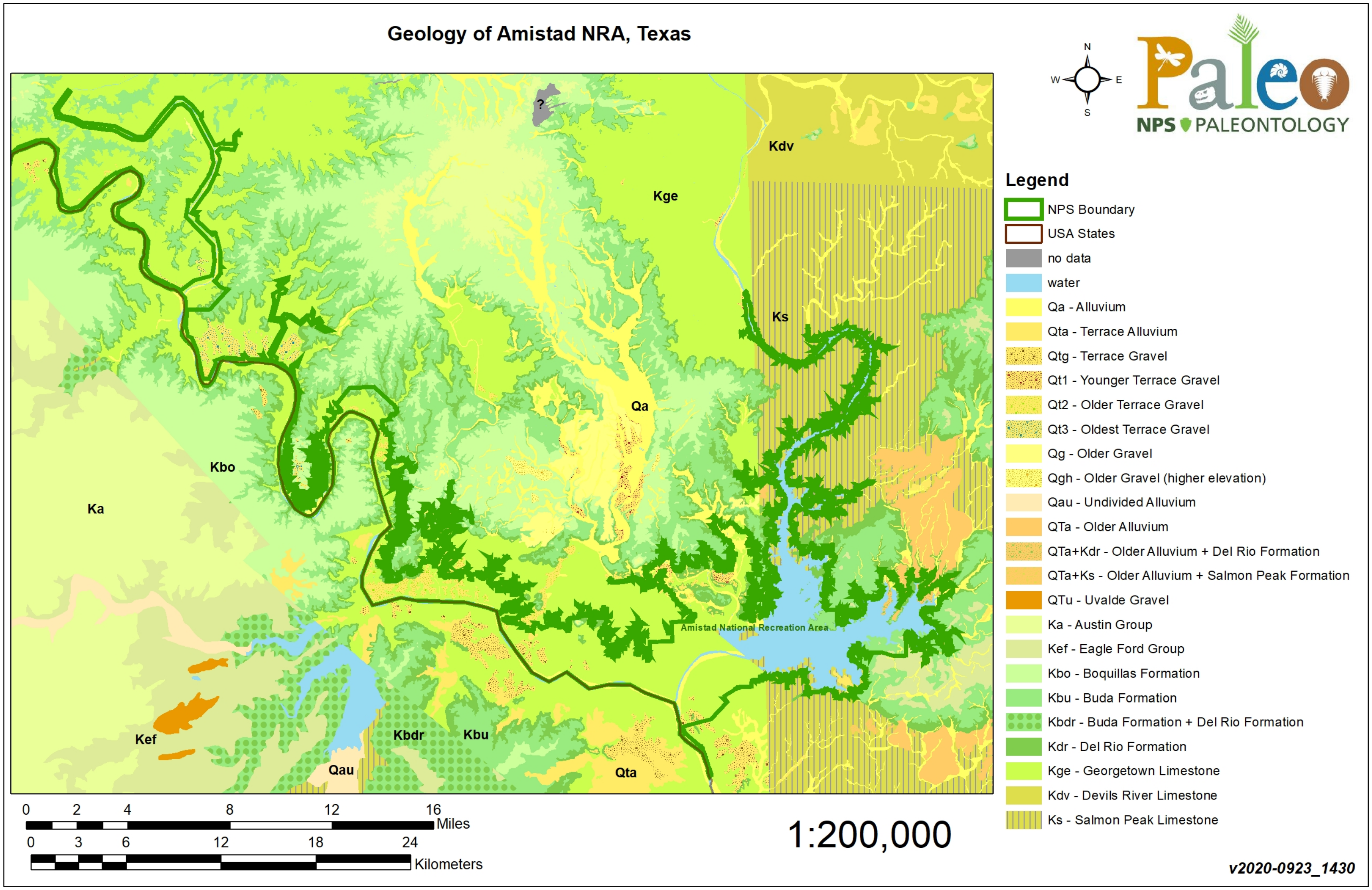


Figure 6. Geologic map of AMIS, Texas.

As of the writing of this paper, there are no designated stratotypes identified within the boundaries of AMIS. There are also no identified stratotypes located within 48 km (30 mi) of AMIS boundaries.

Big Bend National Park

Big Bend National Park (BIBE) lies at the southernmost tip of Trans-Pecos Texas in Brewster County, southwestern Texas along the U.S.–Mexico border (Figure 7). The park was established June 20, 1935 and encompasses approximately 324,219 hectares (801,163 acres). Mountains contrast with desert within the great bend of the Rio Grande, with an elevation of less than 549 m (1,800 ft) along the river valley to nearly 2,438 m (8,000 ft) in the Chisos Mountains (Anderson 2017). The natural beauty of BIBE includes massive canyons, vast desert expanses, volcanic landscapes, forested mountains, and an ever-changing river. The park was designated a Biosphere Reserve in 1976.

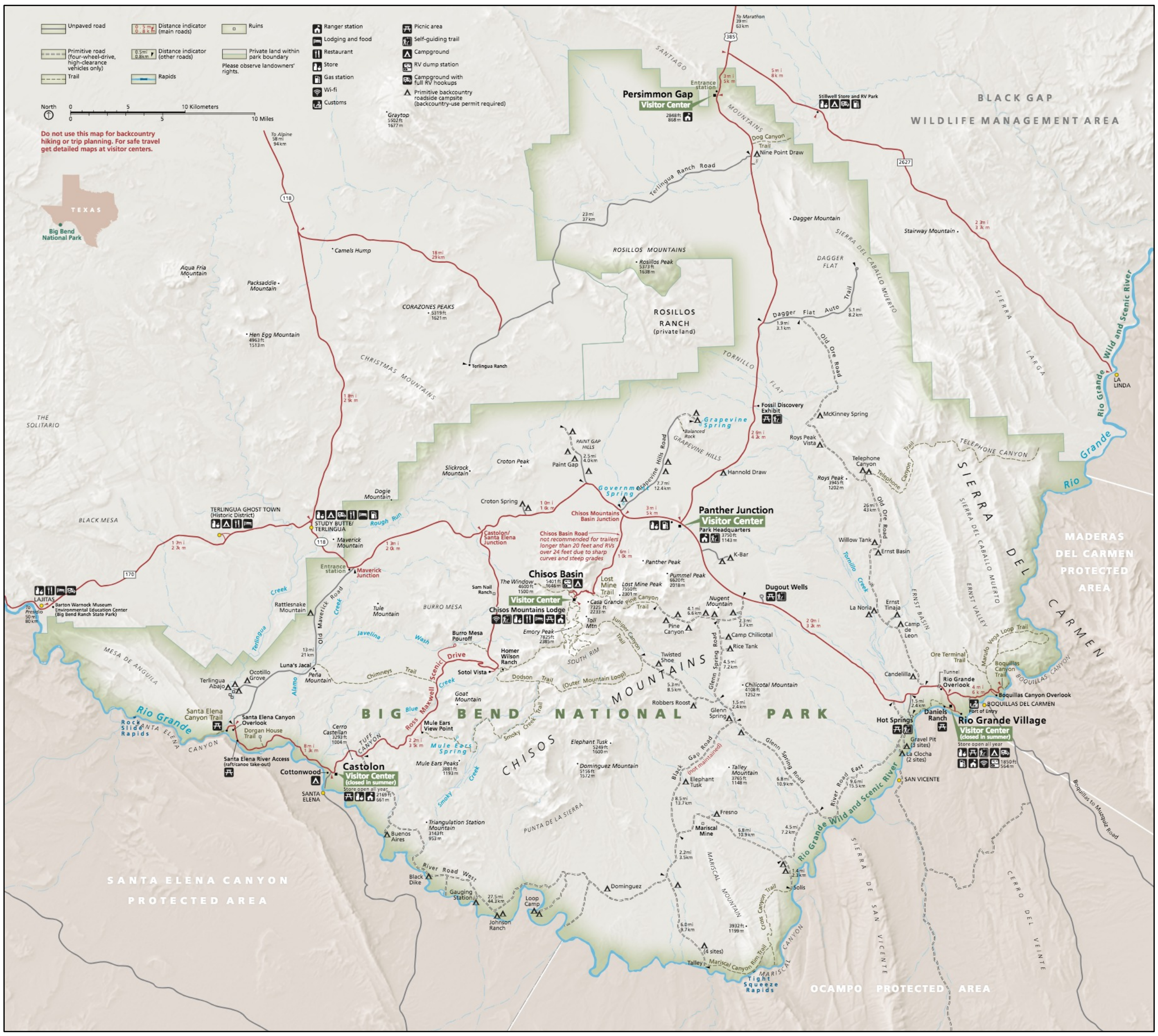


Figure 7. Park map of BIBE, Texas (NPS)

The geology of BIBE is complex as the region has hosted a diversity of depositional environments coupled with multiple tectonic events. A wide variety of sedimentary, extrusive volcanic, and intrusive igneous rocks are exposed in the park, and the span of geologic time represented by them extends from the early Paleozoic to Quaternary (Figures 8 and 9; Maxwell et al. 1967; Turner et al. 2011). However, most of the chaotic, disturbed landscape of BIBE is composed of exposures of rocks dating to the Cretaceous or younger. Throughout much of the Paleozoic the BIBE area was occupied by an ancient ocean that subsequently disappeared as two large land masses collided to form the Ouachita Mountains. Shallow seas flooded the park region during the Cretaceous and began to retreat as a second mountain-building event occurred that formed the Rocky Mountains and resulted in large-scale uplifts of rock. Regional crustal extension (pulling apart of Earth's crust) resulting in several volcanic eruptions and vertical faulting in BIBE beginning around 30 million years ago. The subsequent history of the park is dominantly that of erosion, where the Rio Grande has carved deep, steep-walled canyons along the folded strata and tilted fault blocks (Maxwell et al. 1967).

BIBE contains 31 identified stratotypes that are subdivided into ten type sections, seventeen type localities, and four reference sections (Table 1; Figure 10).

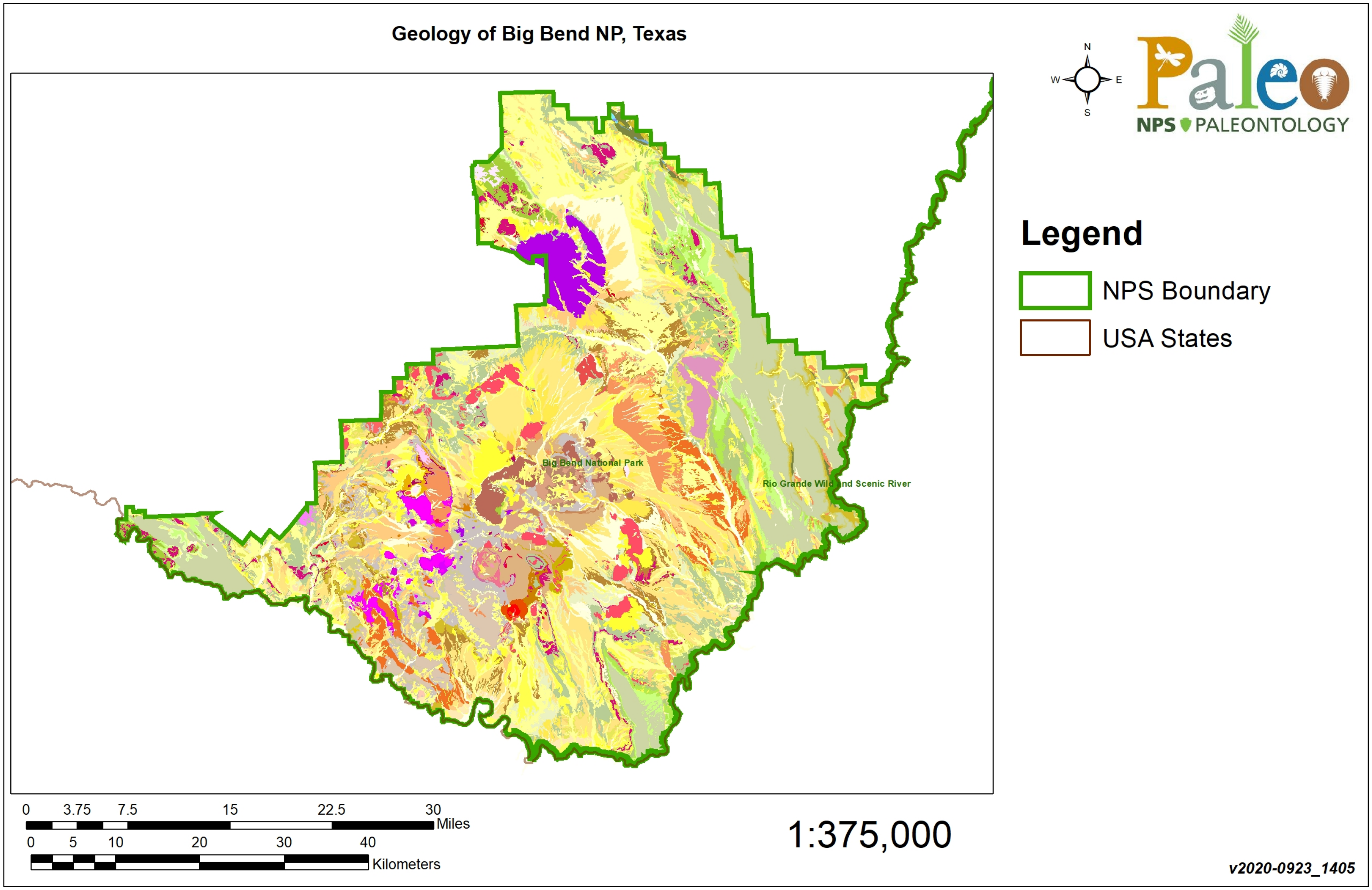


Figure 8. Bedrock geologic map of BIBE, Texas.

Figure 9. Bedrock geologic map legend of BIBE, Texas.

Table 1. List of BIBE stratotype units sorted by age with associated reference publications and locations.

Unit Name (map symbol)	Reference	Stratotype Location	Age
Burro Mesa Rhyolite Member, South Rim Formation (Tbr)	Maxwell et al. 1967	Type locality: Burro Mesa, where the member is the flow forming the highest peak on the western rim	Oligocene
Wasp Spring Flow Breccia Member, South Rim Formation (Tbw)	Maxwell and Dietrich 1965	Type locality: northwestern side of Goat Mountain	Oligocene
South Rim Formation (Ts)	Maxwell et al. 1967	Type locality: the South Rim of the Chisos Mountains, where most of the lava-flow breccia units are prominent	Oligocene
Tule Mountain Trachyandesite Member, Chisos Formation (Tctm)	Maxwell et al. 1967	Type locality: forms the cap rock on Tule Mountain northwest of the Chisos Mountains	Oligocene
Bee Mountain Basalt Member, Chisos Formation (Tcbm)	Maxwell et al. 1967	Type locality: western side of Bee Mountain	Oligocene
Mule Ear Spring Tuff Member, Chisos Formation (Tcme)	Maxwell et al. 1967	Type locality: Mule Ear Spring, 2.4 km (1.5 mi) northwest of Mule Ear Peaks	Oligocene
Ash Spring Basalt Member, Chisos Formation (Tcas)	Maxwell et al. 1967	Type locality: Ash Spring on the northwest side of the Chisos Mountains	Eocene
Alamo Creek Basalt Member, Chisos Formation (Tcac)	Maxwell et al. 1967	Type locality: Alamo Creek, west of the Chisos Mountains, where exposures are almost continuously from near Dawson Creek southward to the Rio Grande River	Eocene
Canoe Formation (Tc)	Maxwell et al. 1967	Type section: ~0.8 km (0.5 mi) north of the abandoned rock crusher site Type locality: Canoe Valley in northeastern Tornillo Flat, northeast of the abandoned rock crusher on the southern edge of Tornillo Flat	Eocene
Big Yellow Sandstone Member, Canoe Formation (Tc)	Maxwell et al. 1967	Type locality: Big Yellow arroyo in southern Tornillo Flat	Eocene

Table 1 (continued). List of BIBE stratotype units sorted by age with associated reference publications and locations.

Unit Name (map symbol)	Reference	Stratotype Location	Age
Hannold Hill Formation (Thh)	Maxwell et al. 1967; Lehman et al. 2018	Type section: ~1.2 km (0.75 mi) northeast of the abandoned rock crusher site on southern Tornillo Flat Type locality: Hannold Hill on the Main Park road in south-central Tornillo Flat Reference section: east Park Highway on south side of Tornillo Creek	Eocene
Black Peaks Formation (TKbp)	Maxwell et al. 1967; Lehman et al. 2018	Type section: north-central part of Tornillo Flat Type locality: three small black peaks on Tornillo Flat, northwest of the McKinney Hills Reference section: western Tornillo Flat	Paleocene–Cretaceous
Javelina Formation (Kj)	Maxwell et al. 1967; Lehman et al. 2018	Type section: exposures between the Panther Junction Road and Tule Mountain Type locality: south of Dawson Creek Reference section: west side of Park Highway on south side of Dawson Creek	Cretaceous
Aguja Formation (Ka)	Adkins 1933	Type locality: Sierra Aguja (Needle Peak), in the flat in front of Santa Helena fault scarp, 10 km (6 mi) south of Terlingua	Cretaceous
Pen Formation (Kp)	Maxwell et al. 1967	Type section: ~3 km (2 mi) north of Hot Springs Type locality: crops out along the crest of a faulted anticline west of Chisos Pen	Cretaceous
San Vicente Member, Boquillas Formation (Kbs)	Maxwell et al. 1967	Type section: ~2 km (1 mi) east of old village of San Vicente Type locality: ~3 km (2 mi) northeast of the old village San Vicente, immediately east of U.S. Geological Survey benchmark elevation 1,881 ft	Cretaceous
Ernst Member, Boquillas Formation (Kbe)	Cooper et al. 2007	Reference section: Hot Springs Trail reference section	Cretaceous
Boquillas Formation (Kb)	Cooper et al. 2017	Type section: located on the north side of Park Route 12, approximately 0.5 km (0.3 mi) east of the junction with Hot Springs Road	Cretaceous
Santa Elena Limestone (Kse)	Maxwell et al. 1967	Type section: the upper half of the sheer canyon wall at the mouth of Santa Elena Canyon	Cretaceous
Sue Peaks Formation (Ksp)	Maxwell et al. 1967	Type section: on the eastern slope of the Sierra del Caballo Muerto ~2.4 km (1.5 mi) south of Heath Creek	Cretaceous
Del Carmen Limestone (Kdc)	Maxwell et al. 1967	Type section: ~5 km (3 mi) northeast from the head of Boquillas Canyon, along the Marufo Vega trail	Cretaceous
Telephone Canyon Formation (Ktc)	Maxwell et al. 1967	Type locality: in the Sierra del Carmen where Heath Creek excavated Telephone Canyon across the Sierra del Caballo Muerto	Cretaceous

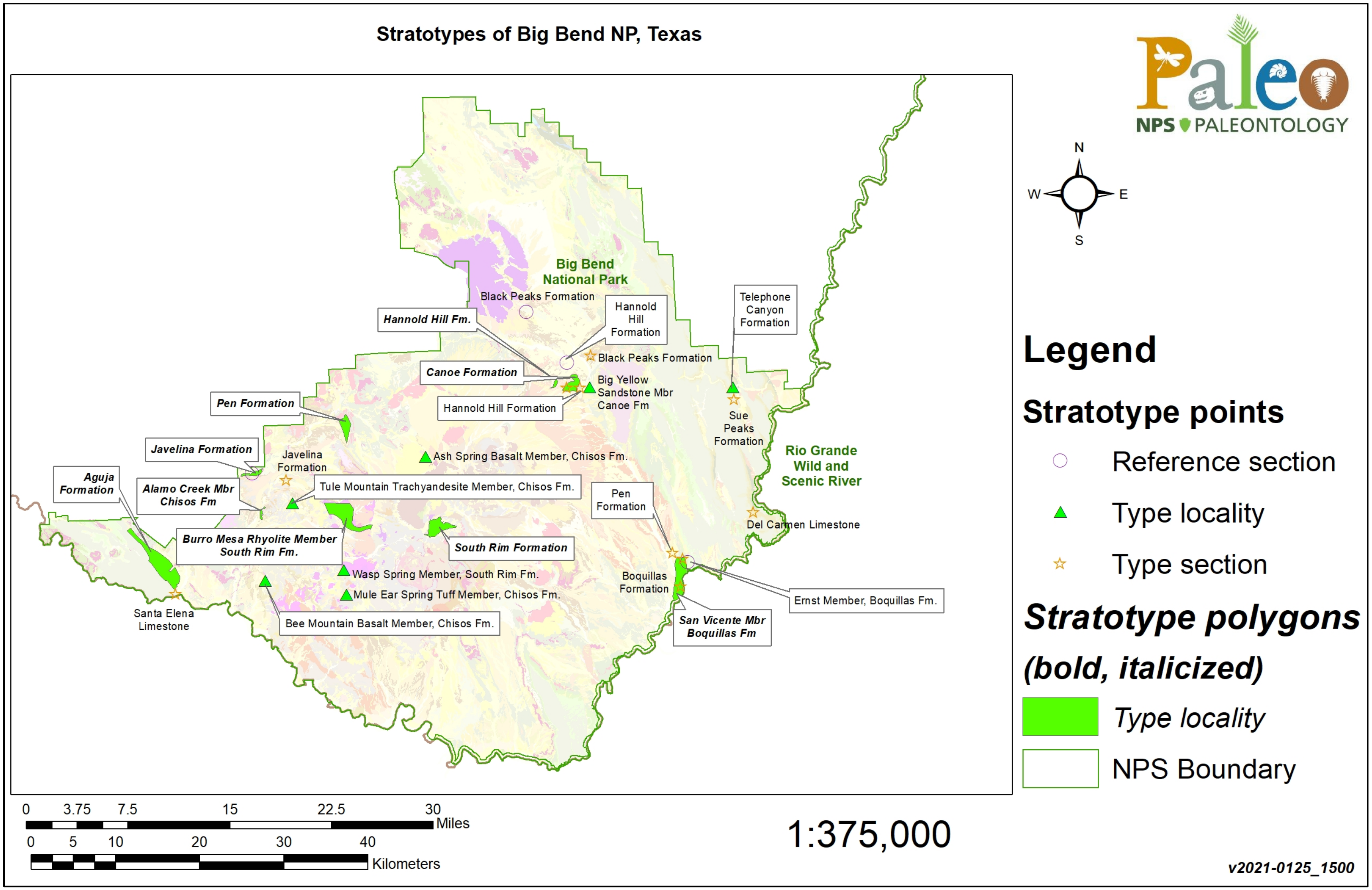


Figure 10. Modified geologic map of BIBE showing stratotype locations. The transparency of the geologic units layer has been increased.

The Cretaceous Telephone Canyon Formation was named by Maxwell et al. (1967) after its type locality exposures in the Sierra del Carmen where Heath Creek carved Telephone Canyon across the Sierra del Caballo Muerto (Table 1; Figure 10). Type locality exposures consist of 23 m (75 ft)-thick sequences of yellowish-gray and brownish-gray, nodular limestone and dense, flaggy limestone that lie between the more resistant Glen Rose Formation and the overlying hard, massive, cherty Del Carmen Limestone (Maxwell et al. 1967). Most beds of the formation are fossiliferous with some of the best preservation occurring on the south side of Telephone Canyon along a bench that is normally above flood water (Maxwell et al. 1967). Other notable exposures of the formation occur along the Marufo Vega trail, the southern end of the Santiago Mountains, and the mouth of Santa Elena Canyon.

The Cretaceous Del Carmen Limestone was designated by Maxwell et al. (1967) after Sierra del Carmen where the limestone is exposed. The type section of the Del Carmen Limestone occurs about 5 km (3 mi) northeast from the head of Boquillas Canyon, where the Marufo Vega trail descends a steep narrow canyon consisting of the formation (Table 1; Figure 10; Maxwell et al. 1967). The formation is 103 m (338 ft) thick at the type section and forms a sheer escarpment on both sides of the trail that are marked by small open caverns with overhanging ledges (Maxwell et al. 1967). Maxwell et al. (1967) states that these are the most accessible, non-faulted exposures of the formation in BIBE. Other notable occurrences of the formation are located at Santa Elena Canyon, Sierra del Caballo Muerto, and the southern Santiago Mountains. The unit is characterized as a rough-surfaced, fine- to medium-crystalline limestone that is gray when fresh but weathers to shades of dark brown, yellowish-brown, and pinkish-brown. The limestone contains brown chert that occurs as concretionary masses up to 20–25 cm (8–10 in) in diameter but also as lenticular bodies up to 3 m (10 ft) long (Maxwell et al. 1967).

The Cretaceous Sue Peaks Formation was designated by Maxwell et al. (1967) after Sue Peaks, the highest elevation in the Sierra del Carmen. In the Sierra del Carmen Mountains, the best exposures of the formation occur at the type section location on the eastern slope of the Sierra del Caballo Muerto about 2.4 km (1.5 mi) south of Heath Creek (Table 1; Figure 10). Type section exposures are 77 m (252 ft) thick and occur along the sides of small channels situated between the overlying Santa Elena Limestone and underlying Del Carmen Limestone (Maxwell et al. 1967). The formation is divisible into two members, a lower marly shale interval that is yellowish-gray and an upper interval consisting of massive gray limestone and thin, gray nodular limestone (Maxwell et al. 1967). Other notable exposures of the Sue Peaks Formation are located at Santa Elena Canyon and Boquillas Canyon along the Marufo Vega trail.

The Cretaceous Santa Elena Limestone was named by Maxwell et al. (1967) for its type section exposures that form the upper half of the sheer canyon walls at the mouth of Santa Elena Canyon (Table 1; Figures 10 and 11; Table 1). The type section at Santa Elena Canyon contains the thickest exposures of the formation in BIBE and measure approximately 226 m (740 ft) thick. Exposures of the Santa Elena Limestone at the type section are massive 2–3 m (8–10 ft) beds that are light gray or white when fresh but weather to dark gray or brown and contain chert nodules and silicified rudistid bivalves (Maxwell et al. 1967). Other notable exposures occur at Mariscal Mountain and in the Sierra del Caballo Muerto.

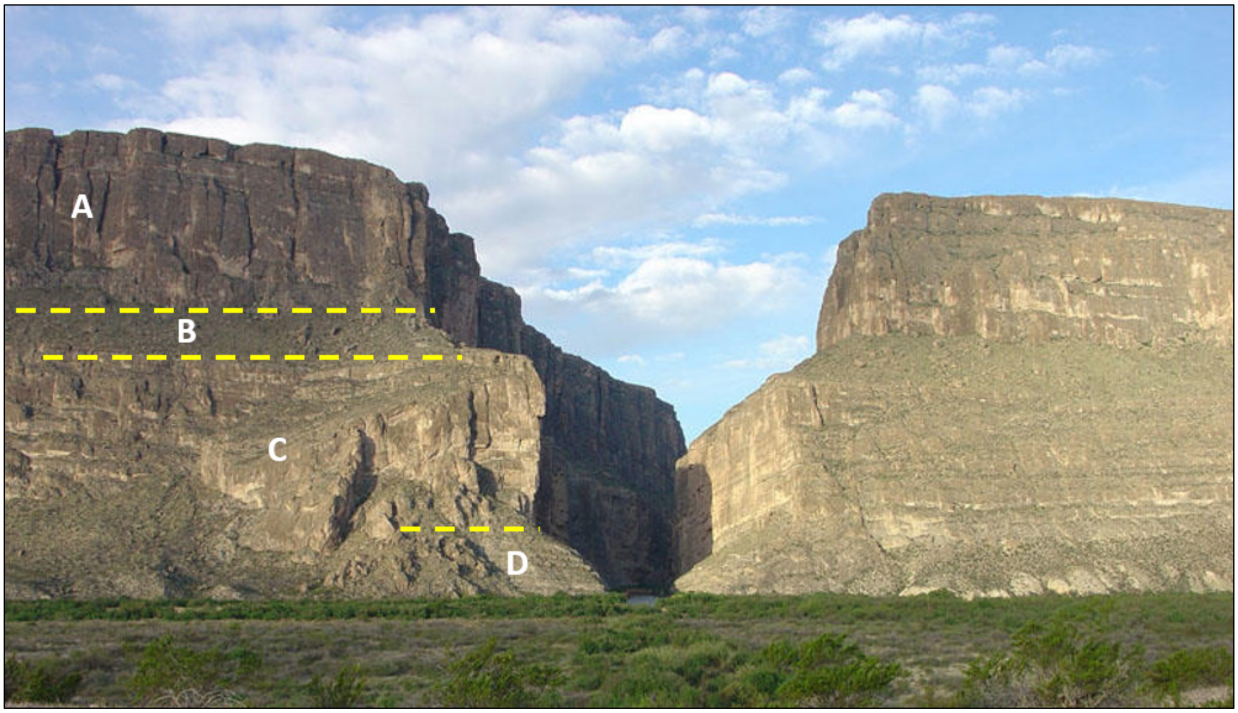


Figure 11. Mouth of the Santa Elena Canyon in BIBE. The type section of the Santa Elena Limestone is situated in the northern canyon wall to the right. A) Santa Elena Limestone; B) Sue Peaks Formation; C) Del Carmen Limestone; and D) undivided Telephone Canyon and Glen Rose formations (USGS).

The Cretaceous Boquillas Formation was originally named by Udden (1907) after the old Boquillas post office on Tornillo Creek, about 12 km (7.5 mi) from present-day Boquillas. The formation is divisible into two members, the lower Ernst Member and the upper San Vicente Member. The type section of the Boquillas Formation is located on the north side of Park Route 12, approximately 0.5 km (0.3 mi) east of the junction with Hot Springs Road (N 29°11.777', W 102°59.805') (Table 1; Figure 10; Cooper et al. 2017). Type section exposures consist of alternating layers of limestone and shale and contain distinctive pyrite and limonite marks (Cooper et al. 2017). The Boquillas Formation is typically 245–267 m (805–875 ft) thick in the region of BIBE and stratigraphically occurs between the overlying Buda Limestone and underlying Pen Formation (Maxwell et al. 1967).

The Ernst Member of the Boquillas Formation was named by Maxwell et al. (1967) from Ernst Tinaja approximately 3 km (2 mi) east-northeast of the old Boquillas post office. A reference section for the Ernst Member (the "Hot Springs Trail reference section") is located in the Hot Springs–San Vicente area south of Park Route 12 approximately 0.4 km (0.25 mi) southeast of the Boquillas Formation type section (Table 1; Figure 10; Cooper et al. 2007). Maxwell et al. (1967) states that the Ernst Member in BIBE is about 137 m (450 ft) thick and consists of silty limestone, siltstone, with calcareous clay that is bluish-gray when fresh and weathers to light yellowish-gray.

The San Vicente Member of the Boquillas Formation was designated by Maxwell et al. (1967) after the old village of San Vicente in BIBE. The type locality of the member is located about 3 km (2 mi) northeast of the old village, immediately east of U.S. Geological Survey benchmark elevation 1,881 (Table 1; Figures 10 and 12; Maxwell et al. 1967). Type locality exposures of the San Vicente Member consist of siltstone, sandstone, argillaceous limestone, and bentonite clays beds that are overlain by chalk and finely crystalline limestone (Maxwell et al. 1967). The type section of the member is located 2 km (1 mi) east of the abandoned village of San Vicente and measures 101 m (331 ft) thick (Table 1; Figure 10).

Figure 12. Chalky limestone ledges of the San Vicente Member near type locality northeast of the old village of San Vicente, BIBE. Figure from Maxwell et al. (1967).

The Cretaceous Pen Formation was named for Chisos Pen north of the Chisos Mountains by Maxwell et al. (1967). The type section of the formation is located about 3.2 km (2 mi) north of Hot Springs and measures 139 m (457 ft) thick (Table 1; Figures 10 and 13). At the type locality the Pen Formation is exposed along the crest of a faulted anticline west of Chisos Pen and is 193 m (634 ft) thick (Table 1; Figure 10). In BIBE, the formation reaches a maximum thickness of about 213 m (700 ft) and consists of yellowish calcareous clay with interbedded chalk, clay with scattered sandy beds, and an upper sandy clay that contains sandstone up to 1.5 m (5 ft) thick (Maxwell et al. 1967). Other notable exposures of the Pen Formation occur at Mariscal Mountain, the Cow Heaven anticline, McKinney Hills, Study Butte, and the southeastern Christmas Mountains.

Figure 13. Pen Formation near the type locality at Chisos Pen. Figure from Maxwell et al. (1967).

The Cretaceous Aguja Formation was originally named Rattlesnake Beds by Udden (1907) and were renamed by Adkins (1933) after its type locality at Sierra Aguja (Needle Peak), approximately 10 km (6 mi) south of Terlingua in the flat in front of the Santa Helena fault scarp (Table 1; Figure 10). At the type locality the formation crops out in the lower slopes beneath a cap of Cenozoic volcanic rocks (Adkins 1933; Maxwell et al. 1967). The formation rests unconformably above the Pen Formation and consists of a basal sandstone, fossiliferous marine shale, and alternating clay and sandstone beds that grade upward into non-marine, lacustrine and lagoonal deposits (Maxwell et al. 1967).

The Cretaceous Javelina Formation was designated by Maxwell et al. (1967) from Javelina Creek in the northeastern part of Tornillo Flat. The type section of the formation is exposed between the Panther Junction Road and Tule Mountain and measures 163 m (534 ft) thick (Table 1; Figures 10 and 14). Type section exposures consist of mottled and banded gray, yellowish-gray, and maroon bentonite clay with small calcareous nodules and thin beds of gray or brown sandstone that conformably overlie the Aguja Formation and rest unconformably below the Alamo Creek Basalt Member of the Chisos Formation (Maxwell et al. 1967). The type locality of the Javelina Formation is located south of Dawson Creek and consists of the thickest exposures of the unit in BIBE (Table 1; Figure 10). Although the basal 11 m (35 ft) are partially obscured, the formation is 285 m (936 ft) thick and consists of bentonite clay, sandy clay, and thin irregular sandstone lenses (Maxwell et al. 1967). An additional reference section published by Lehman et al. (2018) is located along the west side of Park Highway south of Dawson Creek and measures approximately 123 m (404 ft) thick (Table 1; Figure 10).

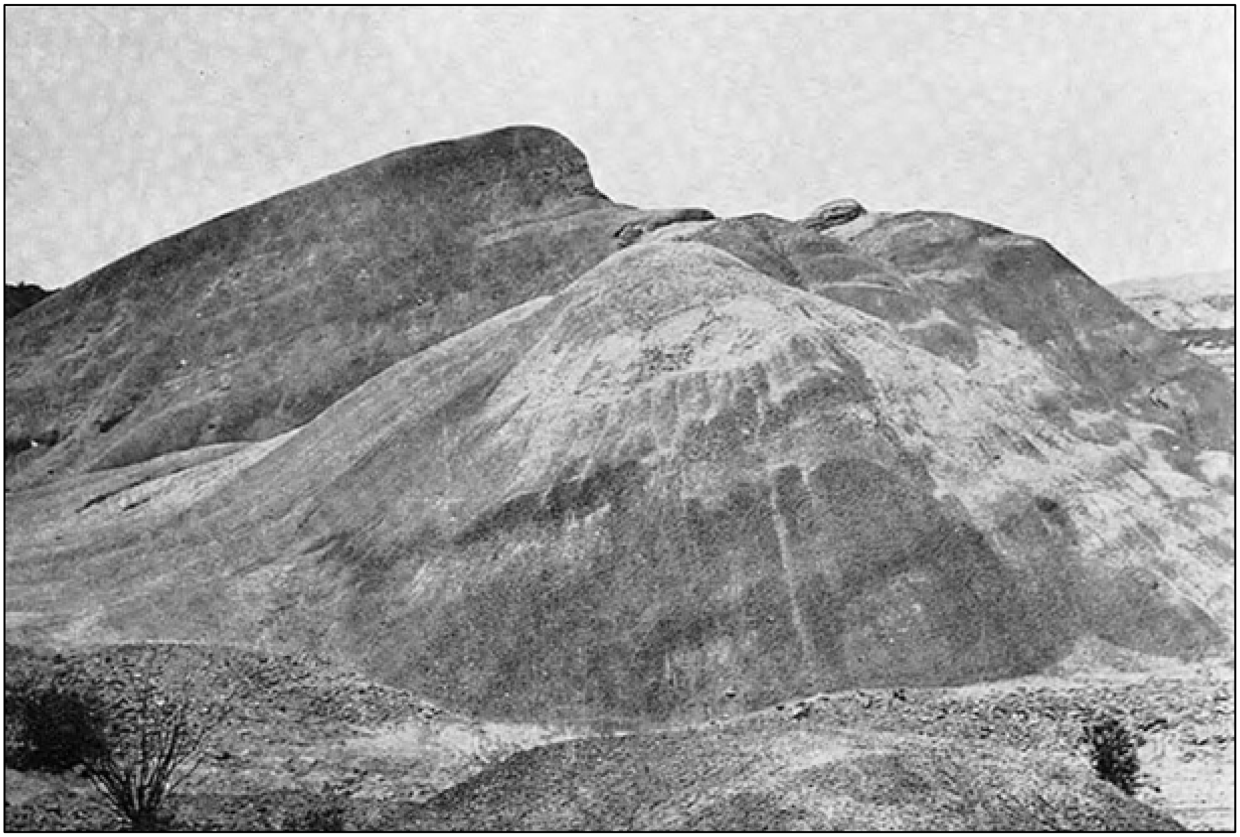


Figure 14. Rounded knob of clays consisting of the Javelina Formation in the type locality south of Dawson Creek. Figure from Maxwell et al. (1967).

The Cretaceous–Paleocene Black Peaks Formation represents the oldest Cenozoic rocks in west Texas and was named by Maxwell et al. (1967) after its type locality near three small black peaks on east-central Tornillo Flat, northwest of the McKinney Hills (Table 1; Figures 10 and 15). The type section is located in the north-central part of Tornillo Flat and represents the thickest section of the formation at 264 m (866 ft). Type section exposures consist of a basal, massive sandstone that contains clay nodules with an overlying sequence of gray and maroon clay alternating with gray, gray-white, and light yellowish-gray sandstone (Maxwell et al. 1967). An additional reference section is located on western Tornillo Flat and measures approximately 300 m (984 ft) thick (Table 1; Figure 10; Lehman et al. 2018).

The Eocene Hannold Hill Formation was designated by Maxwell et al. (1967) after its type locality at Hannold Hill along Main Park Road in south-central Tornillo Flat (Table 1; Figure 10). The type section, located about 1.2 km (0.75 mi) northeast of the site of an abandoned rock crusher on southern Tornillo Flat (N 29°22’52.79”, W 103°7’7.90”), contains the thickest exposures of the formation at 254 m (833 ft) (Table 1; Figure 10). The section consists of a basal gray-white channel sandstone overlain by a thick sequence of alternating sandstone and vari-colored clay (Maxwell et al. 1967). An additional reference section published by Lehman et al. (2018) is located along east Park Highway on the south side of Tornillo Flat and measures approximately 45 m (148 ft) thick (Table 1; Figure 10).

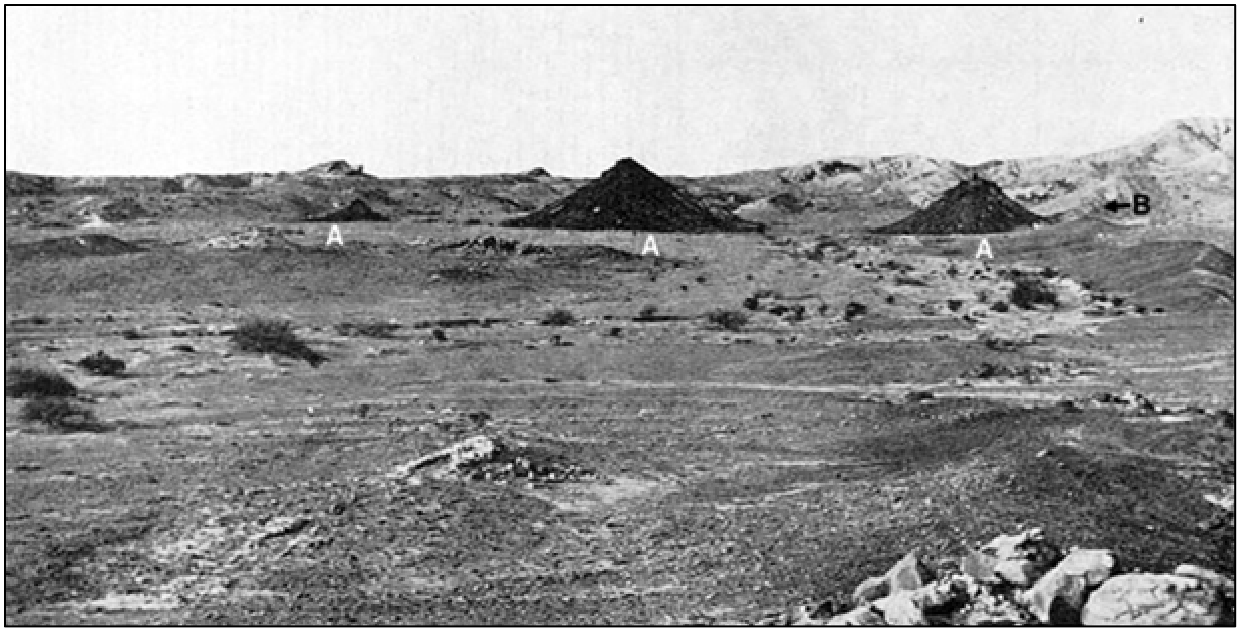


Figure 15. Type locality exposures of the Black Peaks Formation northwest of the McKinney Hills. A) Three black basaltic peaks from which the formation was named; and B) Javelina–Black Peaks Formation contact. Figure modified from Maxwell et al. (1967).

The Eocene Canoe Formation was named by Maxwell et al. (1967) after Canoe Valley in northeastern Tornillo Flat, where its basal unit is folded into a canoe-shaped syncline. The type locality of the formation is located northeast of the site of an abandoned rock crusher on the southern edge of Tornillo Flat (Table 1; Figures 10 and 16; Maxwell et al. 1967). The type section is located about 0.8 km (0.5 mi) north of the abandoned rock crusher site (N 29°22’55.24”, W 103° 8’7.11”) and measures 354 m (1,161 ft) thick (Table 1; Figure 10; Maxwell et al. 1967). The section consists of basal cross-bedded sandstone of the Big Yellow Sandstone Member that is overlain by alternating clay, mudstone, tuffaceous clay and mudstone, calcareous tuff, vitric tuff, basalt, sandstone and conglomerate. The uppermost beds are composed of limestone that are capped by terrace gravel deposits of possible Quaternary age (Maxwell et al. 1967).

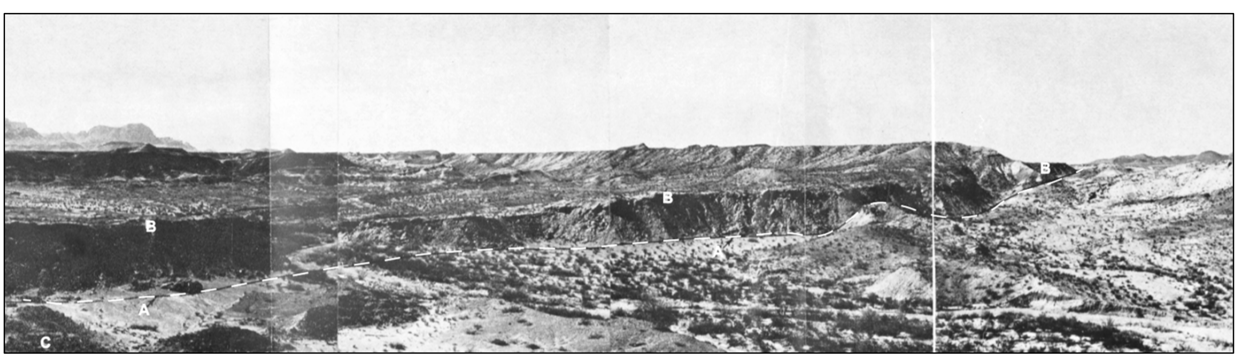


Figure 16. Basalt, tuff, tuffaceous clay, and sandstone conglomerate of the Canoe Formation at its type locality in southeastern Tornillo Flat. A) Fault trace; B) Big Yellow Sandstone Member; and C) basalt. Figure modified from Maxwell et al. (1967).

The Big Yellow Sandstone Member of the Canoe Formation was named by Maxwell et al. (1967) after its type locality at Big Yellow arroyo in southern Tornillo Flat (Table 1; Figure 10). Type locality exposures vary in thickness from approximately 9–15 m (30–50 ft) (Maxwell et al. 1967). The unit commonly forms ledges and buttes and is composed of massive yellow sandstone and conglomerate with pebbles of igneous rocks, dark chert, and novaculite (Maxwell et al. 1967). The member has an irregular basal contact and occurs within channel scours of the underlying Hannold Hill Formation (Maxwell et al. 1967).

The Eocene Alamo Creek Basalt Member of the Chisos Formation was named by Maxwell et al. (1967) after its type locality at Alamo Creek west of the Chisos Mountains, where the lava is exposed almost continuously from Dawson Creek south to the Rio Grande (Table 1; Figures 10 and 17). The member is the lowermost unit of the western Chisos Formation facies and its distribution is confined to western BIBE by the central Chisos Mountains and the crest of the Cow Heaven anticline. The thickest exposures of the Alamo Creek Basalt are located in the Round Mountain–Kit Mountain–Cerro Castellan area and measure approximately 63 m (208 ft) thick (Maxwell et al. 1967). The basalt is characterized as a fine-grained, hard, dark lava that contains small phenocrysts and a scoriaceous base (Maxwell et al. 1967).

The Eocene Ash Spring Basalt Member of the Chisos Formation was designated by Maxwell et al. (1967) after its type locality at Ash Spring on the northwest side of the Chisos Mountains (Table 1; Figures 10 and 18). Type locality exposures vary in thickness from 20–61 m (65–200 ft) and form a massive ledge on the north side of the Chisos Mountains where the basalt is conspicuously porphyritic (texture of large crystals surrounded by featureless groundmass) with phenocrysts (large crystals in a porphyry) of plagioclase that measure more than 1.3 cm (0.5 in) long (Maxwell et al. 1967). Exposures thicker than 15 m (50 ft) are composed of multiple lava flows.

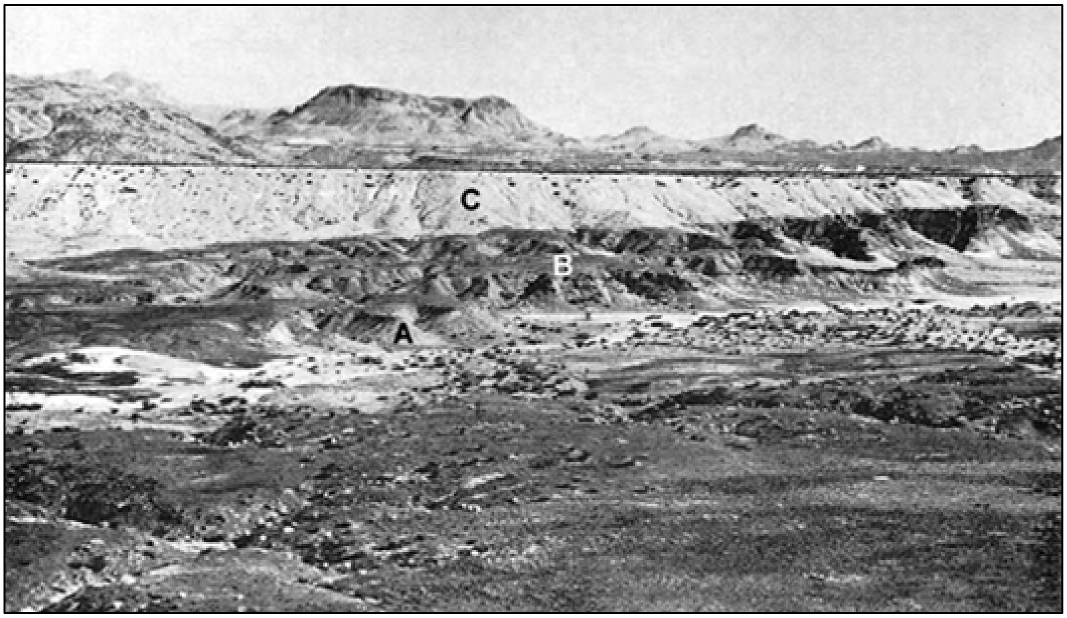


Figure 17. Type locality exposures of the Alamo Creek Basalt Member in Upper Alamo Creek. Basalt and overlying volcanic sequences rest on the Javelina Formation. A) Javelina Formation; B) Alamo Creek Basalt Member; and C) tuff beds in the Chisos Formation. Figure modified from Maxwell et al. (1967).

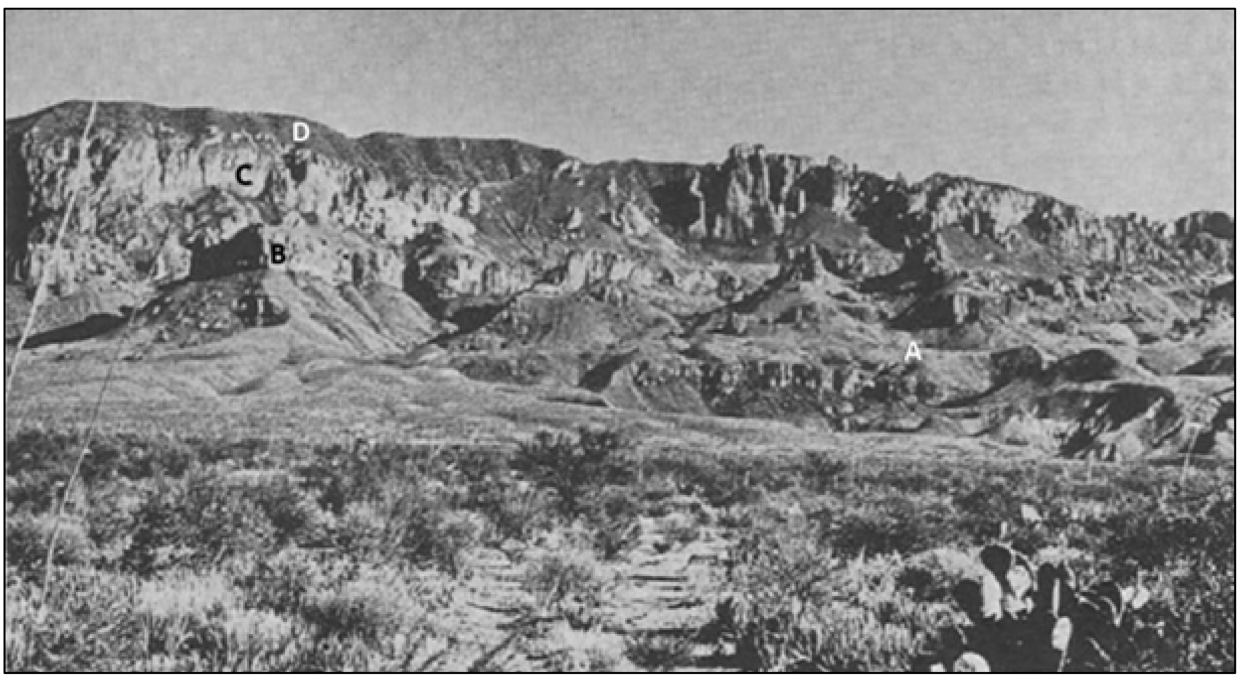


Figure 18. Type locality exposures of the Ash Spring Basalt Member, on the north side of the Chisos Mountains. A) Ash Spring Basalt Member; B) Tule Mountain Trachyandesite Member; C) Wasp Spring Flow Breccia Member; and D) Pulliam Peak intrusion. Figure modified from Maxwell et al. (1967).

The Oligocene Bee Mountain Basalt Member of the Chisos Formation was named by Maxwell et al. (1967) from its type locality on the western side of Bee Mountain (Table 1; Figures 10 and 19). At the type locality, the basalt composes the lower slopes of Bee Mountain and can be traced to the west where it caps mesas adjacent to the mountain. The basalt is characterized as mostly fine- to medium-grained, with scoriaceous or vuggy contacts filled with secondary minerals that produce a mottled appearance (Maxwell et al. 1967). At the type locality, the member is approximately 7.6–24 m (25–80 ft) thick. Several lava flows here are separated by 3–15 cm (1–6 in) thick tuff beds and contain small, irregular quartz veins (Maxwell et al. 1967). The Bee Mountain Basalt is one of the most extensive members of the Chisos Formation and is located west and southwest of the Chisos Mountains and extends south into Mexico.

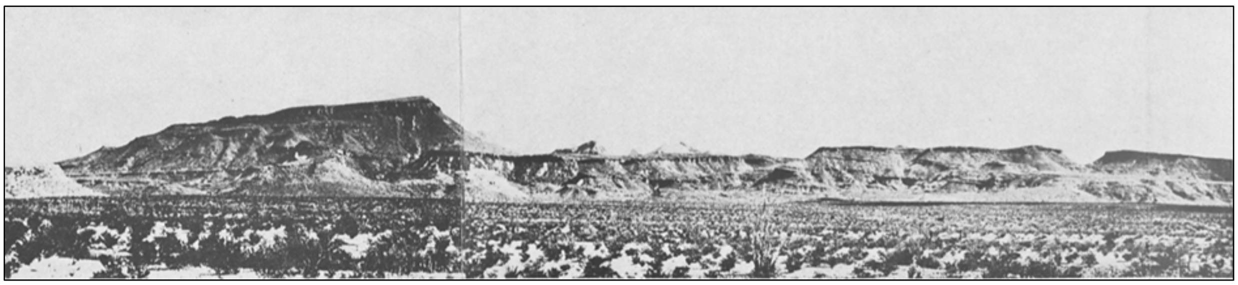


Figure 19. Bee Mountain (at left), the type locality of the Bee Mountain Basalt. The Bee Mountain Basalt Member caps the mesa on the right, and the outcrop can be traced to the left into the lower slopes of Bee Mountain. Figure from Maxwell et al. (1967).

The Oligocene Mule Ear Spring Tuff Member of the Chisos Formation was named by Maxwell et al. (1967) after its type locality at Mule Ear Spring, approximately 2.4 km (1.5 mi) northwest of Mule Ear Peaks (Table 1; Figure 10). The member is typically 2–3.7 m (8–12 ft) thick and consists of hard, brittle, silicified tuff with conchoidal fracture that ranges in color from pink, brick red, and gray in fresh exposures but weathers brown (Maxwell et al. 1967). At the type locality the Mule Ear Spring Tuff rests on the Bee Mountain Member and is overlain by the Tule Mountain Trachyandesite Member.

The Oligocene Tule Mountain Trachyandesite Member of the Chisos Formation was designated by Maxwell et al. (1967) after its type locality at Tule Mountain (Table 1; Figures 10 and 20). Type locality exposures of the member are approximately 61 m (200 ft) thick and consist of gray or brownish-gray porphyritic trachyandesite that contains feldspar phenocrysts up to 1.3 cm (0.5 in) in diameter (Maxwell et al. 1967). The Tule Mountain Trachyandesite forms a cap layer on Tule Mountain that overlies the Mule Ear Spring and Ash Spring members of the Chisos Formation. The member is the most prominent lava unit in the Chisos Formation and reaches a maximum thickness of 106 m (348 ft) south of the type locality at Kit Mountain (Maxwell et al. 1967).

The Oligocene South Rim Formation was named after its type locality exposures along the South Rim of the Chisos Mountains by Maxwell et al. (1967) (Table 1; Figures 10 and 21). The unit consists of thick lava and flow breccia bodies, conglomerate, sandstone, tuff, and tuffaceous mudstone that range in thickness from 84–305 m (275–1,000 ft) with the thickest exposures found at the type locality. Type locality exposures of the South Rim Formation contain the prominent flow-breccia units of the Wasp Spring Member and overlie the Chisos Formation and the Bee Mountain Basalt Member.

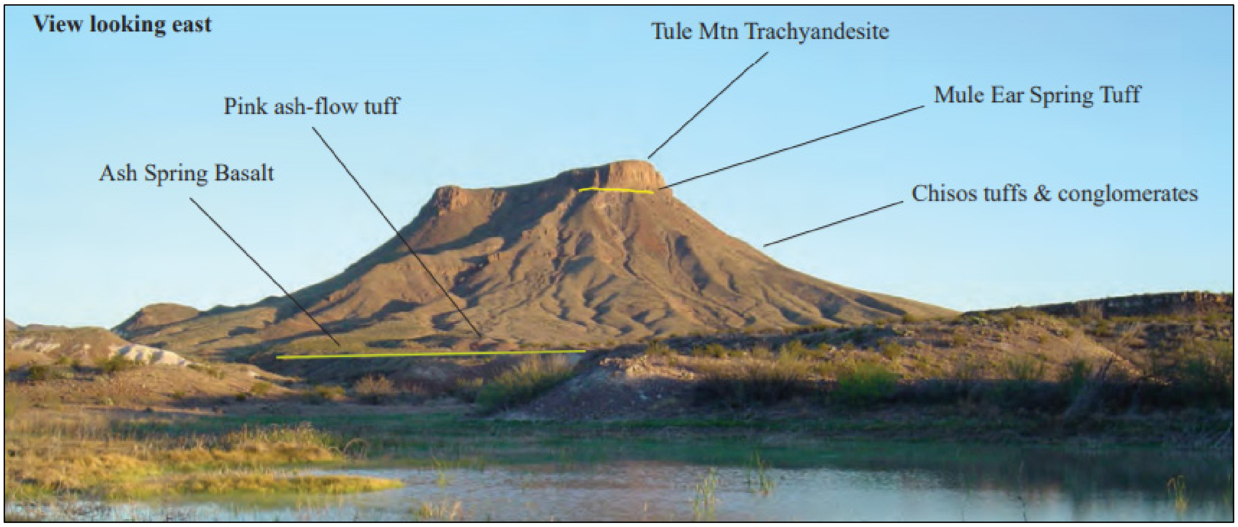


Figure 20. Type locality of the Tule Mountain Trachyandesite Member, Tule Mountain, BIBE (USGS).

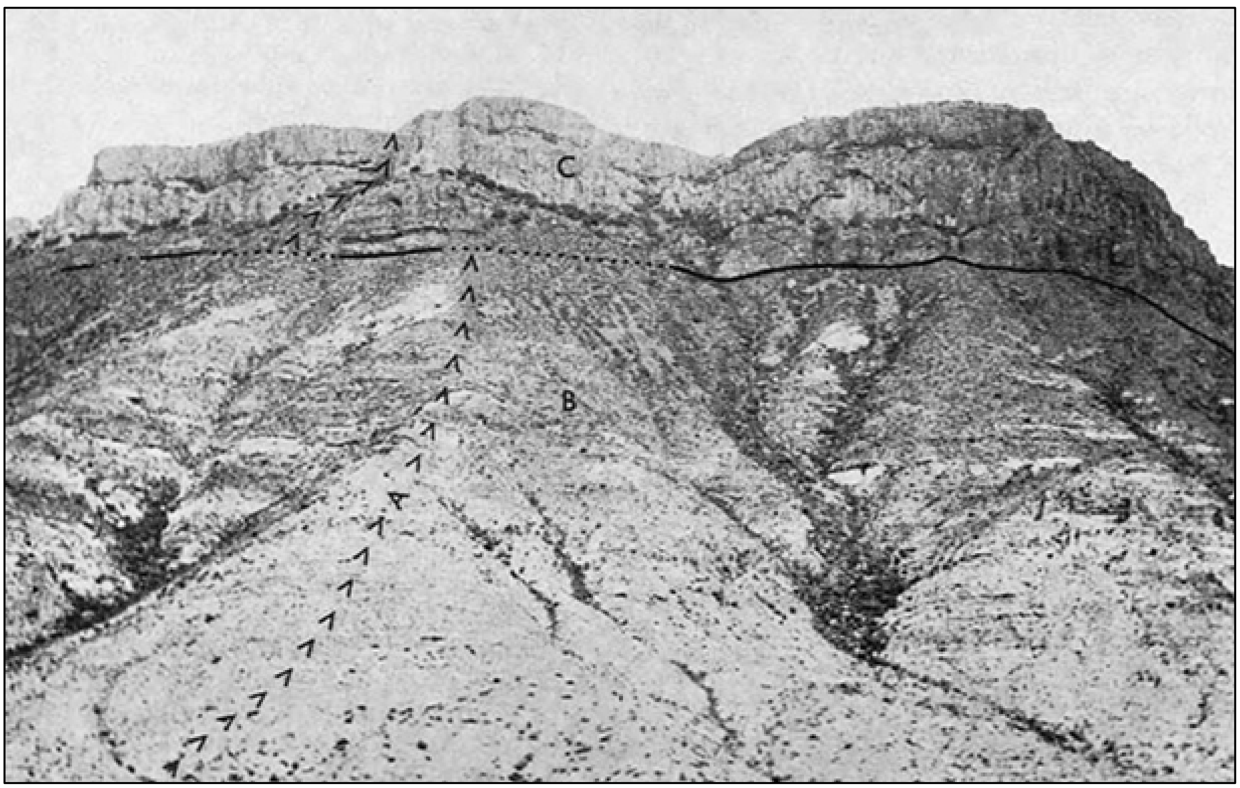


Figure 21. View looking north at the type locality of the South Rim Formation. Chisos Formation in the foreground is unconformably overlain by the South Rim Formation at the top of the rim. A) Line of measured section; B) Chisos Formation; and C) lava and flow breccia units of the South Rim Formation. Figure from Maxwell et al. (1967).

The Wasp Spring Flow Breccia Member of the South Rim Formation was designated by Maxwell and Dietrich (1965). The type locality of the member is on the northwestern side of Goat Mountain, where it overlies the Tule Mountain Member of the Chisos Formation and underlies the Burro Mesa Riebeckite Rhyolite Member of the South Rim Formation (Table 1; Figures 10 and 22; Maxwell and Dietrich 1965; Maxwell et al. 1967). The member is characterized as a flow breccia unit that contains rhyolitic lava, coarse massive conglomerate, coarse sandstone, and tuff that varies in thickness from 30.5–107 m (100–350 ft) (Maxwell et al. 1967).

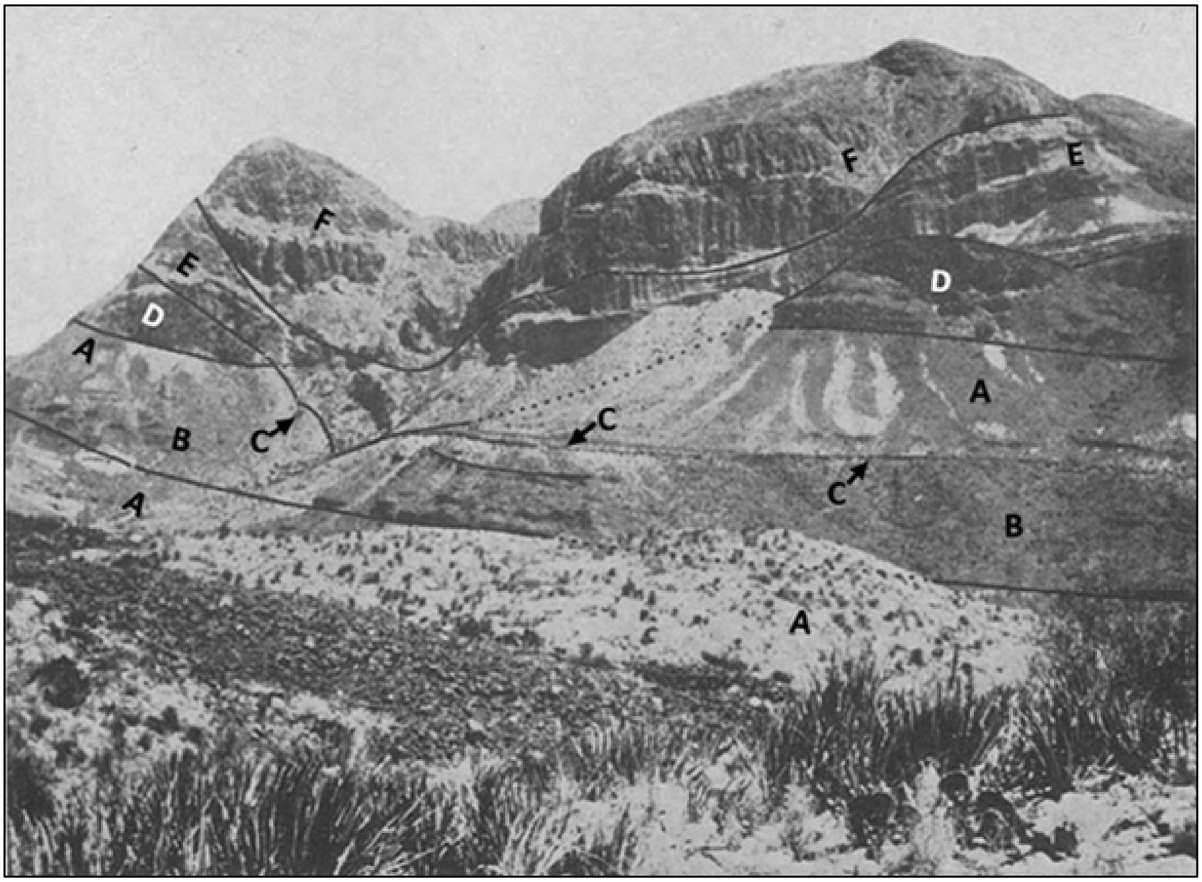


Figure 22. Type locality exposures of the Wasp Spring Flow Breccia Member of the South Rim Formation along the side of Goat Mountain, BIBE. A) Tuff, sandstone, and conglomerate of the Chisos Formation; B) Bee Mountain Basalt Member; C) Mule Ear Spring Tuff Member; D) Tule Mountain Trachyandesite Member; E) Wasp Spring Flow Breccia Member; and F) Burro Mesa Riebeckite Rhyolite Member. Figure modified from Maxwell et al. (1967).

The Burro Mesa Rhyolite Member of the South Rim Formation was named by Maxwell et al. (1967) after its type locality at Burro Mesa (Figures 10 and 23; Table 1). Exposures at the type locality form the highest peak on the western rim and measure 122–152 m (400–500 ft) thick. The member is characterized as a highly siliceous, medium-grained, gray rhyolite with quartz phenocrysts in a finely crystalline to glassy matrix that displays evident flow structure (Maxwell et al. 1967). The Burro Mesa Riebeckite Rhyolite is the youngest member of the South Rim Formation and truncates the older members southeast of Emory Peak and directly overlies the Wasp Spring Member in most areas outside the Chisos Mountains (Maxwell et al. 1967).

Figure 23. Type locality exposures of the Burro Mesa Rhyolite Member at Burro Mesa, BIBE. A) Burro Mesa Rhyolite Member; B) Wasp Spring Flow Breccia Member; C) Gravel conglomerate; D) Chisos Formation cover; and E) Bee Mountain Basalt Member (USGS).

Carlsbad Caverns National Park

Carlsbad Caverns National Park (CAVE) is located in Eddy and Union Counties, New Mexico, about 32 km (20 mi) from Carlsbad and 8 km (5 mi) from Guadalupe Mountains National Park (Figure 24). The park was established as a national monument on October 25, 1923 and upgraded to national park status on May 14, 1930 (Anderson 2017). Situated in the Guadalupe Mountains, CAVE encompasses approximately 18,926 hectares (46,766 acres) and preserves more than 120 separate caves decorated with spectacular gypsum chandeliers, sheet-like draperies, towering columns and domes, delicate soda-straw stalactites, and other cave formations ("speleothems") (Graham 2007). Carlsbad Cavern and other caves of the park are formed within an ancient fossil reef and hosts a unique ecosystem of bats, cave climate, speleothems, hydrology, cave fauna, and microbes (Graham 2007). The United Nations recognized the worldwide significance of the natural resources at CAVE by designating the park a World Heritage Site on December 9, 1995.

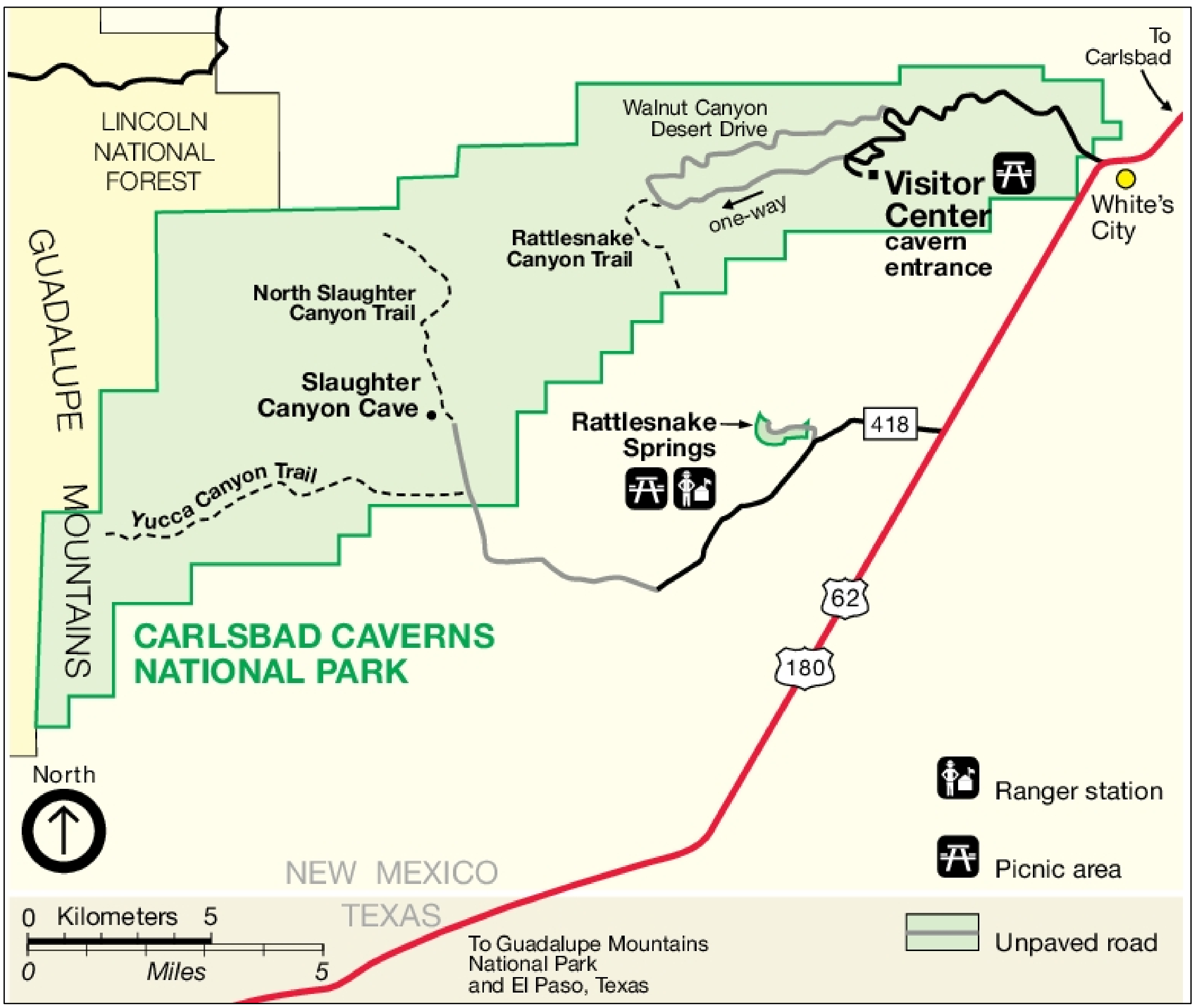


Figure 24. Park map of CAVE, New Mexico (NPS).

The geology of CAVE is dominated by Permian-age units that formed an ancient reef system (Figure 25). The world-renowned cave network of the park is an extraordinary example of sulfuric acid dissolution. Limestones of the ancient reef complex have been slowly dissolved by weak carbonic acid that forms as groundwater interacts with carbon dioxide. At Carlsbad Cavern, hydrogen sulfide originating from deeply buried petroleum reservoirs has migrated upward and reacted with groundwater, forming sulfuric acid that enhanced the dissolution of limestone (Graham 2007). Over the span of millions of years, the continuous dissolution and re-precipitation of limestone has created the vast cave chambers and delicate speleothems seen today. One of the major cave systems of CAVE, Lechuguilla Cave, is the nation's deepest limestone cave at 486 m (1,590 ft) and represents the third longest. The Big Room in Carlsbad Cavern is the largest, most easily accessible chamber in North America covering 3.2 hectares (8 acres) with a 76 m (250 ft) ceiling (Graham 2007; Anderson 2017).

As of the writing of this paper, there are no designated stratotypes identified within the boundaries of CAVE. There are 11 identified stratotypes located within 48 km (30 mi) of CAVE boundaries, for the Permian-age units of the Bell Canyon Formation (type locality), Lamar Limestone Member of the Bell Canyon Formation (type locality), Cherry Canyon Formation (type area), Getaway Limestone Member of the Cherry Canyon Formation (type locality), South Wells Member of the Cherry Canyon Formation (type locality), Brushy Canyon Formation (type locality), Castile Formation (type locality), Queen Formation (type section), Grayburg Formation (type section), Yates Formation (reference section), and the Tansill Formation (type locality).

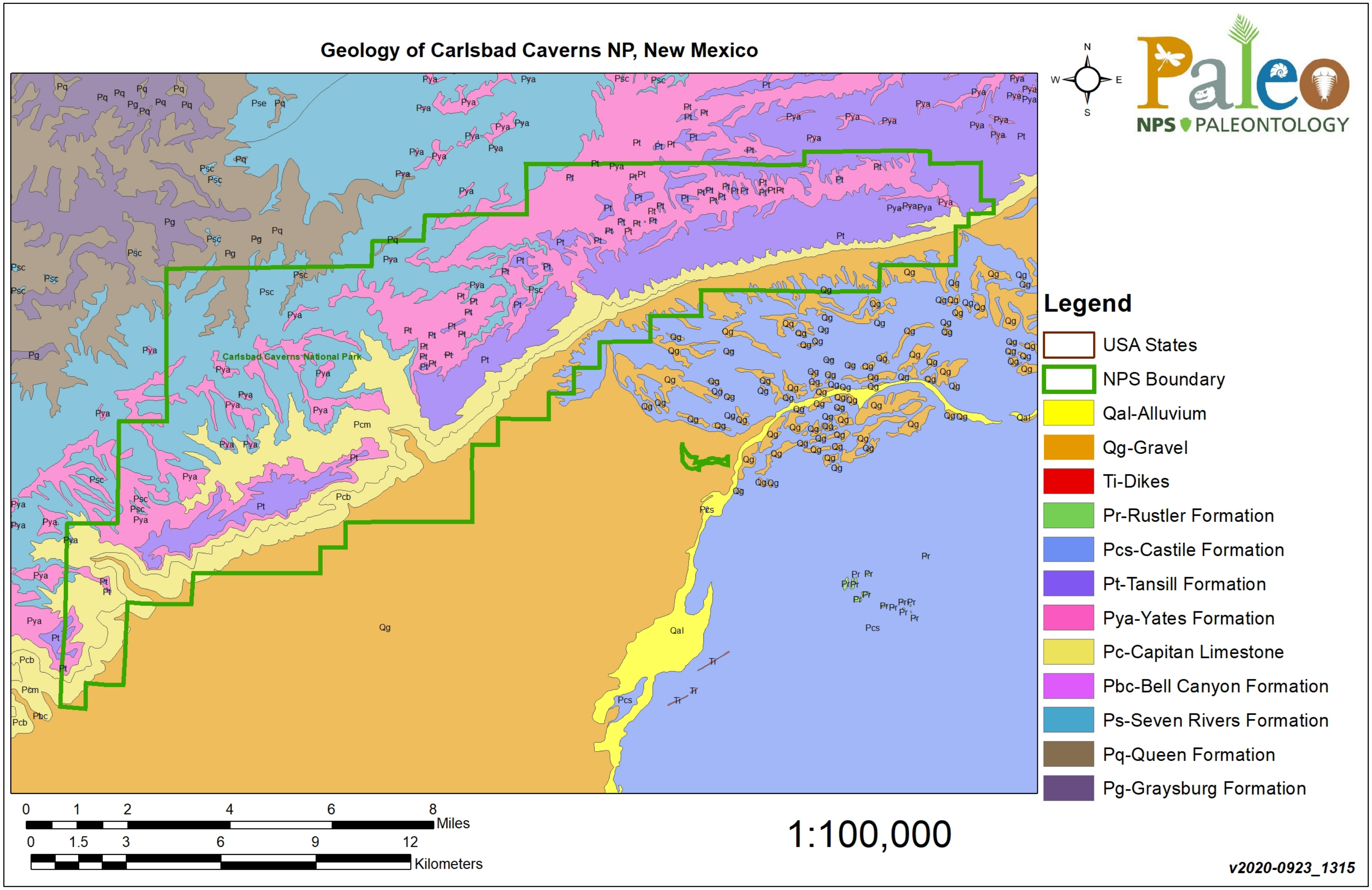


Figure 25. Bedrock geologic map of CAVE, New Mexico.

Fort Davis National Historic Site

Fort Davis National Historic Site (FODA) is located in Jeff Davis County, western Texas and represents one of the best surviving examples of a frontier military post in the American Southwest (Figure 26). Soldiers from Fort Davis helped open the west to settlement and protected emigrants, mail coaches, and freight wagons along the San Antonio–El Paso Road from 1854 to 1891 (Anderson 2017). Established on July 4, 1963, FODA encompasses 212 hectares (523 acres) and preserves five buildings that have been restored and refurbished to the 1880s, along with 100 ruins and foundations (Anderson 2017). Visitors to FODA are encouraged to take a self-guided tour of the frontier post or hike along trails that lead to a spectacular overlook of the fort and connect with trails of the Davis Mountains State Park.

Figure 26. Regional map of FODA, Texas (NPS).

The geology of the FODA area consists primarily of Cenozoic-age volcanic rocks that include the Frazier Canyon, Sleeping Lion, and Barrel Spring Formations (Figure 27). Volcanism in the region of FODA occurred between 36–35 million years ago. The nearby Davis Mountains represent a heavily eroded volcanic field that probably covered 5–10 times the present areal extent of approximately 5,180 km^2 (2,000 mi^2) (Anderson 1968). Much of the volcanic rock in FODA and parts of western Trans-Pecos Texas is believed to have erupted from the nearby central Davis Mountains (Anderson 1968).

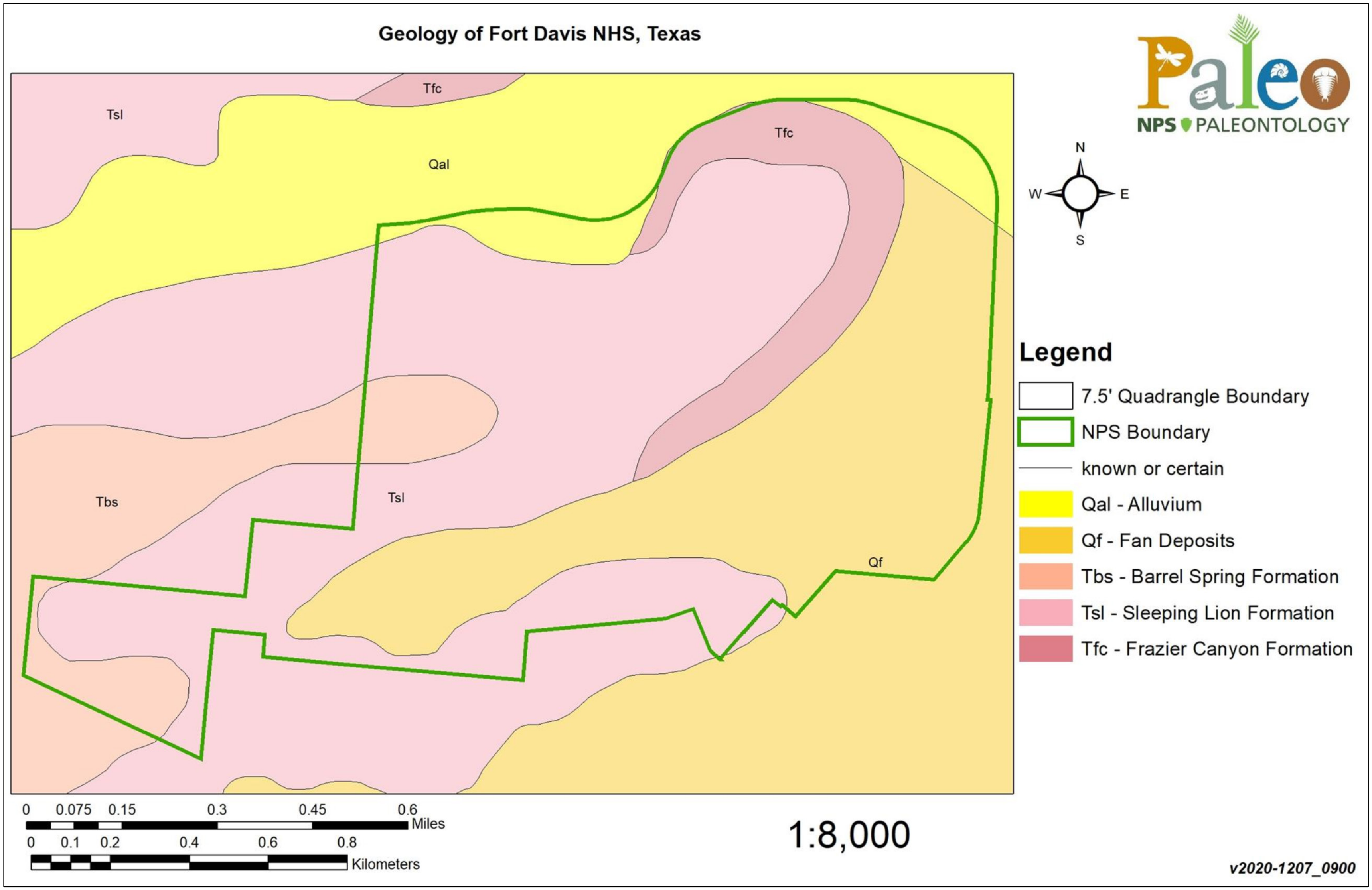


Figure 27. Bedrock geologic map of FODA, Texas.

As of the writing of this paper, there are no formally designated stratotypes identified within the boundaries of FODA. However, two academic theses completed by Smith (1975) and Hicks (1982) mention a type locality for the Eocene-age Sleeping Lion Formation at Sleeping Lion Mountain, FODA. According to Smith (1975) and Hicks (1982), type locality exposures measure 108 m (354 ft) and thicken east of Fort Davis to a maximum of about 200 m (656 ft). The formation consists of porphyritic rhyolite that weathers reddish-brown to gray that forms palisades that cap mesas and contains boulder-strewn slopes (Smith 1975; Hicks 1982). The Sleeping Lion displays a vertical zonation with a basal breccia unit overlying the Frazier Canyon Formation, a middle unit of foliated rhyolite, and an uppermost vitrophyre and breccia unit (Hicks 1982). It is recommended that this information be utilized toward designating a formal stratotype (see "'Recommendations" section #3).

There are three identified stratotypes located within 48 km (30 mi) of FODA boundaries, for the Cretaceous-age Dry Tank Member of the Boquillas Formation (type locality), the Eocene–Oligocene Barrel Spring Formation (type section), and the Oligocene Mount Locke Formation (type section).

Guadalupe Mountains National Park

Guadalupe Mountains National Park (GUMO) is located along the Guadalupe Mountains south of the New Mexico–Texas border in Culberson and Hudspeth Counties, northwest Texas (Figure 28). Authorized as a national park on October 15, 1966, GUMO encompasses 34,951 hectares (86,367 acres) of Permian-age fossil reef strata. Exposures of the world-renowned reef have been studied by geologists from around the globe (KellerLynn 2008). GUMO hosts multiple peaks that rise high above the Texas and New Mexico landscape, including Guadalupe Peak, the highest summit in Texas at 2,667 m (8,751 ft). Rugged canyons, red quartz and white gypsum sand dunes, and diverse habitats from desert dunes to montane forests are at the junction of three major biomes, where flora and fauna of the Chihuahuan, Rocky Mountain, and Great Plains meet (Anderson 2017). In addition to their scenic value, the geology of GUMO provides visitors with spectacular vistas including the cliffs of the western and eastern escarpments including the iconic El Capitan. GUMO rocks contain major faults, fault scarps, massive ancient submarine debris flow deposits with boulders the size of small houses and sedimentary structures such as cross-bedding, erosion scars, and a plethora of fossils (KellerLynn 2008).

The carbonate and siliciclastic sequences revealed at GUMO represent some of the world's finest and most extensive exposures of middle Permian (274.4–259.5 million years ago) rocks called the Permian Reef Complex (Figure 29; Wu et al. 2020). The reef system rimmed the middle Permian Delaware basin but today is mostly buried in the subsurface. Reef rocks crop out in the Glass, Apache, and Guadalupe Mountains. Today the exposures of the reef stretch across 563 km (350 mi) of western Texas and southeastern New Mexico into Carlsbad Caverns National Park. Two escarpments at GUMO offer tremendous exposures of reef system architecture. The western escarpment exposes a section ~2 km (1 mi) thick and ~16 km (10 mi) long in oblique cross-section. The eastern escarpment affords a view that more closely approximates the trend of the reef front. Both escarpments have been highly modified by Neogene erosion. Nearly 305 m (1,000 ft) of Permian rock have been removed from the top of the existing strata and the reef front at GUMO has retreated some 610–914 m (2,000–3,000 ft). In 1991, the International Commission on Stratigraphy (ICS) proposed subdividing the Permian into three series, lower, middle, and upper. The Permian geology of the Guadalupe Mountains is so exceptional that the commission selected this section of rocks to be the exemplar of the middle Permian and named the series the Guadalupian. This chronostratigraphic scheme was adopted in 1996 (Glenister 1996) and the series is subdivided into three stages marked by Global Stratotype Sections and Points (GSSPs): the Roadian, Wordian, and Capitanian.

The stratotype designations at GUMO can be divided into two groups: chronostratigraphic units (series and stages) and lithostratigraphic units that consist of ten type sections, five type localities, and six reference sections (Table 2; Figures 30 and 31;).

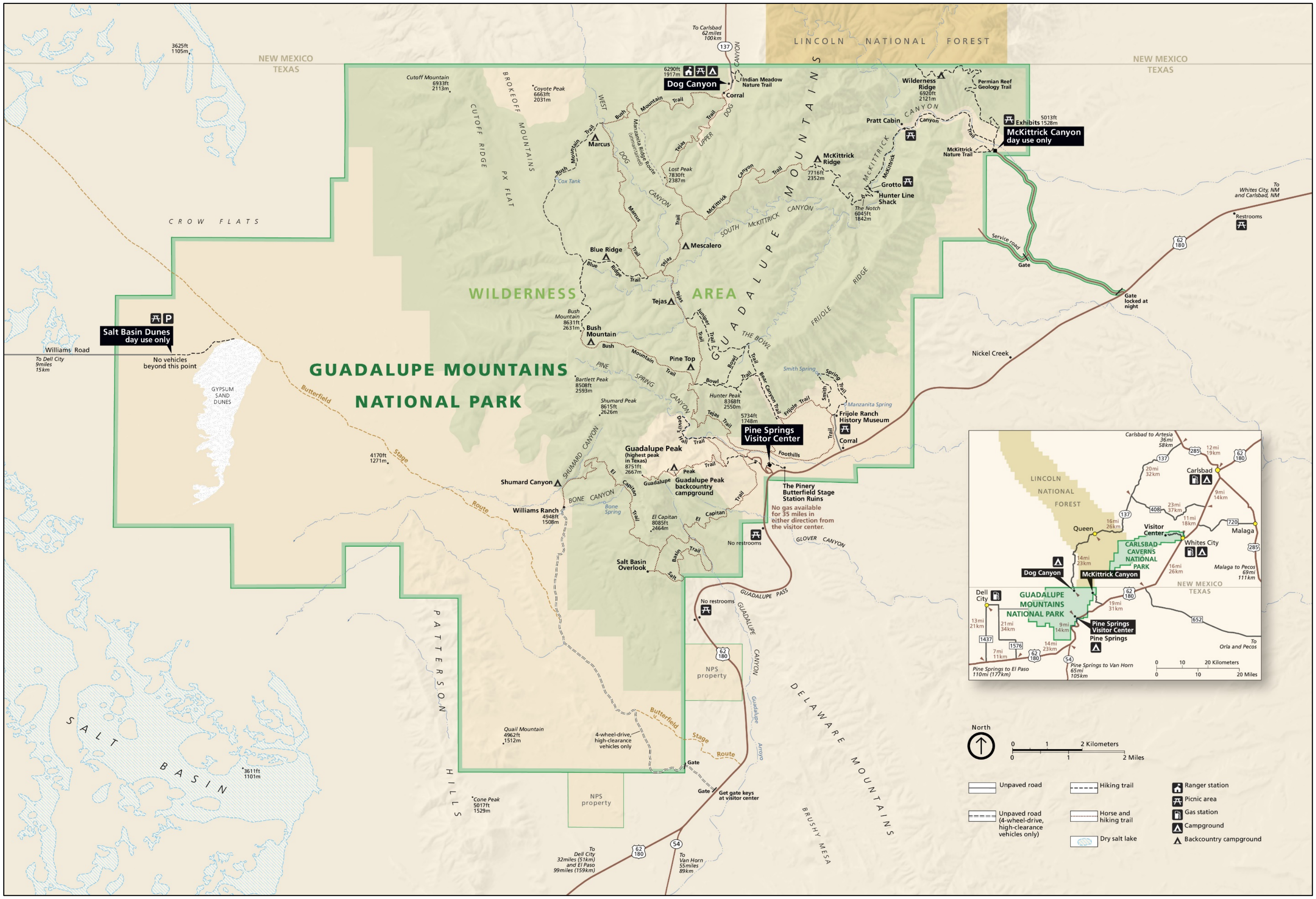


Figure 28. Park map of GUMO, Texas (NPS).

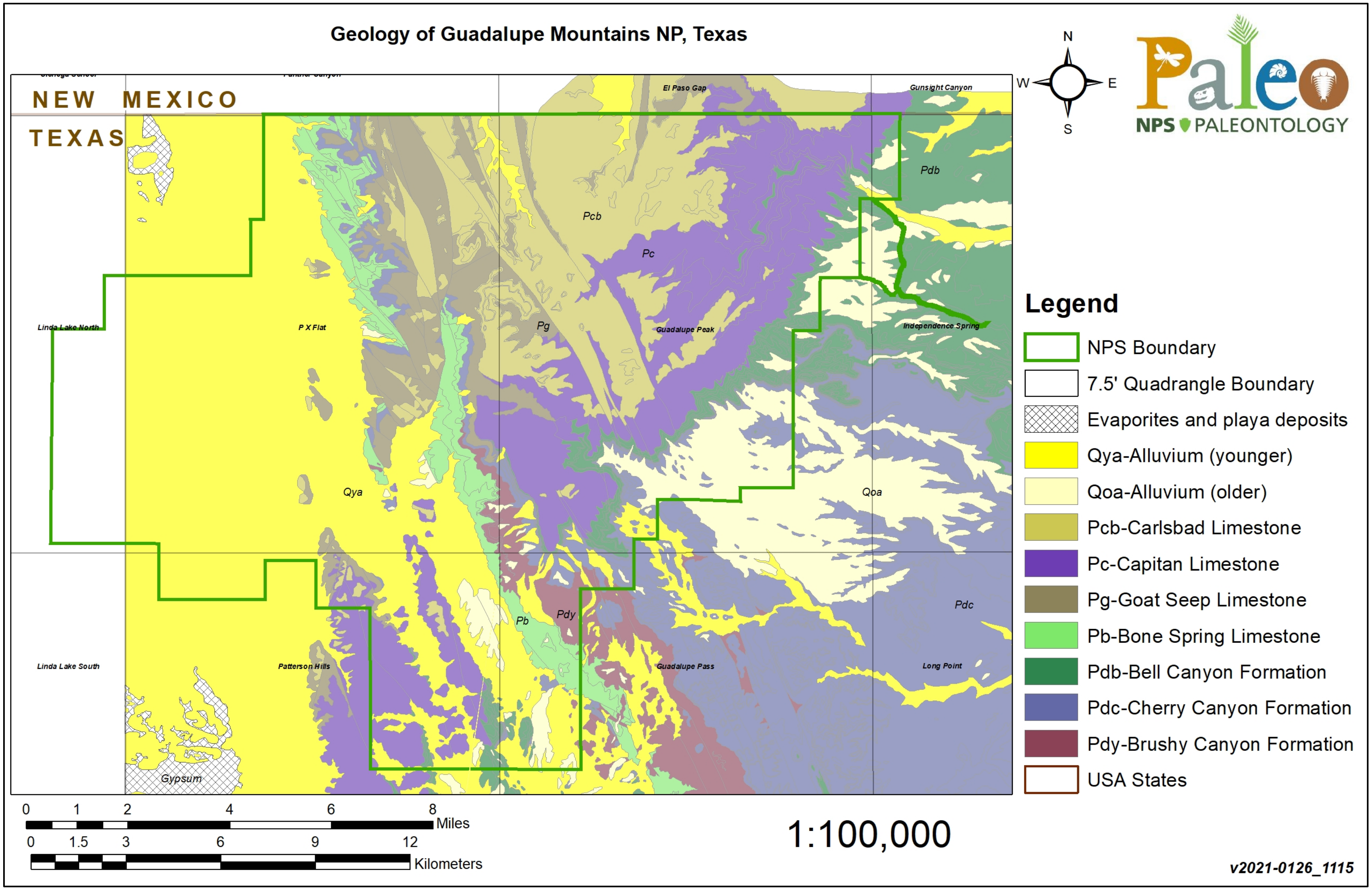


Figure 29. Bedrock geologic map of GUMO, Texas.

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

Unit Name	Reference	Stratotype Location	Age
Capitan Limestone	King 1948	Type locality: Guadalupe Peak, about 2 km (1 mi) north of the summit of El Capitan	Permian
Rader Limestone Member, Bell Canyon Formation	King 1942	Type locality: at Rader Ridge, which projects from the foot of the Reef Escarpment near the Hegler Ranch	Permian
Pinery Limestone Member, Bell Canyon Formation	King 1942	Type section: on the slope above Pine Spring ~4.0 km (2.5 mi) east of Guadalupe Peak	Permian
Reef Trail Member, Bell Canyon Formation	Wilde et al. 1999; Lambert et al. 2010; Bell et al. 2015	Type section: at an escarpment approximately 0.8 km (0.5 mi) northeast of the GUMO Contact Station in McKittrick Canyon Reference section: ~200 m (656 ft) southeast of the type section in McKittrick Canyon Reference sections (2): in the Patterson Hills, south-central GUMO	Permian
McCombs Limestone Member, Bell Canyon Formation	King 1948; King and Newell 1956	Type section: section 34, bed 15 of King (1948), located a short distance southeast of McCombs Ranch	Permian
Goat Seep Limestone	King 1942, 1948	Type section: in a spur north of Goat Seep and beyond Shirttail Canyon, where thick limestone ledges merge to form a single group of cliffs Type locality: Goat Seep, on western slope of Guadalupe Mountains, 2.4 km (1.5 mi) northwest of Guadalupe Peak	Permian
Manzanita Limestone Member, Cherry Canyon Formation	King 1942	Type section: Nipple Hill, east of Manzanita Spring	Permian
Williams Ranch Member, Cutoff Shale Formation	Harris 2000; Hurd et al. 2018	Type section: located in Operahouse Canyon below the Western Escarpment of the Guadalupe Mountains Reference section: near the southern limit of the complete exposures of the El Centro Member	Permian
Rest Area Member, Cutoff Formation	Hurd et al. 2018	Type section: located in Blackstove Canyon	Permian
Butterfield Member, Cutoff Formation	Hurd et al. 2018	Type section: south side of Beesting Canyon	Permian
El Centro Member, Cutoff Shale Formation	Harris 2000; Hurd et al. 2018	Type section: in Stratotype Canyon located 0.85 km (0.53 mi) south of Bone Canyon Reference section: near the southern limit of the complete exposures of the El Centro Member	Permian

Table 2 (continued). List of GUMO stratotype units sorted by age with associated reference publications and locations.

Unit Name	Reference	Stratotype Location	Age
Shumard Member, Cutoff Shale Formation	Harris 2000; Hurd et al. 2018	Type section: on the north side of the south fork of Shumard Canyon Reference section: in Stratotype Canyon located 0.85 km (0.53 mi) south of Bone Canyon	Permian
Cutoff Formation	King 1942; Harris 1988	Type locality: west face of Cutoff Mountain in the northern Guadalupe Mountains	Permian
Bone Spring Limestone	Sellards 1933	Type locality: Bone Spring Canyon on the west side of Guadalupe Mountains	Permian
Capitanian Stage, Guadalupian Series	Henderson et al. 2012	GSSP: the top of Nipple Hill, approximately 1.1 km (0.7 mi) east of Frijole Ranch	Permian
Wordian Stage, Guadalupian Series	Henderson et al. 2012	GSSP: near the southeastern GUMO boundary at the top of the east wall of Guadalupe Canyon	Permian
Roadian Stage, Guadalupian Series	Henderson et al. 2012	GSSP: in Stratotype Canyon approximately 1 km (0.6 mi) south of Bone Canyon near Williams Ranch House	Permian

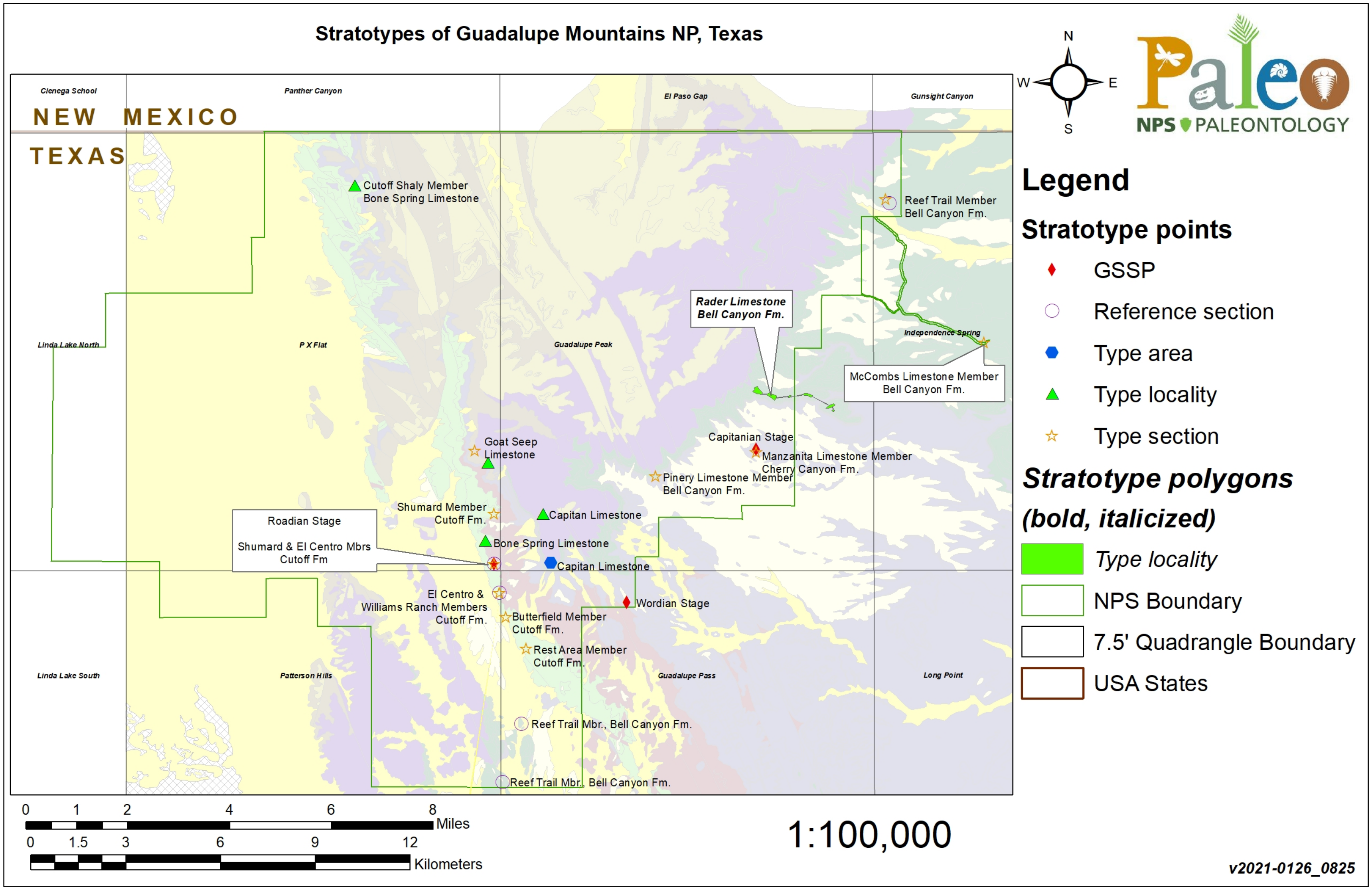


Figure 30. Modified geologic map of GUMO showing stratotype locations. The transparency of the geologic units layer has been increased.

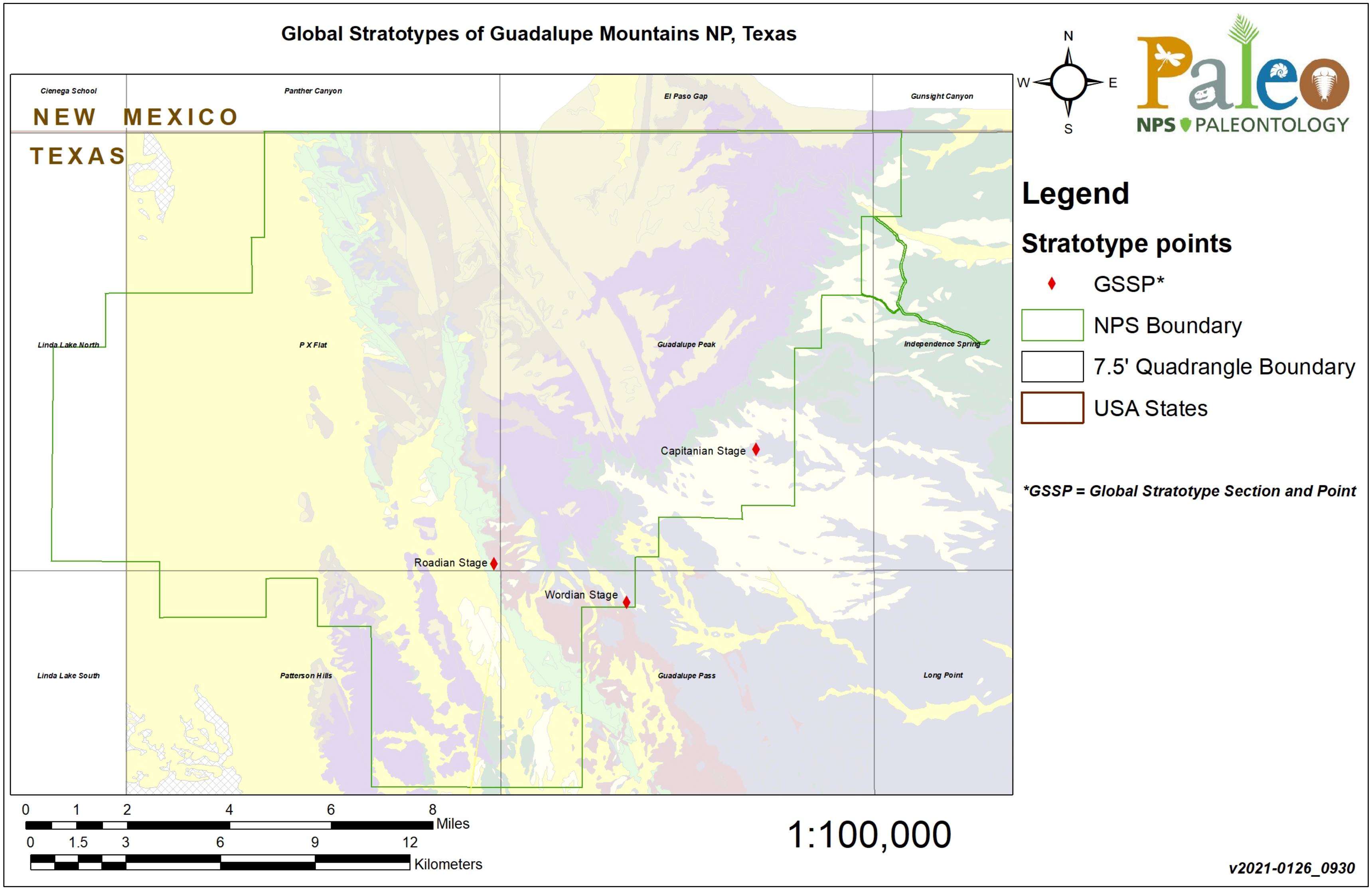


Figure 31. Modified geologic map of GUMO showing Global Stratotype locations. The transparency of the geologic units layer has been increased.

Chronostratigraphic Units

Much of the research on rocks of the middle Permian was done in the Glass, Apache, and Guadalupe Mountains of west Texas. When the ICS proposed to divide the Permian into three series, the rocks of GUMO were chosen as a standard because of the extensive early work by numerous authors going back to 1859 and for the spectacular exposures spanning virtually the entire middle Permian. Neither the Apache nor Glass Mountains outcrops are publicly accessible unlike outcrops in GUMO. The National Park Service is in a position to ensure protection and preservation of the outcrops as well as ensuring public and research access. GUMO contains three GSSPs: the Roadian Stage marks the base of both the series as well as the oldest stage of the middle Permian, the Wordian Stage the next youngest, and the Capitanian, the youngest stage in the series. The Roadian ties into lower Permian outcrops in Russia and upper Permian outcrops in China.

The lower Guadalupian Series is represented by the Roadian Stage, located in Stratotype Canyon approximately 1 km (0.6 mi) south of Bone Canyon near Williams Ranch House and situated in the middle of the El Centro Member of the Cutoff Formation (Table 2; Figure 31; KellerLynn 2008). The base of the middle stage, the Wordian Stage, is located near the southeastern GUMO boundary near the top of the east wall of Guadalupe Canyon within the Getaway Limestone Member of the Cherry Canyon Formation (Table 2; Figures 31 and 32; KellerLynn 2008). The base of the upper stage, the Capitanian Stage, is located near the top of Nipple Hill, approximately 1.1 km (0.7 mi) east of Frijole Ranch within the Pinery Limestone Member of the Bell Canyon Formation (Table 2; Figures 31 and 33; KellerLynn 2008).

Figure 32. GSSP of the Wordian Stage at the Getaway Section (NPS).

Figure 33. GUMO Superintendent Dennis Vasquez, GUMO Physical Science Program Manager Dr. Jonena Hearst, Dr. Charles Henderson, Dr. Shuzhong Shen after installing the Capitanian GSSP marker on Nipple Hill, May 2013 (NPS). Dr. Henderson and Dr. Shen are both members of the Subcommittee on Permian Stratigraphy on the International Commission on Stratigraphy.

Lithostratigraphic Units

The Bone Spring Limestone was named by Blanchard and Davis (1929) after Bone Springs Canyon in northwest Culberson County, Texas. The type locality of the formation is at Bone Springs Canyon on the west side of Guadalupe Mountain, but the best exposures are in the Sierra Diablo on the southwest (Table 2; Figure 30; Sellards 1933; King 1942). The formation consists primarily of limestone of varied types that are interbedded and interfingered (King 1942).

The Cutoff Formation was originally designated by King (1942) as the “Cutoff Shaly Member of the Bone Spring Limestone” and raised to formation status by King (1965). Harris (1988) modified the name to the Cutoff Formation. The type locality is in the northern Guadalupe Mountains on the west face of Cutoff Mountain near the Texas–New Mexico border (Table 2; Figure 30; King 1942). At the type locality, the formation consists of several hundred feet of gray or black, thin-bedded limestone and siliceous shale that overlies gray limestones of the Victorio Peak Member of the Bone Spring Formation and grade upward conformably into the overlying Brushy Canyon Formation (King 1942).

The Shumard Member of the Cutoff Formation was first recognized by King (1948) and formally designated by Harris (2000) after Shumard Canyon on the western escarpment. The type section of the member is located on the north side of the south fork of Shumard Canyon (Table 2; Figure 30; Harris 2000). The type section occurs within a 40 m (130 ft) deep channel carved into the Victorio Peak Member of the Bone Spring Limestone and contains here the thickest expression of the unit measuring 49 m (160 ft) (Harris 2000). Lithologically, the type section consists of black to dark gray, medium-bedded, cherty lime mudstone with thin laminations, thin-laminated, very fine-grained sandstone, intraclastic rudstone lenses, and shale (Harris 2000). The Shumard Member is bounded by unconformities. A reference section of the Shumard Member is in the first canyon 0.85 km (0.53 mi) south of Bone Canyon along the western escarpment of the Guadalupe Mountains, and measures approximately 18.3 m (60.0 ft) thick (Table 2; Figure 30; Harris 2000).

The El Centro Member of the Cutoff Formation was designated by Harris (2000) after El Centro Draw, an arroyo south of Bone Canyon. The type section is in Stratotype Canyon, an informal name given to the canyon by the NPS, located ~0.85 km (0.53 mi) south of Bone Canyon along the western escarpment of the Guadalupe Mountains (Table 2; Figure 30). The type section measures 20.5 m (67.3 ft) and consists of interbedded dark gray, to black, to dark brown lime mudstone-shale and medium-bedded lime mudstone (Harris 2000). Approximately half of the type section consists of the lime mudstone interval and serves as a useful marker horizon within the member (Harris 2000). The lower contact of the type section represents an unconformity with an abrupt shift from cherty lime mudstone of the Shumard Member to interbedded lime mudstone-shale of the El Centro Member (Harris 2000). The upper contact of the type section with the overlying Williams Ranch Member is also an intraformational unconformity and represents minor channel scours (Harris 2000). A reference section of the member is designated near the southern limit of the complete exposures of the El Centro Member and measures approximately 50 m (160 ft) thick (Table 2; Figure 30; Harris 2000).

The Butterfield Member of the Cutoff Formation was designated by Hurd et al. (2018) after the Butterfield Stage Route that extends north of Highway 62-180 and connects with Williams Ranch Road south of Liquid Canyon. The type section of the member is located on the south side of Beesting Canyon and measures 10 m (33 ft) (Table 2; Figure 30). At the type section the unit overlies the upper shale of the El Centro Member and consists of silty skeletal peloidal wackestone to packstone beds which are thin and normally graded and display cross-bedding and planar stratification (Hurd et al. 2018).

The Rest Area Member of the Cutoff Formation was named by Hurd et al. (2018) and is derived from the informal "Rest Area Gully" situated near a rest area below El Capitan along Highway 62-180. The type section of the member is located in Blackstove Canyon and consists of a succession of black shales, carbonates, and sandstones with a thickness of 10 m (33 ft) (Table 2; Figure 30; Hurd et al. 2018). At the type section, exposures of the Rest Area Member overlie the Butterfield Member and underlie limestones of the Williams Ranch Member (Hurd et al. 2018).

The Williams Ranch Member of the Cutoff Formation was named by Harris (2000) after the Williams Ranch House located at the mouth of Bone Canyon. The type section of the member is located in Operahouse Canyon below the western escarpment of the Guadalupe Mountains (Table 2; Figure 30). The type section measures 13 m (43 ft) thick and consists predominantly of dark gray, medium-bedded lime mudstone that is well-laminated with the exception of minor burrow disturbances (Harris 2000). Small lenses of intraclastic and skeletal rudstone mark the erosional base of the member, which represents an intraformational unconformity (Harris 2000). The upper contact of the Williams Ranch Member with the overlying Brushy Canyon Formation is also unconformable and marks a change from carbonate sedimentation to mostly clastic deposition. A reference section of the member is designated near the southern limit of the complete exposures of the El Centro Member and measures approximately 10.7 m (35.1 ft) thick (Table 2; Figure 30; Harris 2000).

The Manzanita Limestone Member of the Cherry Canyon Formation was named by King (1942) after Manzanita Spring, near Frijole Post Office (now the Frijole Ranch Cultural Museum). The type section is located on Nipple Hill east of Manzanita Spring (Table 2; Figures 30 and 34). The member is widely distributed throughout the southern Guadalupe Mountains where it forms prominent exposures below the dark limestone ledges of the Hegler and Pinery Members of the Bell Canyon Formation (King 1942). The Manzanita Limestone Member measures 7.6–30.5 m (25–100 ft) thick and consists of thick-bedded, tan limestone with abundant geode cavities and several intercalated beds of volcanic ash (King 1942).

Figure 34. Nipple Hill, type section location of the Manzanita Limestone Member of the Cherry Canyon Formation and GSSP marker site for the base of the Capitanian Stage of the Guadalupian Series. Photograph by user “Fredlyfish4” available via Wikimedia Commons https://commons.wikimedia.org/wiki/File:Nipple_Hill.JPG (Creative Commons Attribution-Share Alike 3.0 Unported [CC BY-SA 3.0]; https://creativecommons.org/licenses/by-sa/3.0/deed.en).

The Goat Seep Limestone was named by King (1942, 1948) after Goat Seep, on the western slopes of the Guadalupe Mountains 2.4 km (1.5 mi) northwest of Guadalupe Peak. Well-exposed sections of the formation are located on the west-facing escarpment of the Guadalupe Mountains for several miles north of the type locality (King 1948). The Goat Seep Limestone consists of massive or thick-bedded, gray dolomitic limestone that is similar to the Capitan Limestone. The type section of the formation is situated in a spur north of Goat Seep and beyond Shirttail Canyon, where thick limestone ledges merge to form a single group of cliffs (Table 2; Figure 30; King 1948).

The McCombs Limestone Member of the Bell Canyon Formation was first designated by Newell et al. (1953). The member is named after McCombs Ranch in western GUMO where the limestone was quarried (King 1948). Originally called the "flaggy limestone bed" of the Bell Canyon Formation by King (1948), the unit was raised to formal member rank in King and Newell (1956). The type section of the McCombs Limestone Member is considered part of an exposure measured by King (1948) in section 34, bed 15, located a short distance southeast of McCombs Ranch in Culberson County, Texas (Table 2; Figure 30). The exposures occur along the present route of U.S. Highway 62 and near the former route of the highway as it existed before 1939 (King and Newell 1956). The member measures approximately 3 m (10 ft) thick and consists of fine-grained, gray limestone that forms a strong, persistent scarp that is traceable for 48 km (30 mi) or more southward from the Guadalupe Mountains (King 1948; King and Newell 1956).

The Reef Trail Member of the Bell Canyon Formation was originally referred to as the "post-Lamar" unit in King (1948) and was formally named by Wilde et al. (1999) after the nearby Geology Reef Trail southeast of the McKittrick Contact Station on the east side of the park. The Geology Reef Trail is known in park brochures as the Permian Reef Geology Trail. The type section of the member is located at an escarpment on the north side of McKittrick Creek approximately 0.8 km (0.5 mi) northeast of the Contact Station and continues to the top of the hill west of the park boundary line (Table 2; Figure 30; Wilde et al. 1999). The type section exposure measures 5.5 m (18 ft) thick and consists of yellowish calcareous siltstone and alternating silty lime mudstone and lime mudstone overlying the Lamar Limestone Member of the Bell Canyon Formation (Wilde et al. 1999). A more continuous, complete reference section of the Reef Trail Member was designated by Lambert et al. (2010) and is located about 200 m (656 ft) southeast of the type section (Table 2; Figure 30). The reference section measures approximately 14 m (47 ft) thick and consists predominantly of siltstone, sandstone, peloidal and skeletal packstone, and calcareous mudstone that rests upon the Lamar Limestone Member (Lambert et al. 2010). Two additional reference sections have been described by Bell et al. (2015) in the Patterson Hills, south-central GUMO (Table 2; Figure 30).

The Pinery Limestone Member of the Bell Canyon Formation was designated by King (1942) after "The Pinery", an old stage stand on the Butterfield trail. The type section of the member is located 4.0 km (2.5 mi) east of Guadalupe Peak on the slope above Pine Spring and measures 46 m (150 ft) thick (Table 2; Figure 30). At the type section and along the foot of the Reef Escarpment, the Pinery Limestone Member is situated approximately 9 m (30 ft) above the base of the Bell Canyon Formation and consists of dark gray, fine-grained, somewhat cherty limestone in thin beds with several thick, light gray basal layers (King 1942).

The Rader Limestone Member of the Bell Canyon Formation was designated by King (1942) after its type locality at Rader Ridge, which projects from the foot of the Reef Escarpment near the Hegler Ranch (now the Ligon Ranch) (Table 2; Figure 30). Type locality exposures form the cap of the ridge, situated above the ledges of the Pinery and Hegler Members. Exposures measure approximately 30 m (100 ft) at the type locality and along the Reef Escarpment and are situated 68.5 m (225 ft) above the base of the Bell Canyon Formation (King 1942). The Rader Limestone Member consists of massive, light gray limestone similar to that of the Capitan Limestone but with a few layers of thin, dark limestone (King 1942).

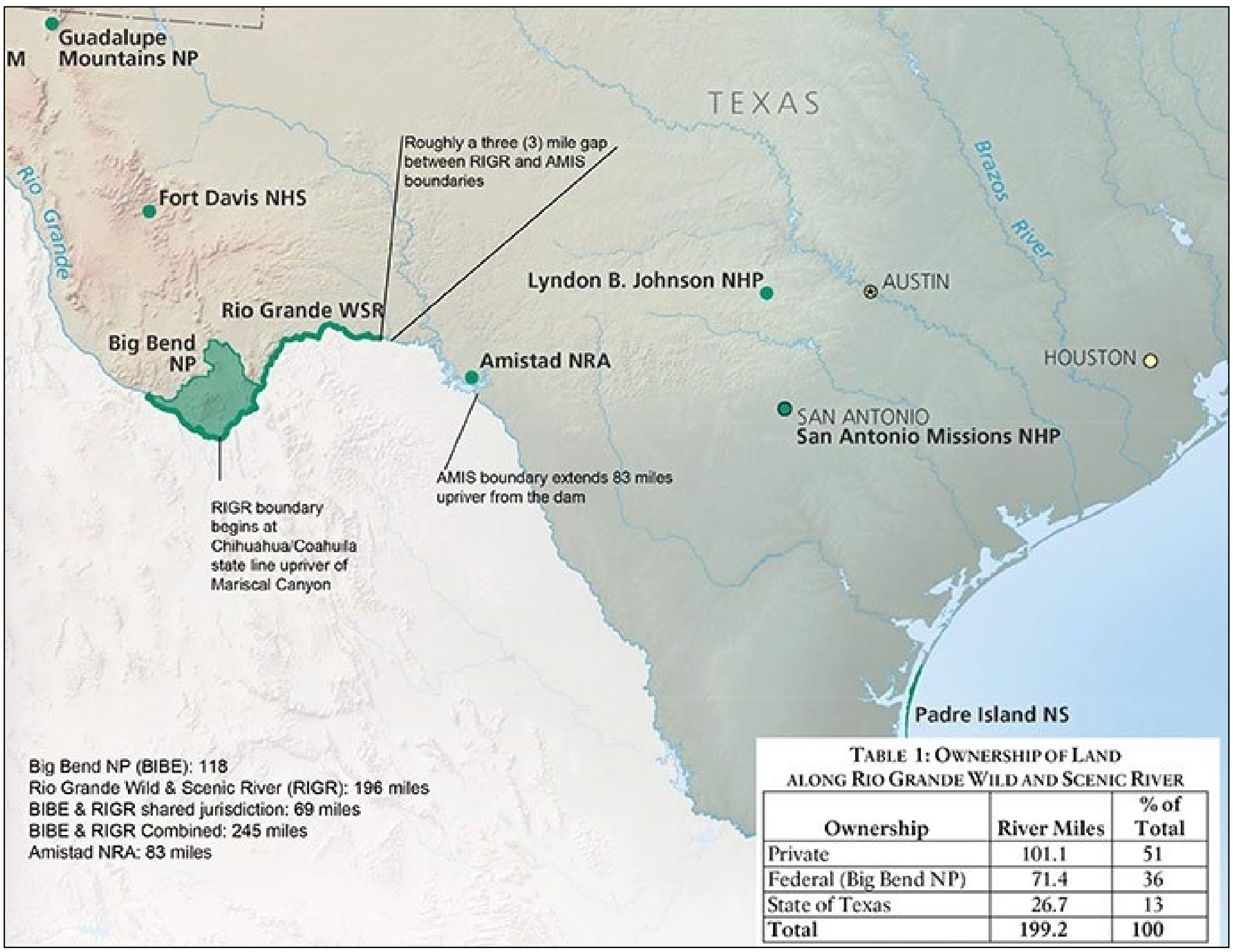
The Capitan Limestone was named by Richardson (1904) from El Capitan Peak at the southern end of the Guadalupe Mountains, who estimated its thickness at 549 m (1,800 ft). King (1942, 1948) restricted the Capitan Limestone to that of its reef and forereef facies, thereby excluding the Hegler and Pinery Members at the base of the cliff, and stated that the type locality is Guadalupe Peak, about 2 km (1 mi) north of the summit of El Capitan (Table 2; Figures 30 and 35). Type locality exposures measure 411.5 m (1,350 ft) thick and consist of light-gray or white calcitic limestone and gray dolomitic limestone that form smooth-surfaced ledges and cliffs (King 1948).

Figure 35. Southwest view of Guadalupe Peak, type locality of the Capitan Limestone (NPS).

In addition to the designated stratotypes located within GUMO, a list of stratotypes located within 48 km (30 mi) of park boundaries is included here for reference. These nearby stratotypes include the Permian-age units of the Bell Canyon Formation (type locality), Lamar Limestone Member of the Bell Canyon Formation (type locality), Hegler Limestone Member of the Bell Canyon Formation (type locality), Cherry Canyon Formation (type area), Getaway Limestone Member of the Cherry Canyon Formation (type locality), South Wells Member of the Cherry Canyon Formation (type locality), Brushy Canyon Formation (type locality), Castile Formation (type locality), Queen Formation (type section), Grayburg Formation (type section), and Yates Formation (reference section).

Rio Grande Wild and Scenic River

The Rio Grande Wild and Scenic River (RIGR) is a 315 km (196 mi) strip of the Rio Grande that serves as the U.S.–Mexico border and is located along Brewster and Terrell Counties, southwestern Texas (Figure 36). RIGR begins in Big Bend National Park near Mariscal Canyon and continues downstream to the Terrell–Val Verde County line, approximately 5 km (3 mi) from Amistad National Recreation Area (Anderson 2017). Authorized on November 10, 1978, RIGR encompasses 3,885 hectares (9,600 acres) of protected free-flowing natural and scenic conditions of the river and its immediate environment. This strip of the Rio Grande was designated for its remarkable scenic, geologic, recreational, and cultural values (Anderson 2017).



Ownership	River Miles	% of Total
Private	101.1	51
Federal (Big Bend NP)	71.4	36
State of Texas	26.7	13
Total	199.2	100

Figure 36. Regional map of RIGR, Texas (NPS).

The geology of RIGR is dominated by Cretaceous-age limestone units that form spectacular canyon cliffs that can rise 427 m (1,400 ft) above the river valley (Figure 37). The shortest canyon in the park is the 16 km (10 mi)-long Mariscal Canyon, which has varied scenery and some of the deepest canyon walls of RIGR. Visitors who decide to travel the 53 km (33 mi) journey through Boquillas Canyon will be inspired by 366 m (1,200 ft) cliffs and the remains of candelilla wax mining camps on the Mexican side of the river. The landscape of the Lower Canyons of RIGR are decorated with open desert, rugged hills, and deep canyons that offer one the longest float trips through the park (134 km [83 mi]).

As of the writing of this paper, there are no designated stratotypes identified within the boundaries of RIGR. There are also no identified stratotypes located within 48 km (30 mi) of RIGR boundaries.

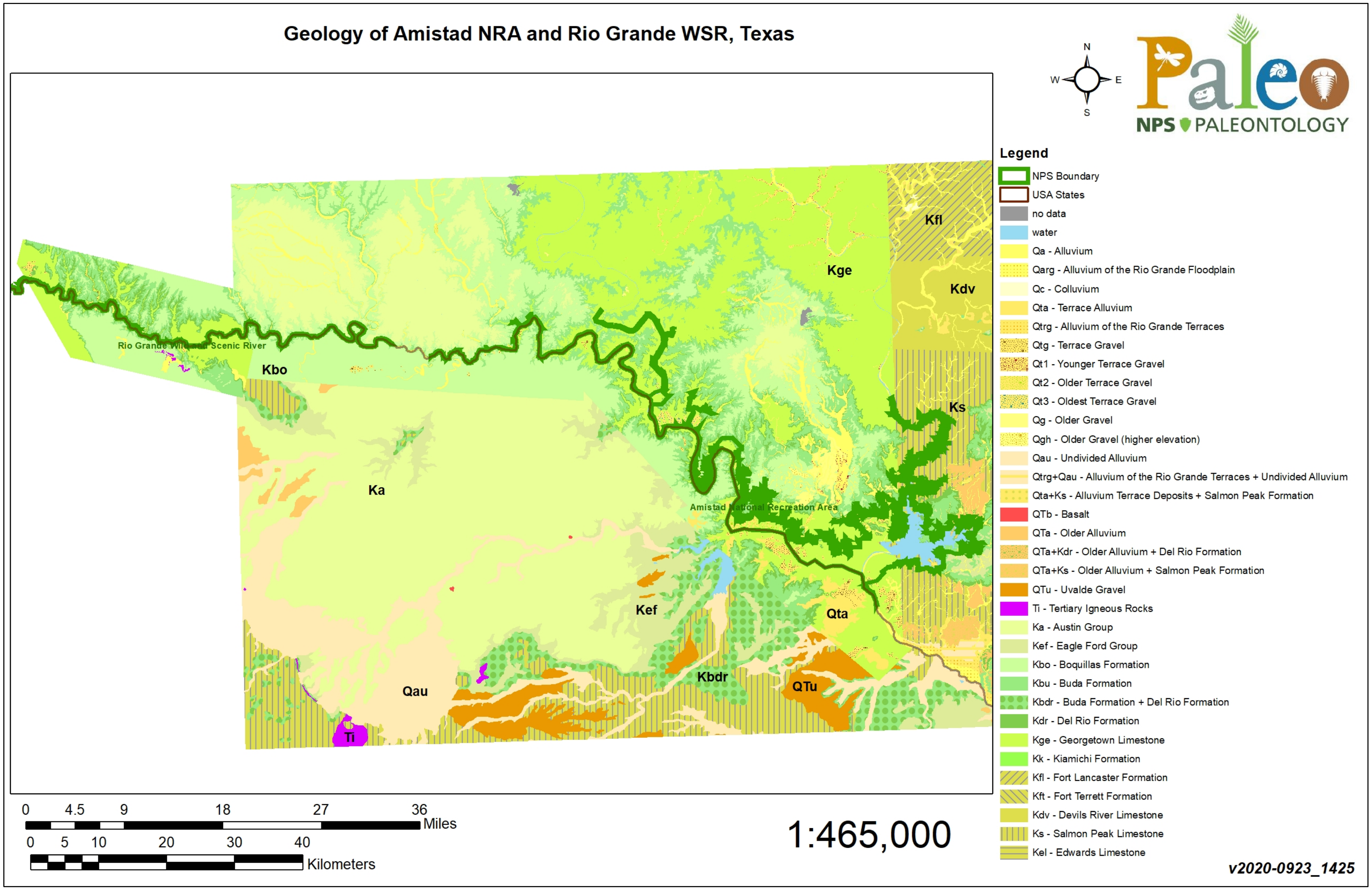


Figure 37. Bedrock geologic map of RIGR, Texas.

White Sands National Park

White Sands National Park (WHSA) is located in Dona Ana and Otero Counties, New Mexico (Figure 38). The park was originally established as a national monument on January 18, 1933 and was upgraded to national park status on December 20, 2019. White Sands National Park encompasses 58,987.8 hectares (145,762 acres) and preserves a significant portion of the world's largest gypsum dune field, hosting about 200 km^2 (115 mi^2) of the entire field. The glistening white dunes can reach 18 m (60 ft) tall and have been sculpted by eolian (wind-related) processes. The White Sands dune field is situated within the Tularosa Basin between the San Andres and Sacramento Mountains. Major geomorphic features of the region include extensive floors of intermontane basins, contiguous piedmont slopes (or bajada), and upland areas including mountain ranges (e.g., San Andes and Sacramento) and high plateaus bounded by steep escarpments (KellerLynn 2012).

The geologic story of the White Sands National Park region encompasses billions of years, with some of the oldest rocks in the area dating back ~1.4 billion years to the Precambrian (Figure 39). These Precambrian schists and gneisses represent the formation and subsequent erosion of an ancient mountain or rift system (KellerLynn 2012). Rock formations that are Cambrian through Cretaceous-age (~541–66 million years ago) record the dynamic rise and fall of shallow seas that periodically flooded the area of WHSA. Uplifted mountains shed sediments into the region throughout the Pennsylvanian, Permian, and Cretaceous Periods that are recognized today as the Panther Seep, Hueco, Abo, Yeso, San Andres, Dakota, and Sarten Formations. The Cenozoic history of WHSA is dominated by crustal extension and volcanism during the Oligocene, and the development of an ancient lake called Lake Otero (KellerLynn 2012). Subsequent evaporation of Lake Otero left behind a dry lakebed (or "playa") and the modern Lake Lucero. The slow, continuous evaporation and subsequent wind erosion of these lakes over thousands of years have produced the spectacular gypsum dunes that are the park's namesake.

As of the writing of this paper, there are no designated stratotypes identified within the boundaries of WHSA. There are four identified stratotypes located within 48 km (30 mi) of WHSA boundaries, for the Permian San Andres Limestone (type section), Pennsylvanian-age units of the Lead Camp Limestone (type section) and Panther Seep Formation (type section), and the Cenozoic Love Ranch Formation (type locality).

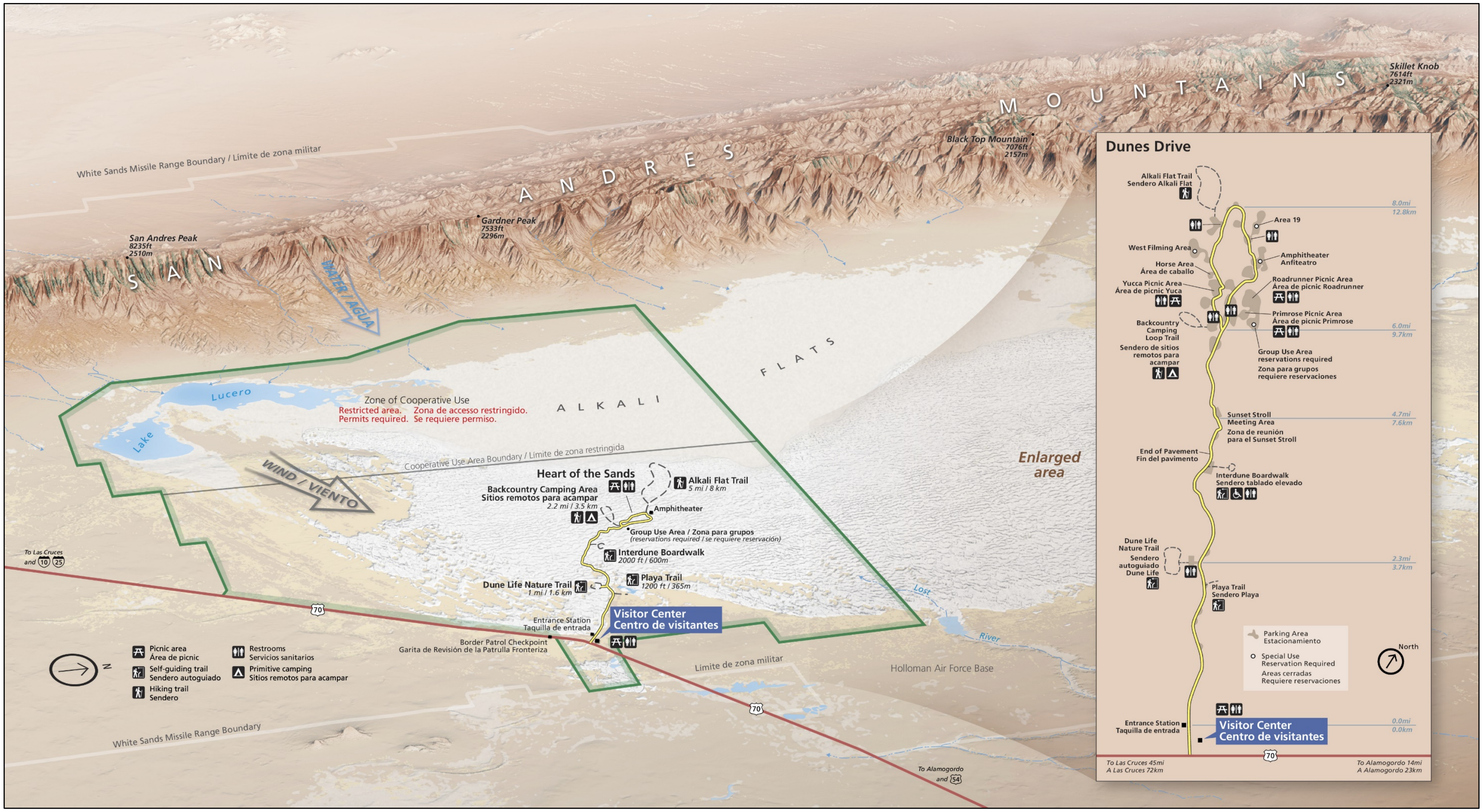


Figure 38. Park map of WHSA, New Mexico (NPS).

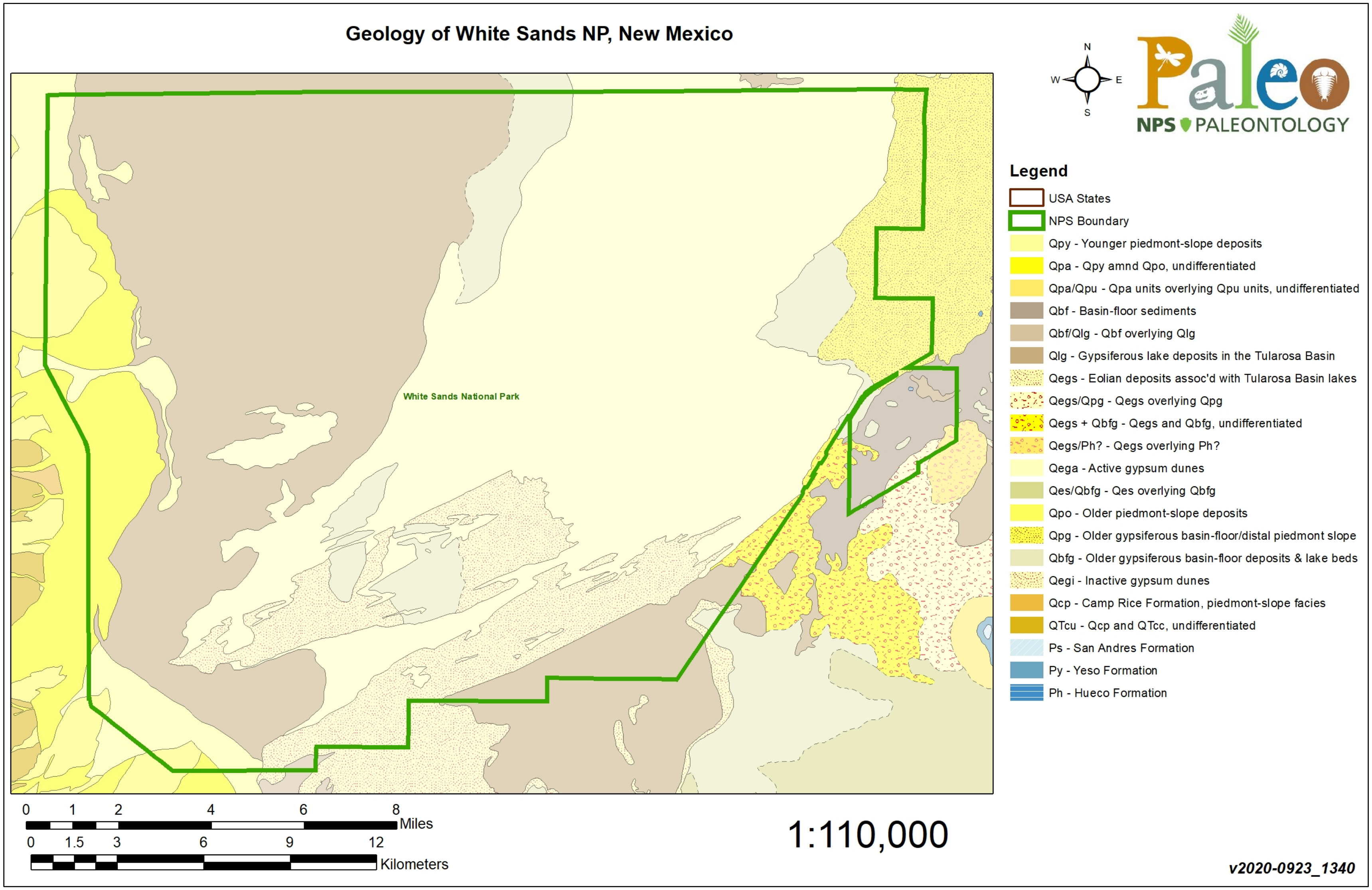


Figure 39. Bedrock geologic map of WHSA, New Mexico.

Recommendations

1) The NPS Geologic Resources Division should work with park and network staff to increase their awareness and understanding about the scientific, historic and geologic heritage significance of geologic stratotypes (type sections/localities/areas, reference sections, lithodemes).
2) Once the CHDN Geologic Type Section Inventory report is finalized, the NPS Geologic Resources Division should schedule a briefing for the staff of the CHDN and respective network parks.
3) Although a type locality for the Sleeping Lion Formation in FODA has been discussed in thesis publications of Smith (1975) and Hicks (1982), no formal type section currently exists (Don Parker, pers. comm., 2020). Exposures of the Sleeping Lion Formation within FODA and the adjacent Davis Mountains State Park are the best available publicly accessible sites. The brecciated base of the unit is exposed in upper Hospital Canyon and the upper portions along hiking trails within FODA (Don Parker, pers. comm., 2020). Therefore, we recommend a formal type section be designated in order to A) provide a standard reference for scientific research; B) educate park staff and visitors about the geoheritage significance of the unit; and C) help safeguard the exposure.
4) The NPS Geologic Resources Division should work with park and network staff to ensure they are aware of the location of stratotypes in park areas. This information would be important to ensure that proposed park activities or development would not adversely impact the stability and condition of these geologic exposures.
5) 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.
6) From the assessment in (4), NPS staff 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.
7) The NPS Geologic Resources Division should work with park and network staff to compile and update a central inventory of all designated stratotypes and potential future nominations.
8) The NPS Geologic Resources Division should ensure the park-specific Geologic Type Section Inventory Reports are widely distributed and available online.
9) The NPS Geologic Resources Division should work with park and network staff to regularly monitor geologic type sections to identify any threats or impacts to these geologic heritage features in parks.
10) The NPS Geologic Resources Division should work with park and network staff to obtain good photographs of each geologic type section within the parks. 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 geologic type sections. GPS locations should also be recorded and kept in a database when the photographs are taken.

11) The NPS Geologic Resources Division should work with park and network staff to utilize selected robust internationally and nationally significant type sections as formal teaching/education sites and for geotourism so that the importance of the national- and international-level assets are more widely (and publicly) known, using information boards and walkways.
12) The NPS Geologic Resources Division should work with park and network staff in developing conservation protocols of significant type sections, either by appropriate fencing, walkways, and information boards or other means (e.g., phone apps).

Literature Cited

Adkins, W. S. 1933. The Mesozoic systems in Texas, Part 2. Pages 239–518 *in* E. H. Sellards, W. S. Adkins, and F. B. Plummer, editors. The geology of Texas: Volume 1, Stratigraphy. University of Texas at Austin, Austin, Texas. University of Texas Bulletin 3232.

Anderson, J. E, Jr. 1968. Igneous geology of the central Davis Mountains, Jeff Davis County, Texas. The University of Texas at Austin, Bureau of Economic Geology, Austin, Texas. Geologic Quadrangle Map 36. Scale 1:62,500.

Anderson, M. 2017. National Parks Index: 2012–2016. Official Index of the National Park Service.

Bailey, R. G. 1976. Ecoregions of the United States (map). U.S. Department of Agriculture, U.S. Forest Service, Intermountain Region, Ogden, Utah.

Bell, G. L., Jr., J. M. Hearst, M. K. Nestell, G. P. Nestell, and L. L. Lambert. 2015. Stratigraphic framework and biostratigraphic significance of the terminal Guadalupian Reef Trail Member, Bell Canyon Formation in the Patterson Hills, Type Guadalupian Area, Texas. Stratigraphy 12(2):93–107.

Blanchard, W. G., Jr., and M. J. Davis. 1929. Permian stratigraphy and structure of parts of southeastern New Mexico and southwestern Texas. American Association of Petroleum Geologists Bulletin 13(8):957–995.

Brocx, M., C. Brown, and V. Semeniuk. 2019. Geoheritage importance of stratigraphic type sections, type localities and reference sites—review, discussion and protocols for geoconservation. Australian Journal of Earth Sciences 66(6):823–836.

Cooper, D. A., R. W. Cooper, J. B. Stevens, and M. S. Stevens. 2007. The Hot Springs Trail reference section (Cenomanian/Turonian/Coniacian Stages), Ernst Member, Boquillas Formation, Big Bend National Park, Texas. Geological Society of America – Abstracts with Programs 39(6):635.

Cooper, D. A., R. W. Cooper, J. B. Stevens, M. S. Stevens, W. A. Cobban, and I. Walaszczyk. 2017. The Boquillas Formation of the Big Bend National Park, Texas, USA, a reference Cenomanian through Santonian (Upper Cretaceous) carbonate succession at the southern end of the Western Interior Seaway. Acta Geologica Polonica 67(4):547–565.

Evans, T. J. 2016. General standards for geologic maps. Section 3.1 *in* M. B. Carpenter and C. M. Keane, compilers. The geoscience handbook 2016. AGI Data Sheets, 5th Edition. American Geosciences Institute, Alexandria, Virginia.

Everett, A. G. 1967. Geologic reconnaissance of the Fort Davis National Historic Site, Texas. Texas Memorial Museum, University of Texas at Austin. The Pearce-Sellards Series 8.

Fan, P. H., and D. B. Shaw. 1956. The Tesnus Formation of Trans-Pecos Texas. Journal of Sedimentary Petrology 26(3):258–267.

Fenneman, N. M. 1946. Physical divisions of the United States (map). U.S. Geological Survey, Washington, D.C. Unnumbered. Available at: https://pubs.er.usgs.gov/publication/70207506 (accessed January 28, 2021).

Glenister, B. F. 1996. Report of the Guadalupian Working Group. Permophiles 29:3–4.

Gradstein, F. M., J. G. Ogg, M. D. Schmitz, and G. M. Ogg, editors. 2020. Geologic time scale 2020. Elsevier, Amsterdam, Netherlands.

Graham, J. 2007. Carlsbad Caverns National Park Geologic Resource Evaluation Report. Natural Resource Report NPS/NRPC/GRD/NRR—2007/003. National Park Service, Denver, Colorado. Available at https://irma.nps.gov/DataStore/Reference/Profile/652347 (accessed January 28, 2021).

Harris, M. T. 1988. Sedimentology of the Cutoff Formation (Permian), western Guadalupe Mountains, west Texas. Pages 133–140 *in* S. T. Reid, R. O. Bass, and P. Welch, editors. Guadalupe Mountains revisited, Texas and New Mexico. West Texas Geological Society, Midland, Texas. Publication 88-84.

Harris, M. T. 2000. Members for the Cutoff Formation, western escarpment of the Guadalupe Mountains, west Texas. Pages 101–120 *in* B. R. Wardlaw, R. E. Grant, and D. M. Rohr, editors. The Guadalupian symposium. Smithsonian Institution Press, Washington, D.C. Smithsonian Contributions to the Earth Sciences 32. Available at: https://doi.org/10.5479/si.00810274.32.1 (accessed January 28, 2021).

Henderson, C. M., V. I. Davydov, and B. R. Wardlaw. 2012. The Permian Period. Pages 653–679 *in* F. M. Gradstein, J. G. Ogg, M. Schmitz, and G. Ogg, coordinators. The geologic time scale 2012. Elsevier, Amsterdam, Netherlands.

Henderson, T., V. L. Santucci, T. Connors, and J. S. Tweet. 2020. National Park Service geologic type section inventory: Greater Yellowstone Inventory & Monitoring Network. Natural Resource Report NPS/GRYN/NRR—2020/2198. National Park Service, Fort Collins, Colorado. Available at: https://irma.nps.gov/DataStore/Reference/Profile/2280034 (accessed January 28, 2021).

Hicks, K. A. 1982. Origin and emplacement of the Sleeping Lion Formation, Davis Mountains, west Texas. Senior thesis. Baylor University, Waco, Texas.

Hurd, G. S., C. Kerans, S. Fullmer, and X. Janson. 2018. New members of the Cutoff Formation in the southern Guadalupe Mountains near the Global Stratotype Section and Point for the base of the Roadian Stage, Texas. Stratigraphy 15(2):109–133.

KellerLynn, K. 2008. Guadalupe Mountains National Park Geologic Resource Evaluation Report. Natural Resource Report NPS/NRPC/GRD/NRR—2008/023. National Park Service, Denver, Colorado. Available at: https://irma.nps.gov/DataStore/Reference/Profile/652334 (accessed January 28, 2021).

KellerLynn, K. 2012. White Sands National Monument: geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2012/585. National Park Service, Fort Collins, Colorado. Available at: https://irma.nps.gov/DataStore/Reference/Profile/2190397 (accessed January 28, 2021).

Kerans, C., W. Fitchen, L. Zahm, and K. Kempter. 1995. High-frequency sequence framework of Cretaceous (Albian) carbonate ramp reservoir analog outcrops, Pecos River Canyon, northwestern Gulf of Mexico Basin. University of Texas at Austin, Bureau of Economic Geology. Field trip guidebook.

Keroher, G. C., and others. 1966. Lexicon of geologic names of the United States for 1936-1960. U.S. Geological Survey, Washington, D.C. Bulletin 1200. Available at: https://pubs.er.usgs.gov/publication/b1200 (accessed January 28, 2021).

King, P. B. 1942. Permian of west Texas and southeastern New Mexico. American Association of Petroleum Geologists Bulletin 26(4):535–763.

King, P. B. 1948. Geology of the southern Guadalupe Mountains, Texas. U.S. Geological Survey, Washington, D.C. Professional Paper 215. Available at: https://pubs.er.usgs.gov/publication/pp215 (accessed January 28, 2021).

King, P. B. 1965. Geology of the Sierra Diablo region, Texas. U.S. Geological Survey, Washington, D.C. Professional Paper 480. Available at: https://pubs.er.usgs.gov/publication/pp480 (accessed January 28, 2021).

King, P. B., and N. D. Newell. 1956. McCombs Limestone Member of Bell Canyon Formation, Guadalupe Mountains, Texas. AAPG Bulletin 40(2):386–387.

Lambert, L.L., G. L. Bell, Jr., J. A. Fronimos, B. R. Wardlaw, and M. O. Yisa. 2010. Conodont biostratigraphy of a more complete Reef Trail Member section near the type section, latest Guadalupian Series type region. Micropaleontology 56(1–2):233–253.

Lehman, T. M., S. L. Wick, H. L. Beatty, W. H. Straight, and J. R. Wagner. 2018. Stratigraphy and depositional history of the Tornillo Group (Upper Cretaceous–Eocene) of west Texas. Geosphere 14(5):2206–2244. Available at: https://doi.org/10.1130/GES01641.1 (accessed January 28, 2021).

Maxwell, R. A., and J. W. Dietrich. 1965. Geologic summary of the Big Bend region. Pages 11–33 *in* Geology of the Big Bend area, Texas. West Texas Geological Society, Midland, Texas. Field Trip Guidebook 65-51.

Maxwell, R. A., J. T. Lonsdale, R. T. Hazzard, and J. A. Wilson. 1967. Geology of Big Bend National Park, Brewster County, Texas. University of Texas Bureau of Economic Geology Publication 6711.

Newell, N. D., J. K. Rigby, A. G. Fischer, A. J. Whiteman, J. E. Hickox, and J. S. Bradley. 1953. The Permian reef complex of the Guadalupe Mountains region, Texas and New Mexico. W. H. Freeman and Co., San Francisco.

Noble, P. 1992. Biostratigraphy of the Caballos Novaculite-Tesnus Formation boundary, Marathon Basin, Texas. Palaeogeography, Palaeoclimatology, Palaeoecology, 96(1–2):141–153.

North American Commission on Stratigraphic Nomenclature. 2005. North American stratigraphic code. AAPG Bulletin 89(11):1547–1591.

Omernik, J. M. 1987. Ecoregions of the conterminous United States. Annals of the Association of American Geographers 77(1):118–125.

Richardson, G. B. 1904. Report of a reconnaissance in Trans-Pecos Texas north of the Texas and Pacific Railway. University of Texas, Mineral Survey Bulletin 9.

Sellards, E. H. 1933. The pre-Paleozoic and Paleozoic systems in Texas, Part 1. Pages 15–238 *in* E. H. Sellards, W. S. Adkins, and F. B. Plummer. The geology of Texas: Volume 1, Stratigraphy. University of Texas Bulletin 3232.

Smith, M. A. 1975. Geology and trace element geochemistry of the Fort Davis area, Trans-Pecos Texas. Dissertation. University of Texas at Austin, Austin, Texas.

Turner, K. J., M. E. Berry, W. R. Page, T. M. Lehman, R. G. Bohannon, R. B. Scott, D. P. Miggins, J. R. Budahn, R. W. Cooper, B. J. Drenth, E. D. Anderson, and V. S. Williams. 2011. Geologic map of Big Bend National Park, Texas. U.S. Geological Survey, Reston, Virginia. Scientific Investigations Map 3142. Scale 1:75,000. Available at: https://pubs.usgs.gov/sim/3142/ (accessed January 28, 2021).

Udden, J. A. 1907. A sketch of the geology of the Chisos country, Brewster County, Texas. University of Texas Bulletin 93.

Wilde, G. L., S. F. Rudine, and L. L. Lambert. 1999. Formal designation; Reef Trail Member, Bell Canyon Formation, and its significance for recognition of the Guadalupian–Lopingian boundary. Pages 63–83 *in* A. H. Saller, P. M. Harris, B. L. Kirkland, and S. J. Mazzullo, editors. Geologic framework of the Capitan Reef. Society of Economic Paleontologists and Mineralogists, Tulsa, Oklahoma. Special Publication 65.

Wilmarth, M. G. 1938. Lexicon of geologic names of the United States (including Alaska). U.S. Geological Survey, Washington, D.C. Bulletin 896. Available at: https://pubs.er.usgs.gov/publication/b896 (accessed January 20, 2021).

Wu, Q., J. Ramezani, H. Zhang, D. X. Yuan, D. H. Erwin, C. M. Henderson, L. L. Lambert, Y. C. Zhang, and S. Z. Shen. 2020. High-precision U-Pb zircon age constraints on the Guadalupian in West Texas, USA. Palaeogeography, Palaeoclimatology, Palaeoecology 548:109668.

Appendix A: Source Information for GRI Maps of CHDN Parks

AMIS

- GMAP 1111: Freeman, V. L. 1965. Geologic map of the Bakers Crossing Quadrangle, Val Verde County, Texas. U.S. Geological Survey, Washington, D.C. Miscellaneous Geologic Investigations Map 434. Scale 1:62,500. Available at: http://ngmdb.usgs.gov/Prodesc/proddesc_1293.htm (accessed January 28, 2021).
- GMAP 1112: Webster, R. E. 1982. Geology of the Carta Valley Fault Zone Area: Edwards, Kinney, and Val Verde counties, Texas. University of Texas, Bureau of Economic Geology. Geologic Quadrangle Map 53. Scale 1:96,000.
- GMAP 1113: Freeman, V. L. 1964. Geologic map of the Langtry Quadrangle, Val Verde County, Texas. U.S. Geological Survey, Washington, D.C. Miscellaneous Geologic Investigations Map 422. Scale 1:62,500. Available at: http://ngmdb.usgs.gov/Prodesc/proddesc_1325.htm (accessed January 28, 2021).
- GMAP 1114: Sharps, J. A. 1963. Geologic map of the Malvado Quadrangle, Terrell and Val Verde counties, Texas. U.S. Geological Survey, Washington, D.C. Miscellaneous Geologic Investigations Map 382. Scale 1:62,500. Available at: http://ngmdb.usgs.gov/Prodesc/proddesc_1327.htm (accessed January 28, 2021).
- GMAP 1115: Sharps, J. A. and V. L. Freeman. 1965. Geologic map of the Mouth of Pecos and Feely quadrangles, Val Verde County, Texas. U.S. Geological Survey, Washington, D.C. Miscellaneous Geologic Investigations Map 440. Scale 1:62,500. Available at: http://ngmdb.usgs.gov/Prodesc/proddesc_1330.htm (accessed January 28, 2021).
- GMAP 1116: Freeman, V. L. 1964. Geologic map of the Shumla Quadrangle, Val Verde County, Texas. U.S. Geological Survey, Washington, D.C. Miscellaneous Geologic Investigations Map 424. Scale 1:62,500. Available at: http://ngmdb.usgs.gov/Prodesc/proddesc_1341.htm (accessed January 28, 2021).
- GMAP 74916: Collins, E. W. 2007. Geologic map of the Del Rio, Texas, area. University of Texas, Bureau of Economic Geology. Miscellaneous Map 45. Scale 1:100,000.
- GMAP 74945: R.M.P., N.G.J., and W.B.T. 1963. Major sink areas and karst features near Amistad Dam. International Boundary and Water Commission, El Paso, Texas. Scale 1:12,000.
- GMAP 74976: R.B.H., G.A.K., and L.H.H. 1951. Areal Geologic Map San Francisco Creek to Indian Creek Reach, Area 6. International Boundary and Water Commission, El Paso, Texas. A-245. Scale 1:50,000.
- GMAP 74977: C.G.E., G.A.K., and L.H.H. 1951. Areal Geologic Map Indian Creek to Del Rio Reach, Area 7. International Boundary and Water Commission, El Paso, Texas. A-223. Scale 1:50,000.

- GMAP 74978: C.G.E., G.A.K., and L.H.H. 1950. Areal Geologic Map Indian Creek to Del Rio Reach, Area 8. International Boundary and Water Commission, El Paso, Texas. A-222. Scale 1:50,000.
- GMAP 74979: C.G.E., G.A.K., and L.H.H. 1950. Areal Geologic Map Indian Creek to Del Rio Reach, Area 9. International Boundary and Water Commission, El Paso, Texas. A-221. Scale 1:50,000.
- GMAP 75123: Page, W. R., M. E. Berry, D. P. VanSistine, and S. R. Snyders. 2009. Preliminary geologic map of the Laredo, Crystal City-Eagle Pass, San Antonio and Del Rio 1 x 2 quadrangles, Texas, and the Nuevo Laredo, Ciudad Acuna, Piedras Negras, and Nueva Rosita 1 x 2 quadrangles, Mexico. U.S. Geological Survey, Reston, Virginia. Open-File Report 2009-1015. Scale 1:250,000. Available at: https://pubs.usgs.gov/of/2009/1015/ (accessed January 28, 2021).

BIBE

- GMAP 7246: Turner, K. J., M. E. Berry, W. R. Page, T. M. Lehman, R. G. Bohannon, R. B. Scott, D. P. Miggins, J. R. Budahn, R. W. Cooper, B. J. Drenth, E. D. Anderson, and V. S. Williams. 2011. Geologic map of Big Bend National Park, Texas. U.S. Geological Survey, Reston, Virginia. Scientific Investigations Map 3142. Scale 1:75,000. Available at: https://pubs.usgs.gov/sim/3142/ (accessed January 28, 2021).

CAVE

- GMAP 1039: Hayes, P. T. 1964. Geology of the Guadalupe Mountains, New Mexico. U.S. Geological Survey, Washington, D.C. Professional Paper 446, Plate 1. Scale 1:62,500. Available at: https://pubs.er.usgs.gov/publication/pp446 (accessed January 28, 2021).

FODA

- GMAP 2518: Anderson, J. E., Jr., J. B. Brown, J. C. Gries, E. M. P. Lovejoy, D. McKalips, and V. E. Barnes. 1995. Geologic atlas of Texas: Fort Stockton sheet. Charles Laurence Baker Memorial Edition. Texas Bureau of Economic Geology, Austin, Texas. GA-0016. Scale 1:250,000.

GUMO

- GMAP 1217: King, P. B. 1948. Geology of the southern Guadalupe Mountains, Texas. U.S. Geological Survey, Washington, D.C. Professional Paper 215, Plate 3. Scale 1:48,000. Available at: https://pubs.er.usgs.gov/publication/pp215 (accessed January 28, 2021).
- GMAP 1219: King, P. B. 1948. Geology of the southern Guadalupe Mountains, Texas. U.S. Geological Survey, Washington, D.C. Professional Paper 215, Plate 22. Scale 1:48,000. Available at: https://pubs.er.usgs.gov/publication/pp215 (accessed January 28, 2021).

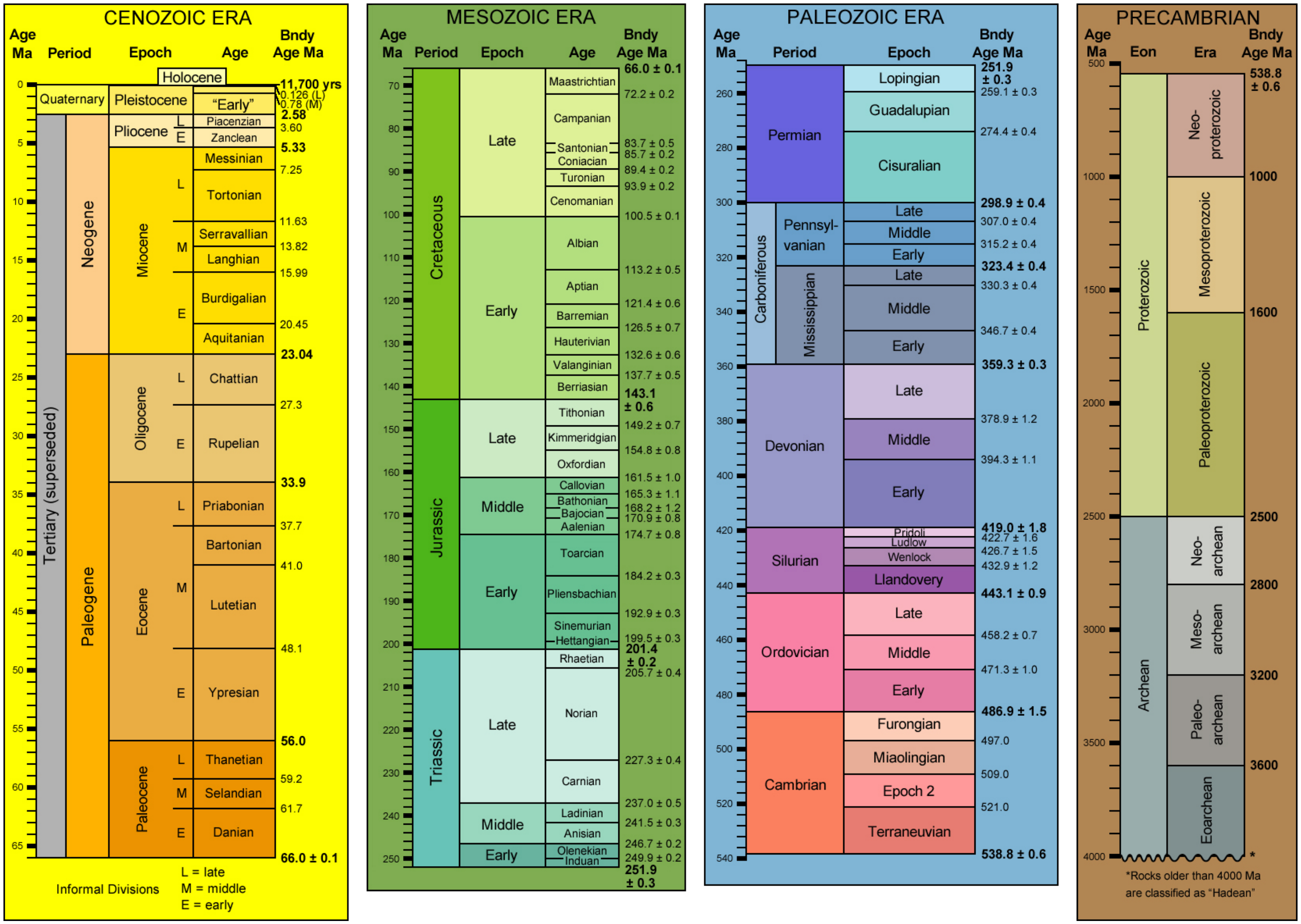
WHSA

- GMAP 75015: Fryberger, S. G. 2001. Reconnaissance geomorphic map of the active White Sands dune field, New Mexico. Figure 2-17A in Geological overview of White Sands

National Monument, Chapter 2: Quaternary geology. Southwest Parks and Monuments Association, Tucson, Arizona.

- GMAP 75532: Seager, W. R., J. W. Hawley, F. E. Kottlowski, and S. A. Kelley. 1987. Geology of east half of Las Cruces and northeast El Paso 1º x 2º sheets. New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico. Geologic Map 57. Scale 1:125,000.

Appendix B: 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).

NPS 960/175233, April 2021

National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science
1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525

EXPERIENCE YOUR AMERICA ™