National Park Service
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Natural Resource Stewardship and Science

National Park Service Geologic Type Section Inventory

Greater Yellowstone Inventory & Monitoring Network

Natural Resource Report NPS/GRYN/NRR—2020/2198



ON THE COVER

Lamar River Formation type area exposures consisting of well-bedded coarse alluvial facies, volcanic conglomerates, sandstones, breccias and air-fall tuff located in the Fossil Forest, along the northeast side of Specimen Ridge, Yellowstone National Park. Photo taken from Smedes and Prostka (1972).

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Natural Resource Report NPS/GRYN/NRR—2020/2198

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Executive Summary

The National Park Service preserves a diverse cross section of park areas and resources representing America's natural and cultural heritage. The collective biotic and abiotic natural resources span from tiny microorganisms thriving in thermal pools to majestic landscapes with iconic and scenic views of mountain ranges, canyons, rivers, and forests. The animals, plants, water, air, rocks, night sky and other natural resources define a moment of time in the evolutionary history of North America, preserving a long record of change. These resources possess an array of human values which draw visitors to parks to discover, experience, study, learn, understand, enjoy, benefit, and for other purposes.

A fundamental responsibility of the National Park Service is to ensure that these 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.

Geologic resources, including the bedrock, are the foundation of the ecosystem. The rocks and geologic features greatly influence the occurrence and distribution of other abiotic and biotic resources. The development and use of geologic maps enable us to better understand the geologic events and processes that shaped both the landforms and lifeforms of a region. Geologic mapping is both a fundamental and an essential tool for geologists, resource specialists, and park managers. The availability of geologic maps for National Park Service areas was identified as one of the critical needs when an initial strategy for the inventory of natural resources in parks was established in the late 1990s. Hence, the development of digital geologic maps was one of the twelve natural resource inventory themes prioritized by the National Park Service Inventory and Monitoring (I&M) Program.

Geologic maps are important tools which display the distribution of the different types of bedrock units, surficial deposits, and other mappable geologic features (faults, folds, etc.). Geologic maps are valuable geospatial representations of geologic material occurrences both on and beneath the surface. These maps are used to identify groundwater aquifers, mineral deposits, fossiliferous rock strata, and a wide variety of other types of information. Stratigraphic units such as formations are the fundamental components of a geologic map and are color-coded and keyed to help identify the distribution and occurrence of these units on a map.

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 available for other researchers to evaluate 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 421 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 (Bighorn Canyon National Recreation Area (BICA), Grand Teton National Park (GRTE), John D. Rockefeller, Jr. Memorial Parkway (JODR), and Yellowstone National Park (YELL) methodologies for data mining and reporting on these resources was established. This report *National Park Service Geologic Type Section Inventory: Greater Yellowstone Inventory & Monitoring Network* is intended as a prototype for similar investigations and reporting for the other I&M networks.

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 GRYN shows there are currently no designated stratotypes for BICA; GRTE has two type sections and two type localities; JODR has one type section and one type area; and YELL has three type sections, three reference sections, five type localities, and 20 type areas.

Acknowledgments

Many individuals were consulted in the preparation of this report on the geologic type sections for the national parks of the Greater Yellowstone Inventory and Monitoring Network. We first want to extend our sincere appreciation to Randy Orndorff, David Soller, and Nancy Stamm (U.S. Geological Survey) for their assistance with this geologic type section inventory and other important NPS projects. Randy, Dave, and Nancy manage the National Geologic Map Database and GEOLEX (The U.S. Geologic Names Lexicon, a national compilation of names and descriptions of geologic units), respectively, for the United States, a critical source of geologic map information for science, industry and the American public. We also extend our appreciation to Tom Casadevall and Laura Walkup (U.S. Geological Survey), Katie McDonald (Montana Bureau of Mines and Geology), Erin Campbell, and Andrea Loveland (Wyoming State Geological Survey).

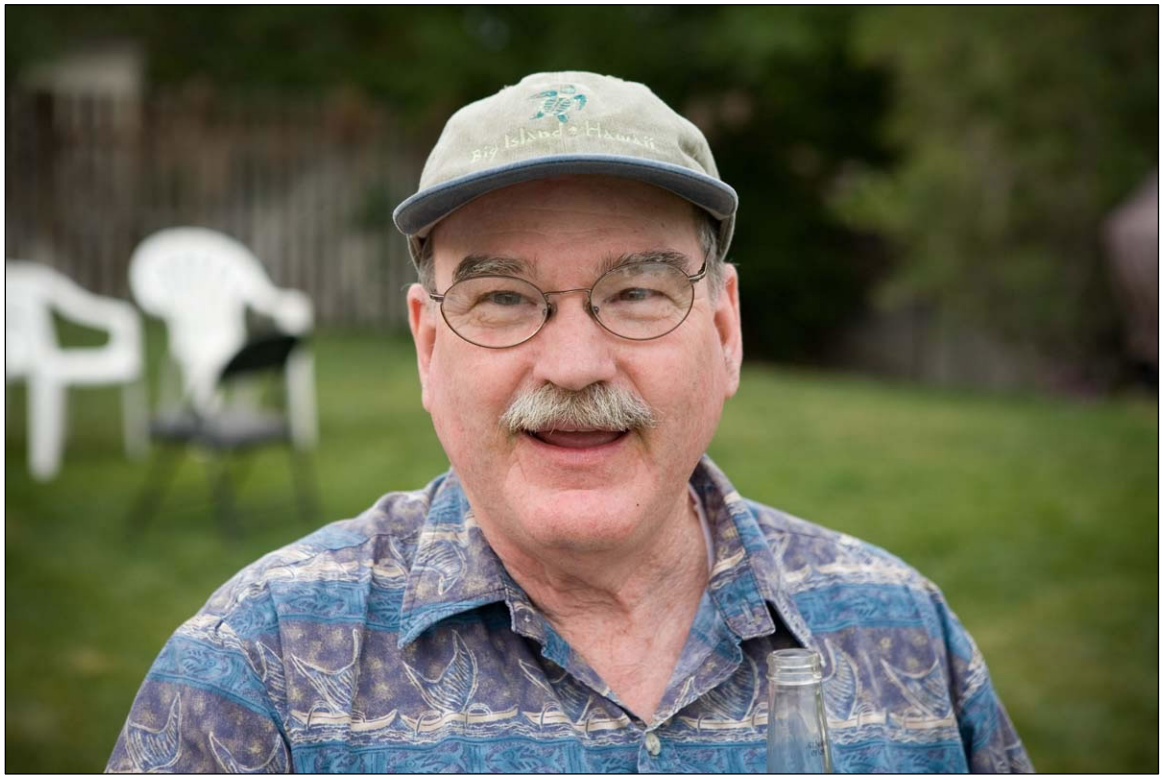
We thank our colleagues and partners in the Geological Society of America (GSA) and Stewards Individual Placement Program for their continued support to the NPS with the placement of geologic interns and other ventures. A special thanks to Jeanette Hammann (GSA Director of Publications) and David Rowley (Editor of the Journal of 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.

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Dedication

This Greater Yellowstone Inventory and Monitoring Network Geologic Type Section Inventory is dedicated to retired NPS Geologist Bob Higgins. For those of us who had the honor and privilege to work with Bob, recognize that his passion and vision inspired many important geology focused projects including this inventory. The young geologists who were mentored by Bob carry on his mission and dream of preserving our geologic features, processes, and heritage throughout the NPS. Thanks for your tremendous service Bob!



Bob Higgins; former NPS-GRD branch chief 1996–2008.

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 knowledge, represent important comparative sites where past knowledge can be built up or reexamined, and can serve as teaching sites for the next generation of students (Brocx et al. 2019). The geoheritage significance of stratotypes is analogous to 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 systematically report the assigned stratotypes that occur within national park boundaries, provide detailed descriptions of the stratotype exposures and their locations, and 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, and will not be presented in this report.

This geologic type section inventory for the parks of the Greater Yellowstone Inventory and Monitoring Network is intended as a pilot project to establish standard practices, methodologies, and organization of information. This initial report will serve as a prototype for the development of other network-specific geologic type section inventory reports. 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 helps 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 a 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 Greater Yellowstone I&M Network Parks

The Greater Yellowstone Network (GRYN) consists of four national park units in northwestern Wyoming, southern Montana, and eastern Idaho (Figure 1). Bighorn Canyon National Recreation Area, Grand Teton and Yellowstone National Parks, and the John D. Rockefeller, Jr. Memorial Parkway are the core of the 7.3-million-hectare (18-million-acre) Greater Yellowstone Ecosystem. These four units include a broad range of climatic zones, habitat types, elevation profiles, and encompass great biological and geological diversity. Geographically the network contains the headwaters of the Bighorn, Shoshone, Snake, and Yellowstone Rivers. These watersheds are characterized by landscapes influenced by a diversity of geologic processes and support distinct plant and animal communities including a diversity of large mammals. Taken together, the unique geologic, hydrologic, and biological characteristics of this region are world-renowned.

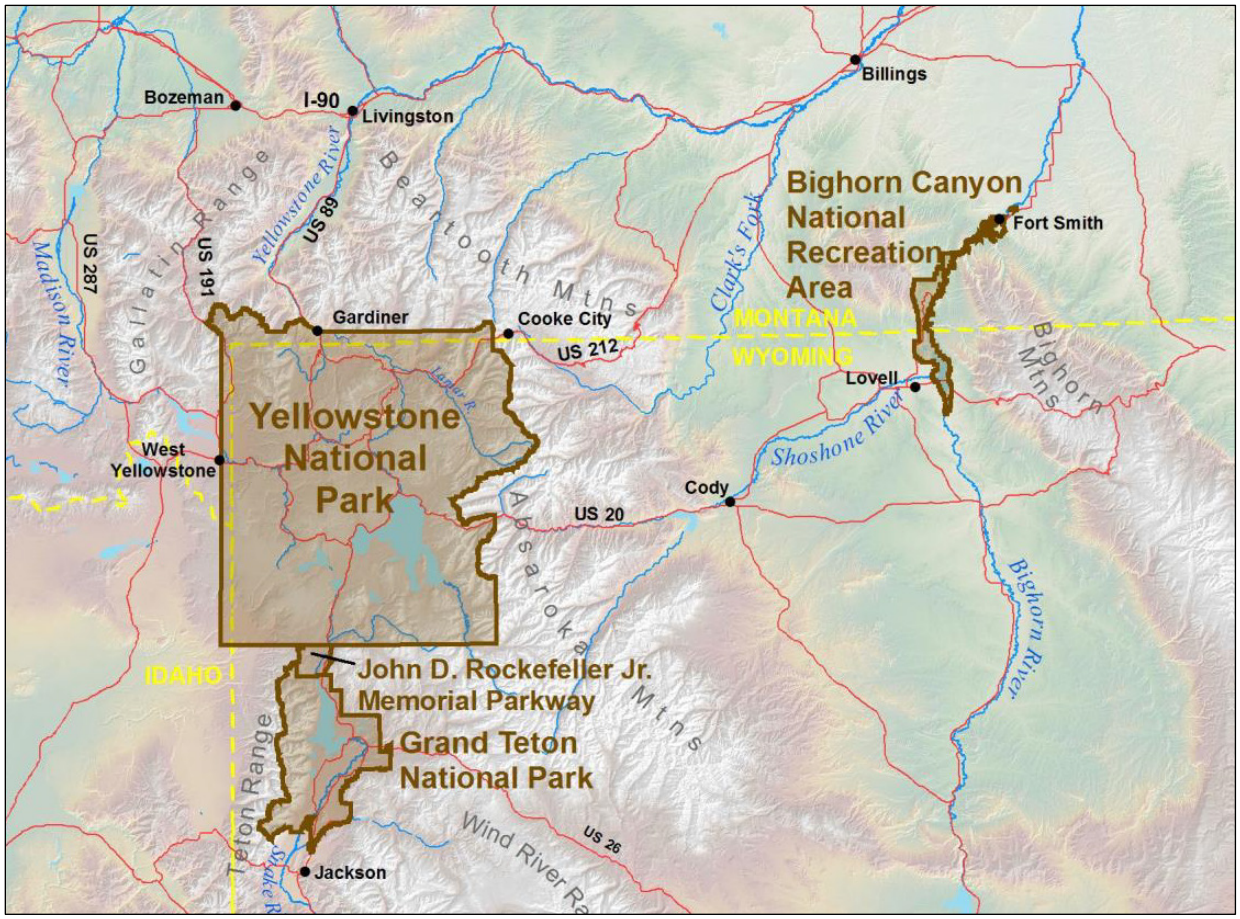


Figure 1. Map of Greater Yellowstone Network parks including: Bighorn Canyon National Recreation Area (BICA), Grand Teton National Park (GRTE), John D. Rockefeller, Jr. Memorial Parkway (JODR), and Yellowstone National Park (YELL) (NPS).

Precambrian

The parks of the GRYN collectively preserve an extensive geologic history spanning from the Archean to the present (see Appendix B for a geologic time scale). This history includes some of the oldest exposed rocks in the NPS, including Precambrian intrusive igneous and high-grade metamorphic rocks exposed on the flank of East Pryor Mountain in BICA, within the Teton Range in GRTE, and in the Beartooth and Gallatin Mountains in YELL (Tweet et al. 2013).

Paleozoic

The beginning of the Paleozoic in the paleogeographic area represented today in part by the parks of the GRYN is marked by the transgression of the shallow Sauk Sea during the early Cambrian. The arrival of this ancient sea is represented by the widespread coastal unit known as the Flathead Sandstone. This sandstone unit is overlain by the Gros Ventre Formation and Gallatin Limestone, representing marginal marine and deeper marine deposition along the fluctuating shoreline. A diverse assemblage of Cambrian marine invertebrate fauna has been documented from these units exposed in each of the network parks. The marine depositional environments spanned into the late Cambrian when there was a transition to a period of erosion. Middle and upper Cambrian rocks are exposed in BICA, GRTE, and YELL.

The Ordovician, Silurian, and Devonian are not well represented in the GRYN parks, with two episodes of deposition found in BICA, GRTE, and YELL. The older rocks belong to the Bighorn Dolomite, another widespread shallow marine formation deposited during a period when the network parks were near the equator. Another extended episode of erosion and non-deposition prevented the preservation of any Silurian rocks. The rock record resumes in the Late Devonian with the Darby Formation and equivalent Jefferson and Three Forks formations, representing another interval of shallow marine deposition.

The Late Devonian formations within the GRYN are the beginning of over 300 million years of geologic history with few substantial gaps. The most complete sedimentary sequence occurs within GRTE, spanning from the Upper Devonian into the Eocene, and it is likely that the only major gaps are in the upper Permian and probably the Middle Triassic. One of the most widespread units mapped in the GRYN parks is the Madison Group (formerly Madison Limestone), deposited during the Early and Middle Mississippian as part of a marine transgression across much of the northwestern United States. A brief depositional hiatus after the deposition of the Madison sediments resulted in an episode of cave and void formation. Much later this expanded into larger caves during the late Cenozoic, as seen at BICA.

The Amsden Formation is a primarily marine Mississippian–Pennsylvanian formation exhibiting time-transgressive deposition across Wyoming from west to east and is exposed in BICA, GRTE, and YELL. Overlying the Amsden Formation is the coastal terrestrial deposition of the Tensleep Sandstone of BICA, GRTE, and southern YELL, and the Quadrant Sandstone of northern YELL. Permian strata are represented by transgression-regression cycles consisting of interfingering of coastal and nearshore sedimentary deposits. There are three predominant formations during the Permian: a carbonate unit named the Park City Formation deposited in mudflat and shallow shelf settings; the Phosphoria Formation composed of phosphatic shales, carbonaceous rocks, and cherts,

deposited in deeper marine basins; and the Shedhorn Sandstone, composed of eolian and beach sandstone.

Mesozoic

The beginning of the Mesozoic in northwestern Wyoming is marked by Lower Triassic rocks, exhibiting evidence of multiple transgression-regression cycles. The Upper Triassic rocks include a more terrestrial sequence known as the Chugwater Formation. In the BICA area, the Permian and Triassic rocks below the Chugwater Formation are a unit locally referred to as the Goose Egg Formation.

The Early Jurassic is poorly known in the parks of the GRYN, being represented only by a small exposure of the Nugget Sandstone in GRTE, the remnant of a large dune system. Marine deposition returned during the Middle and early Late Jurassic, leaving some of the most fossiliferous rocks of the network parks in the form of the Gypsum Spring and Sundance formations of southern BICA, GRTE, JODR, and southern YELL, and the roughly equivalent Ellis Group of northern BICA and northern YELL. A shallow sea known as the Sundance Sea arrived from the northwest and advanced and retreated several times. During periods of marine regression, dinosaurs and other vertebrates left tracks in the coastal regions and in shallow water, as seen at BICA. With the final retreat of the Sundance Sea in the early Late Jurassic, a sustained period of terrestrial deposition began, lasting about 50 million years into the Cretaceous. The latest Jurassic portion is represented by the Morrison Formation.

The Early Cretaceous is represented by the Cloverly Formation in southern BICA, GRTE, JODR, and southern YELL, and the Kootenai Formation in northern BICA and YELL. These formations were predominantly deposited by fluvial and lacustrine processes in a variety of channel, floodplain, and lake settings. A complex and controversial interval of rocks above the main bodies of the Cloverly and Kootenai formations represents the approach of the final shallow continental sea to submerge central North America. This sea, known as the Western Interior Seaway or Cretaceous Interior Seaway, was a major geographic feature of North America for much of the Cretaceous, at its greatest extent bisecting the landmass into eastern and western sections and connecting the Arctic Ocean to the Gulf of Mexico. Seaway deposition often resulted in thick, dark marine shales with occasional pulses of coarser sediment and thin beds of bentonite, the remains of volcanic ash layers. In the GRYN parks, near the western margin of the seaway, marine deposition existed for nearly 30 million years, between approximately 100 and 70 Ma (million years ago), although in GRTE, JODR, and YELL marine deposition was mostly over by about 85 Ma (Tweet et al. 2013).

Near the end of the Cretaceous, as the seaway was retreating, western North America was affected by a major mountain-building event known as the Laramide Orogeny. The Laramide Orogeny is thought to have resulted from a marine plate subducting at a shallow angle under western North America and interacting with the underside of the North American plate, causing large blocks of crust to rise. This process lasted into the Eocene, resulting in the uplift of the present-day Rocky Mountains.

Cenozoic

The geological record for the Cenozoic in the GRYN units becomes more discontinuous with the uplift of more mountainous terrain associated with the Laramide Orogeny. The Cenozoic is not represented by any formal stratigraphic units within BICA. However, Eocene volcanics are represented by widespread deposits in GRTE, JODR, and YELL associated with the nearby Absaroka volcanic field active between approximately 55 and 44 Ma. A thick sequence of extrusive flows, lahars, ash, and volcaniclastic strata are part of the Absaroka Volcanic Supergroup which includes a complex sequence of units including the Sepulcher and Lamar River formations present in the northern portion of YELL (Smedes and Prostka 1972).

Oligocene rocks are not exposed at the surface in any GRYN unit, but the Miocene is well-represented at GRTE, primarily by the Colter and Teewinot formations. The Colter Formation is composed of volcanic debris, indicating the presence of a volcanic source near the north end of Jackson Lake between about 20 and 13 Ma. The succeeding Teewinot Formation was deposited in a large lake. A local volcanic center, the Jackson Hole volcanic field, was active around 8 Ma, but much more extensive volcanism arrived near the end of the Miocene in the form of the Yellowstone hotspot.

The first evidence of the Yellowstone hotspot in the immediate vicinity of the GRYN begins near the end of the Miocene, with the development of the Heise volcanic field in eastern Idaho between 7 and 4 Ma. Evidence of these eruptions is either absent or buried at YELL, but small remnants of the 5.51 Ma Conant Creek Tuff can be found in GRTE and JODR. By about 2 Ma, the hotspot emerged beneath the Yellowstone Plateau. Three major eruptions resulted in the creation of three distinct calderas: the Huckleberry Ridge Caldera (Huckleberry Ridge Tuff) at about 2.05 Ma; the Henry's Fork Caldera (Mesa Falls Tuff) at about 1.3 Ma; and the Yellowstone Caldera (Lava Creek Tuff) at about 0.64 Ma (640,000 years ago).

Quaternary glaciation, beginning approximately 2.6 Ma, has significantly shaped the landscape of the GRYN parks, especially GRTE, JODR, and YELL. The Jackson Lake basin displays dramatic examples of glacial features including glacial outwash deposits and terraces. Small remnant glaciers continue to be present at high elevations in GRTE. Today, the iconic geologic features and landscapes of the GRYN parks attract visitors, photographers, artists and scientists from around the world.

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 GRYN parks: YELL on May 16–17, 2005; BICA on May 18–19, 2005; and GRTE–JODR on June 21–22, 2005.

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 BICA and GRTE–JODR; YELL is still outstanding. 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 GRYN 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 GRYN 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 data set 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 to produce the GRI GIS data sets for the GRYN 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 YELL was compiled using data model version 2.1, which is available at https://www.nps.gov/articles/gri-geodatabase-model.htm; the BICA and GRTE 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 YELL, BICA, JODR, or GRTE 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 GRYN. This report represents a pilot project for 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 GRYN, but are intended for a broader application when the inventory will expand 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 which limits the information contained within the final report. This inventory does not include any field work and is dependent on the existing information related to individual park geology and stratigraphy. Additionally, this inventory does not attempt to resolve any unresolved or controversial stratigraphic interpretations, which is beyond the scope of the project.

Stratigraphic nomenclature may change over time with refined stratigraphic field assessments and discovery of information through the expansion of stratigraphic mapping and measured sections. One important observation regarding stratigraphic nomenclature relates to differences in use of geologic names for units which transcend state boundaries. Geologic formations and other units which cross state boundaries may be referenced with different names in each of the states 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 and Wyoming.

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 may not have a background in geology. Therefore, this document is developed as a reference document that supports science, resource management, and a historic framework for geologic information associated with NPS areas.

Methodology

The process of determining whether a specific stratotype occurs within 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).

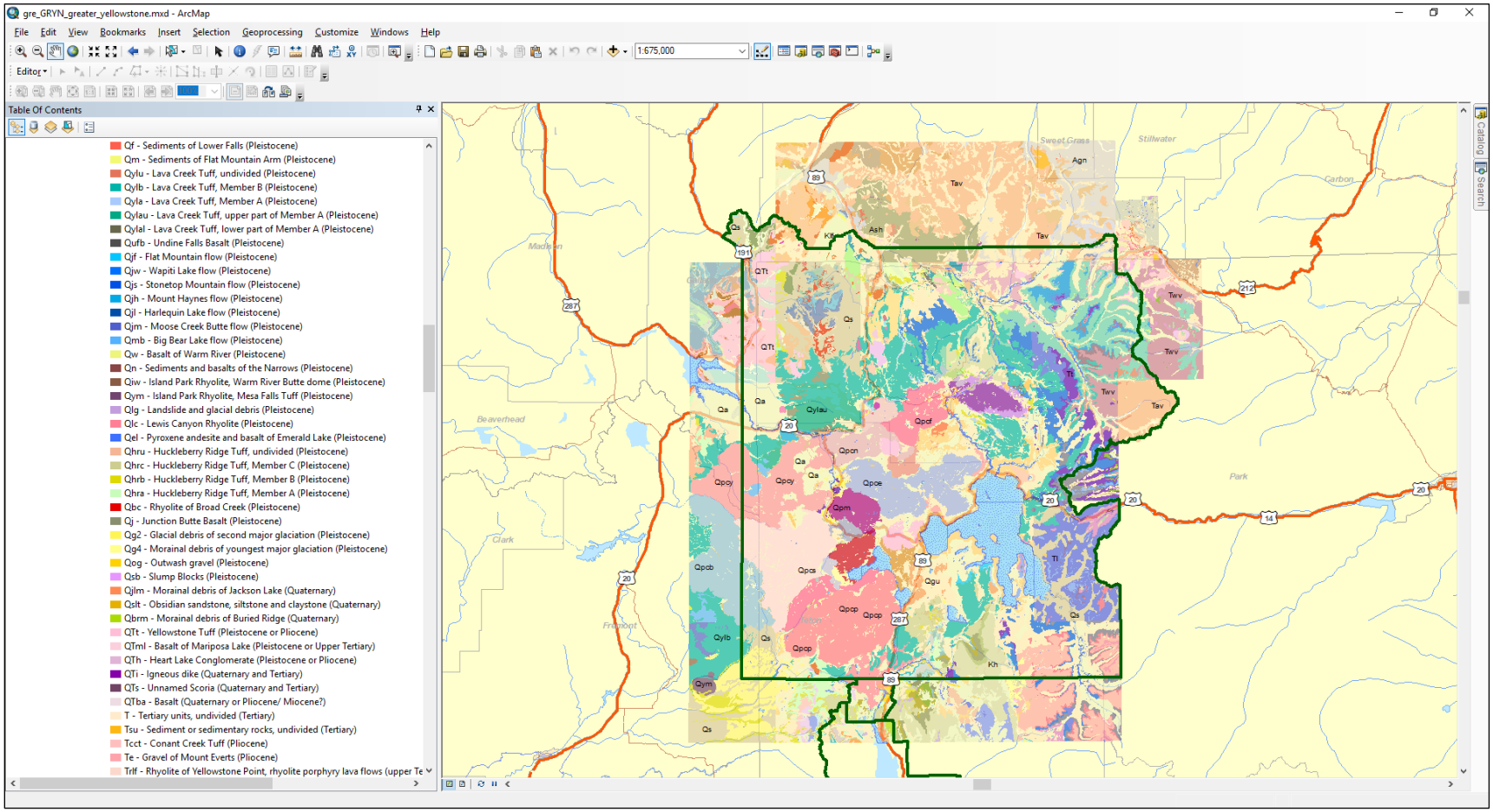


Figure 2. Screenshot of digital bedrock geologic map of Yellowstone National Park showing mapped units.

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 et al.1938; Keroher 1966). Figure 3 below is taken from a search on the Huckleberry Ridge Tuff.

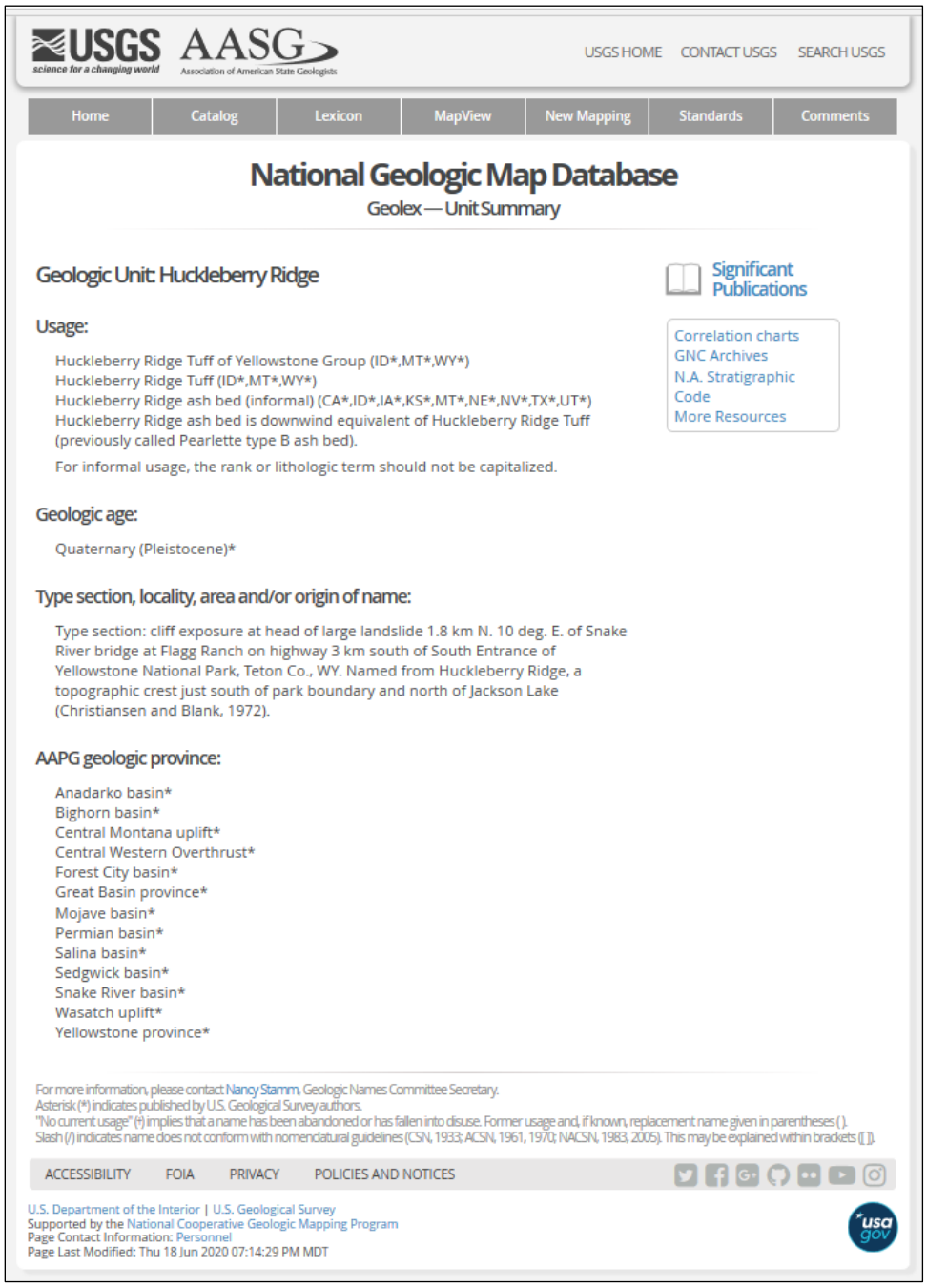


Figure 3. GEOLEX search result for Huckleberry Ridge unit.

Published GEOLEX stratotype spatial information is provided in three formats: (1) descriptive, using distance from nearby points of interest; (2) latitude and longitude coordinates; or (3) Township/Range/Section (TRS) coordinates. TRS coordinates are based upon subdivisions of a single 93.2 km^2 (36 mi^2) township into 36 individual 2.59 km^2 (1 mi^2) sections, and were converted into Google Earth (.kmz file) locations using Earth Point (https://www.earthpoint.us/TownshipsSearchByDescription.aspx). 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 (Figure 4).

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 5).

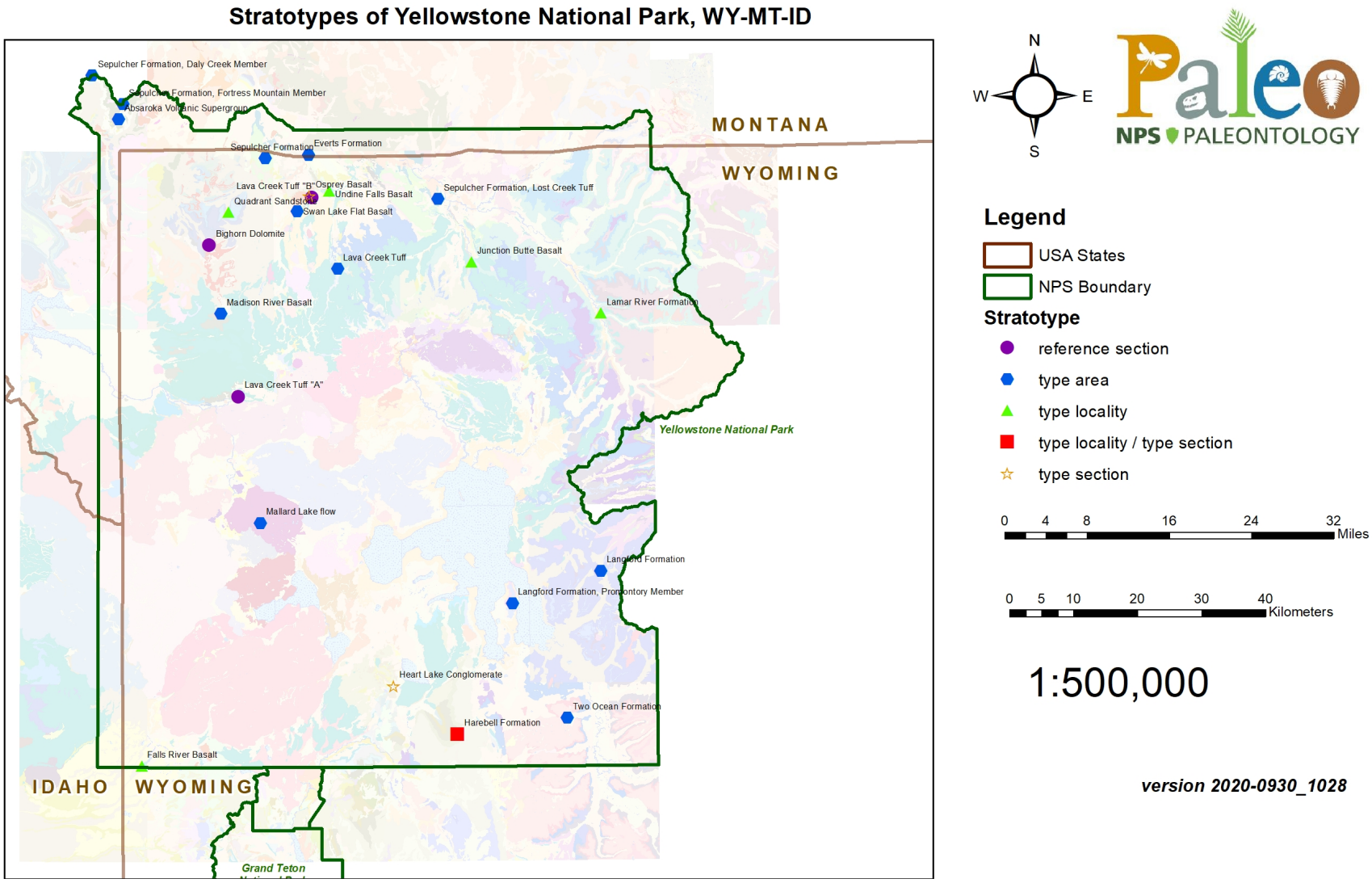
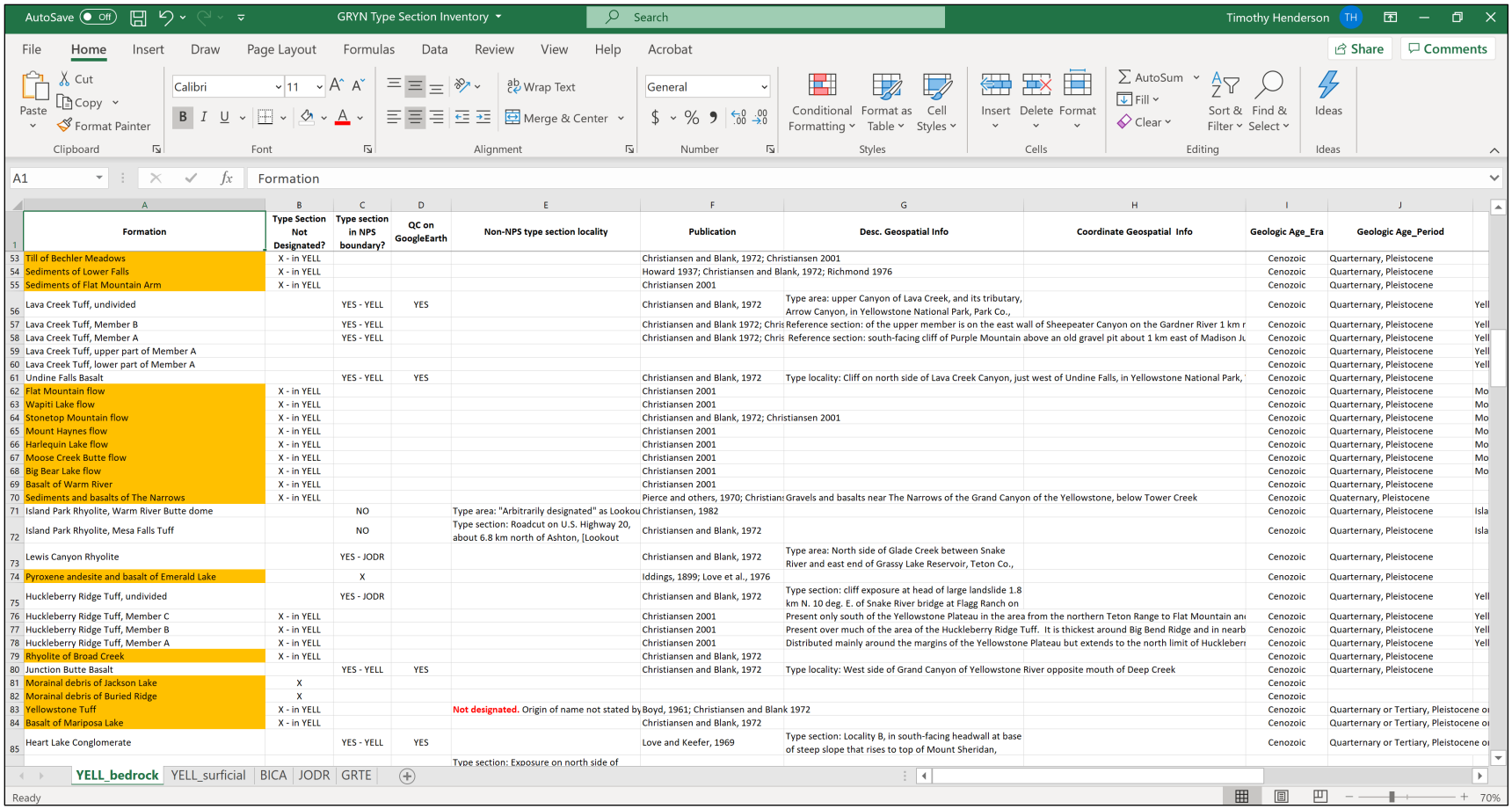


Figure 4. Stratotype geolocations of YELL with digital geologic map overlay for purposes of accuracy and validation.



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
Till of Bechler Meadows	X - in YELL				Christiansen and Blank, 1972; Christiansen 2001			Cenozoic	Quarternary, Pleistocene
Sediments of Lower Falls	X - in YELL				Howard 1937; Christiansen and Blank, 1972; Richmond 1976			Cenozoic	Quarternary, Pleistocene
Sediments of Flat Mountain Arm	X - in YELL				Christiansen 2001			Cenozoic	Quarternary, Pleistocene
Lava Creek Tuff, undivided		YES - YELL	YES		Christiansen and Blank, 1972	Type area: upper Canyon of Lava Creek, and its tributary, Arrow Canyon, in Yellowstone National Park, Park Co.,		Cenozoic	Quarternary, Pleistocene
Lava Creek Tuff, Member B		YES - YELL			Christiansen and Blank 1972; Chris	Reference section: of the upper member is on the east wall of Sheepeater Canyon on the Gardner River 1 km r		Cenozoic	Quarternary, Pleistocene
Lava Creek Tuff, Member A		YES - YELL			Christiansen and Blank 1972; Chris	Reference section: south-facing cliff of Purple Mountain above an old gravel pit about 1 km east of Madison Ju		Cenozoic	Quarternary, Pleistocene
Lava Creek Tuff, upper part of Member A								Cenozoic	Quarternary, Pleistocene
Lava Creek Tuff, lower part of Member A								Cenozoic	Quarternary, Pleistocene
Undine Falls Basalt		YES - YELL	YES		Christiansen and Blank, 1972	Type locality: Cliff on north side of Lava Creek Canyon, just west of Undine Falls, in Yellowstone National Park,		Cenozoic	Quarternary, Pleistocene
Flat Mountain flow	X - in YELL				Christiansen 2001			Cenozoic	Quarternary, Pleistocene
Wapiti Lake flow	X - in YELL				Christiansen 2001			Cenozoic	Quarternary, Pleistocene
Stonetop Mountain flow	X - in YELL				Christiansen and Blank, 1972; Christiansen 2001			Cenozoic	Quarternary, Pleistocene
Mount Haynes flow	X - in YELL				Christiansen 2001			Cenozoic	Quarternary, Pleistocene
Harlequin Lake flow	X - in YELL				Christiansen 2001			Cenozoic	Quarternary, Pleistocene
Moose Creek Butte flow	X - in YELL				Christiansen 2001			Cenozoic	Quarternary, Pleistocene
Big Bear Lake flow	X - in YELL				Christiansen 2001			Cenozoic	Quarternary, Pleistocene
Basalt of Warm River	X - in YELL				Christiansen 2001			Cenozoic	Quarternary, Pleistocene
Sediments and basalts of The Narrows	X - in YELL				Pierce and others, 1970; Christian	Gravels and basalts near The Narrows of the Grand Canyon of the Yellowstone, below Tower Creek		Cenozoic	Quaternary, Pleistocene
Island Park Rhyolite, Warm River Butte dome		NO		Type area: "Arbitrarily designated" as Lookou	Christiansen, 1982			Cenozoic	Quarternary, Pleistocene
Island Park Rhyolite, Mesa Falls Tuff		NO		Type section: Roadcut on U.S. Highway 20, about 6.8 km north of Ashton, [Lookout	Christiansen and Blank, 1972			Cenozoic	Quarternary, Pleistocene
Lewis Canyon Rhyolite		YES - JODR			Christiansen and Blank, 1972	Type area: North side of Glade Creek between Snake River and east end of Grassy Lake Reservoir, Teton Co.,		Cenozoic	Quarternary, Pleistocene
Pyroxene andesite and basalt of Emerald Lake		X			Iddings, 1899; Love et al., 1976			Cenozoic	Quarternary, Pleistocene
Huckleberry Ridge Tuff, undivided		YES - JODR			Christiansen and Blank, 1972	Type section: cliff exposure at head of large landslide 1.8 km N. 10 deg. E. of Snake River bridge at Flagg Ranch on		Cenozoic	Quarternary, Pleistocene
Huckleberry Ridge Tuff, Member C	X - in YELL				Christiansen 2001	Present only south of the Yellowstone Plateau in the area from the northern Teton Range to Flat Mountain an		Cenozoic	Quarternary, Pleistocene
Huckleberry Ridge Tuff, Member B	X - in YELL				Christiansen 2001	Present over much of the area of the Huckleberry Ridge Tuff. It is thickest around Big Bend Ridge and in nearb		Cenozoic	Quarternary, Pleistocene
Huckleberry Ridge Tuff, Member A	X - in YELL				Christiansen 2001	Distributed mainly around the margins of the Yellowstone Plateau but extends to the north limit of Huckleberr		Cenozoic	Quarternary, Pleistocene
Rhyolite of Broad Creek	X - in YELL				Christiansen and Blank, 1972			Cenozoic	Quarternary, Pleistocene
Junction Butte Basalt		YES - YELL	YES		Christiansen and Blank, 1972	Type locality: West side of Grand Canyon of Yellowstone River opposite mouth of Deep Creek		Cenozoic	Quarternary, Pleistocene
Morainal debris of Jackson Lake	X							Cenozoic	
Morainal debris of Buried Ridge	X							Cenozoic	
Yellowstone Tuff	X - in YELL			Not designated. Origin of name not stated by	Boyd, 1961; Christiansen and Blank 1972			Cenozoic	Quarternary or Tertiary, Pleistocene o
Basalt of Mariposa Lake	X - in YELL				Christiansen and Blank, 1972			Cenozoic	Quarternary or Tertiary, Pleistocene o
Heart Lake Conglomerate		YES - YELL	YES		Love and Keefer, 1969	Type section: Locality B, in south-facing headwall at base of steep slope that rises to top of Mount Sheridan,		Cenozoic	Quarternary or Tertiary, Pleistocene o
				Type section: Exposure on north side of					

Figure 5. Stratotype inventory spreadsheet of the GRYN displaying attributes appropriate for geolocation assessment. Orange highlighted cells represent informally named geologic units.

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 following:

(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 principle 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 and 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.

Bighorn Canyon National Recreation Area

Bighorn Canyon National Recreation Area (BICA), located in Big Horn and Carbon counties, Montana and Big Horn County, Wyoming, was established on October 15, 1966 after construction of the Yellowtail Dam created the 114 km (71 mi) long Bighorn Lake (Figure 6). BICA serves as a national recreational area with boating, water skiing, fishing, swimming, hiking, sightseeing, and camping as popular activities. The national recreation area encompasses 48,641 hectares (120,196 acres), where archeological and historical resources complement the natural scene (Anderson 2017). Geographically located on the Montana–Wyoming border and adjacent to Crow tribal land, the national recreation area cooperates with two state governments, the Crow tribal government, and several federal entities including the Bureau of Land Management and the Bureau of Reclamation (KellerLynn 2011).

Bighorn Lake is nestled within the steep walls of Bighorn Canyon and is surrounded by a diverse landscape of broad valleys, flat uplands, and the Bighorn and Pryor mountain ranges (KellerLynn 2011). Shaped by the forces of stream erosion and mountain uplift, much of Bighorn Canyon is narrow with sheer vertical walls that rise above Bighorn Lake. The depth of Bighorn Canyon ranges considerably, from approximately 305 m (1,000 ft) at Devil Canyon to 760 m (2,500 ft) on Bull Elk Ridge. Such depths expose significant sections of the rock record ranging in age from the Archean Eon (4.0–2.5 billion years ago) at the base of the Pryor Mountains, the Cambrian Period (542–488 million years ago), and the Mississippian Period (359–318 million years ago) (Figures 7 and 8).

The Bighorn Canyon National Recreation Area Foundation Document (2016) references the following significance statement: "*Landforms, remnant fossils, and evidence of ancient ecological conditions offer insight and comparison of the region's geologic history and processes. These actions were critical to forming the canyon, the surrounding mountains, and the region's water resources.*"

The following fundamental resources and values have been identified for BICA: "*Bighorn Canyon, created by geologic processes of uplift and erosion beginning about 75 million years ago. Bighorn Canyon reveals a record of its origin, ancient climate, and depositional environments within layers of exposed limestone and other rock strata. Fossil plants and animals exist in sedimentary rock layers deposited by bygone seas. Additional sedimentary layers formed after the seas receded. The Bighorn River gradually carved out the 50-mile-long canyon, with walls that rise to approximately 1,000 feet at Devil Canyon Overlook and more than 2,000 feet where the canyon crosses the northern end of the Bighorn Mountains.*"

As of the writing of this paper, there are no designated stratotypes identified within the boundaries of BICA. There is one stratotype located within 48 km (30 mi) of BICA boundaries, for the Cretaceous Thermopolis Formation Muddy Sandstone Member (reference section).

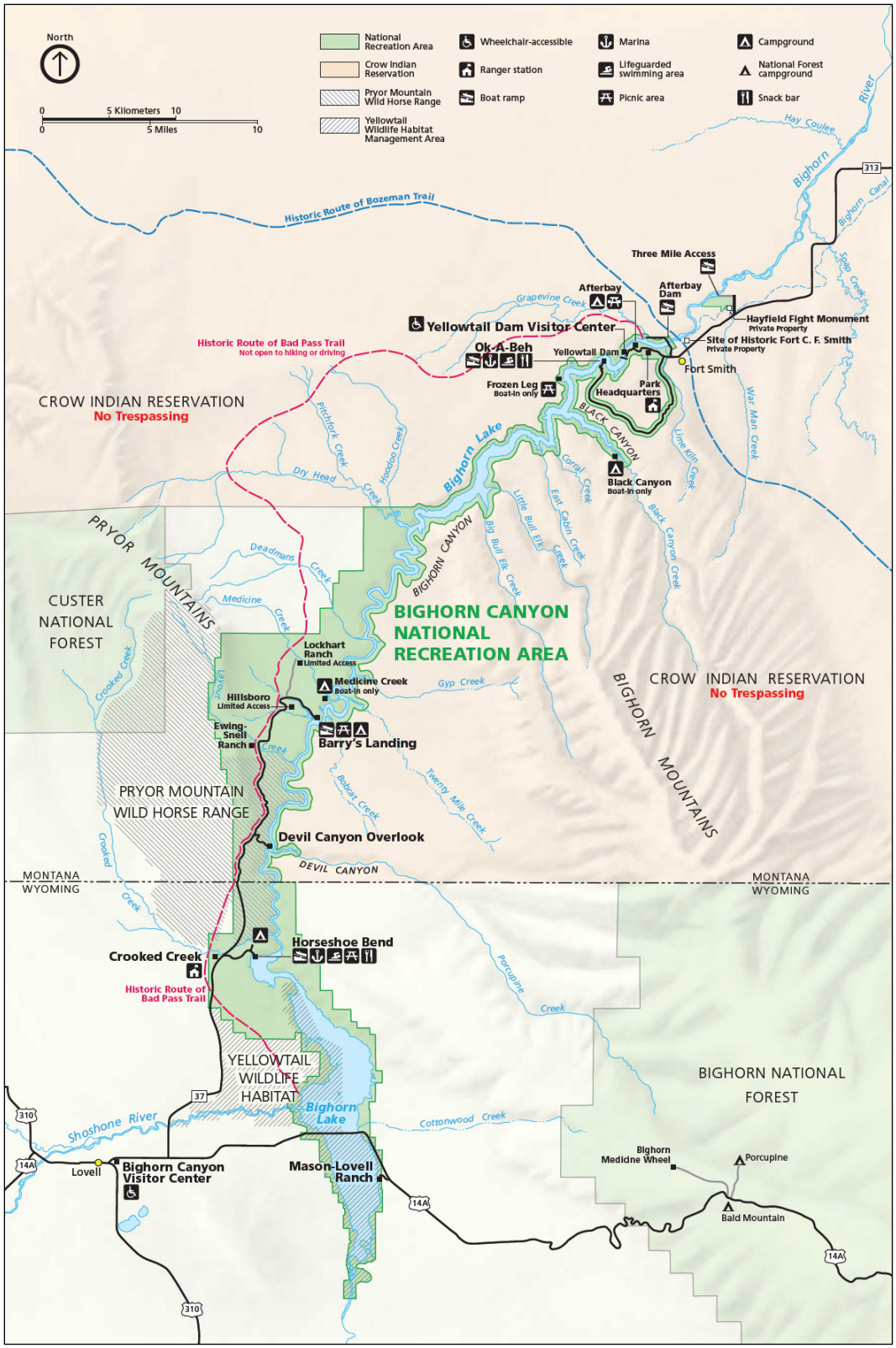


Figure 6. NPS park map of BICA, Montana and Wyoming (NPS).

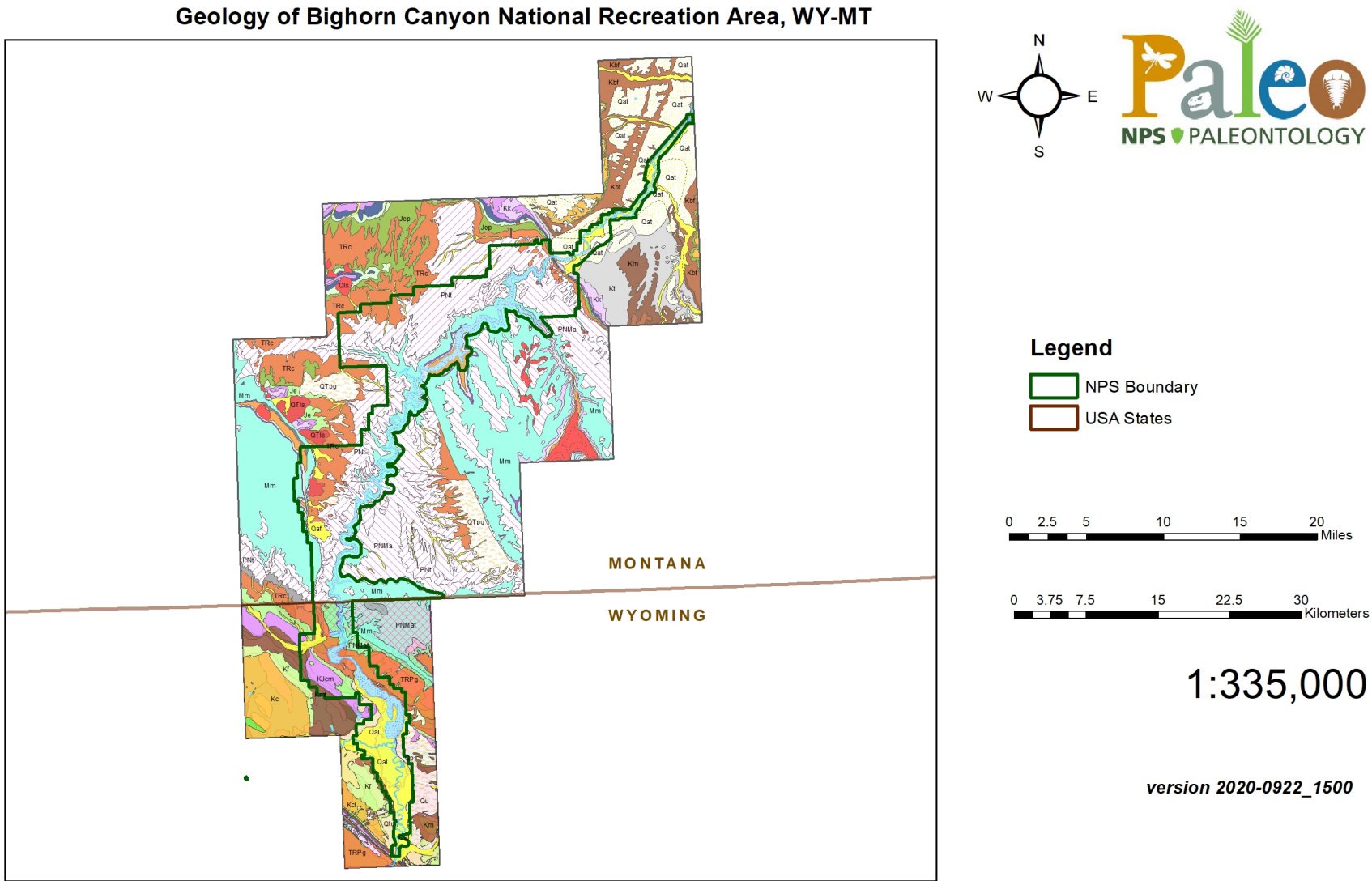


Figure 7. Geologic map of BICA and immediate vicinity, Montana and Wyoming.



Figure 8. Geologic map legend of BICA and immediate vicinity, Montana and Wyoming.

Grand Teton National Park

Grand Teton National Park (GRTE), located in Teton County, Wyoming, was established on February 26, 1929 and features the rugged, iconic peaks of the Teton Range, the expansive valley of Jackson Hole, and the scenic Snake River (Figure 9). Congress enlarged the boundaries of GRTE on September 14, 1950 to incorporate much of the Jackson Hole National Monument, increasing the park area to 125,270 hectares (310,044 acres) (Anderson 2017). Located in northwestern Wyoming, the park is situated within one of the world's largest intact temperate ecosystem that is home to diverse wildlife, including grizzly bears, wolves, bison, moose and elk (Anderson 2017). For centuries the Teton Range has served as an important landmark for Native Americans, trappers, prospectors, explorers, scientists, and tourists. Today, more than 2 million visitors come to the park annually to experience its spectacular landscape.

The dramatic landscape of GRTE has been sculpted by dynamic geologic processes to create a variety of geothermal, glacial, and volcanic features in addition to Snake River terrace deposits. The spectacular topography and scenery of the Teton Range is the result of the active Teton fault, a normal fault extending more than 70 km (40 mi) from north to south along the eastern base of the range (KellerLynn 2010). Tectonic forces along the Teton fault have raised the Teton Range and dropped Jackson Hole to create more than 2,100 m (6,900 ft) of topographic relief. Exposed rock units in GRTE represent a vast range in age from Archean (4.0–2.5 billion years ago) to Quaternary (2.6 million years ago–Present). The Teton Range consists of an uplifted core of igneous and metamorphic Archean and Proterozoic rocks surrounded by Paleozoic and Mesozoic sedimentary rocks. Younger Cenozoic deposits dominate the land surface immediately east of the core in Jackson Hole (Figures 10 and 11).

The Grand Teton National Park and John D. Rockefeller, Jr. Memorial Parkway Foundation Document (2017) references the following significance statement: *"Grand Teton National Park preserves the landscape of one of the world's most impressive and highly visible fault block mountain ranges that abruptly rises up to 7,000 feet above the valley floor along an active fault (the Teton Fault) formed from the collision of tectonic plates. The range is juxtaposed with landscapes shaped by glacial processes and braided river geomorphology. The Teton Range is one of the continent's youngest mountain ranges, yet exposes some of the oldest rocks on earth.*"

The following fundamental resources and values have been identified for GRTE and JODR: *"Geologic Features and Processes. Powerful ongoing geologic forces shape the park, parkway, and nearby Yellowstone National Park. Regional heat from the earth's mantle combined with local heat from the plume of magma under Yellowstone have lifted and cracked the earth's crust. Earthquakes generated along one of these cracks–the Teton fault–tilted the Teton Range skyward while dropping the valley of Jackson Hole. As the mountains were rising, massive glaciers flowed south from Yellowstone and alpine glaciers carved out U-shaped canyons and piedmont lakes ringed by glacial moraines. The glaciers melted, washing soil from the valley floor, and leaving behind an outwash plain covered with cobbles and carving terraces that step down to the modern Snake River. Today, small earthquakes occasionally shake the region, suggesting the power of future mountain-building.*

Remnant glaciers serve as reminders of the powerful and massive glaciers that shaped the landscape. All the while, rainfall and freeze-thaw cycles cause landslides and rockfalls."



Figure 9. NPS park map of GRTE and JODR (NPS).

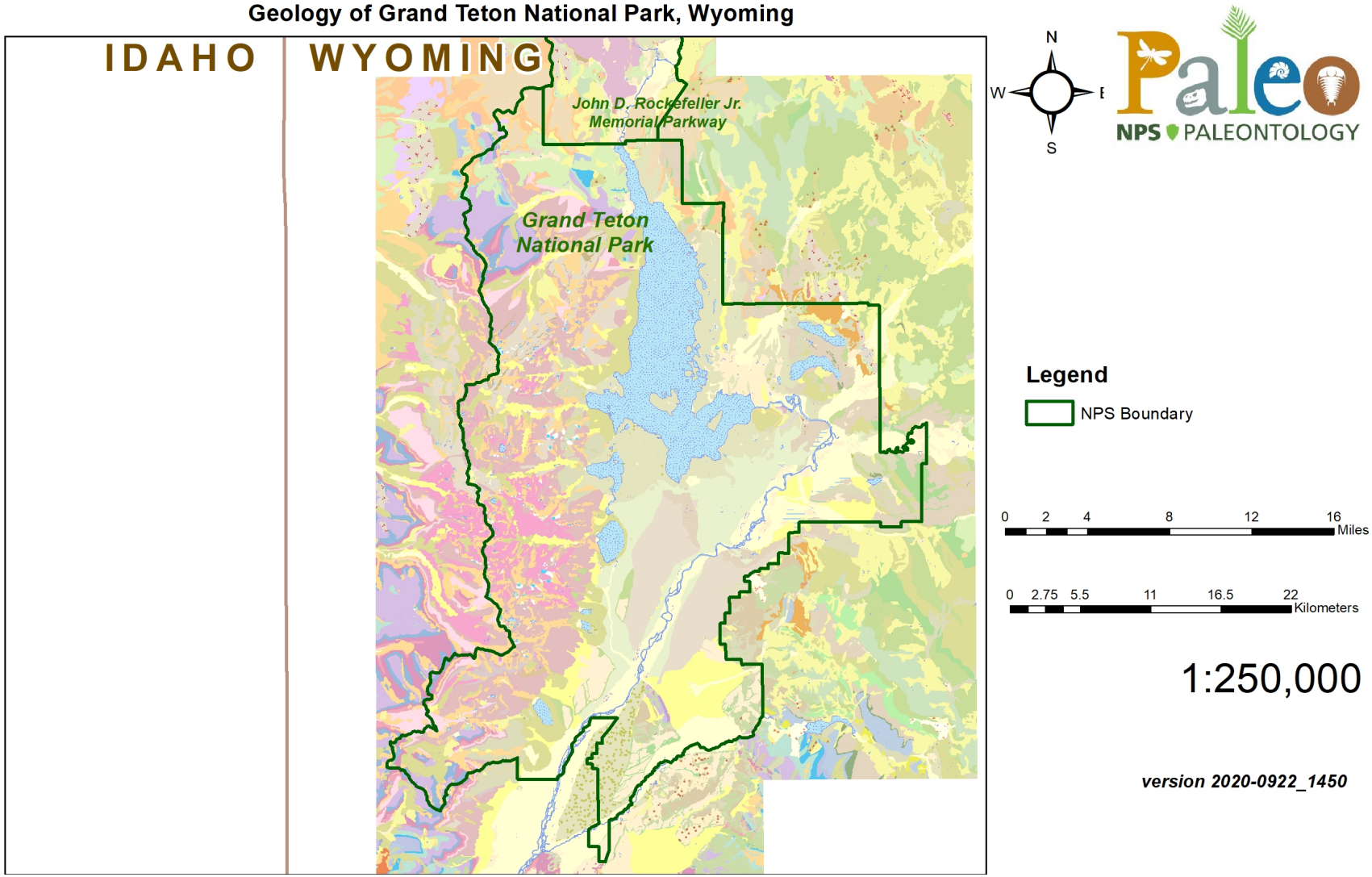


Figure 10. Bedrock geologic map of GRTE, Wyoming.



Figure 11. Bedrock geologic map legend of GRTE, Wyoming.

At the time of the writing of this report, GRTE contains four stratotypes that include two type localities and two type sections (Table 1; Figure 12).

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

Unit Name (map symbol)	Reference	Stratotype Location	Age
Colter Formation (Tc)	Love 1956	Type section: on Pilgrim Creek ~8 km (5 mi) northeast of Colter Bay	Tertiary
Gros Ventre Formation, Death Canyon Limestone Member (Cgd)	Miller 1936	Type section: along divide between Death and Teton Canyons, in Teton Range	Cambrian
Mount Owen Quartz Monzonite (Xmo)	Reed & Zartman 1973	Type locality: exposures along trail in South Fork of Cascade Canyon, ~ 3 km (1.9 mi) due west of the summit of Mount Owen	Proterozoic
Webb Canyon Gneiss (Ww)	Reed & Zartman 1973	Type locality: lower cliffs on northwest side of Moose Creek, in lower part of Webb Canyon	Archean

The two GRTE type localities are the upper Archean Webb Canyon Gneiss and lower Proterozoic Mount Owen Quartz Monzonite, some of the oldest exposed geologic units in the park. Reed and Zartman (1973) characterized the Webb Canyon Gneiss as a medium- to coarse-grained, strongly foliated, non-layered, biotite-and-hornblende-bearing gneiss of quartz monzonitic composition that forms several large concordant bodies in the northern part of the Teton Range. The type locality is designated as the lower parts of the cliffs on the northwest side of Moose Creek in the lower part of Webb Canyon, 3.1 km (1.9 mi) S. 78° E. of Owl Peak in the Ranger Peak 7.5' quadrangle, Wyoming (Figure 12; Reed and Zartman 1973). The type locality is situated near the northeast end of the largest exposed body of the Webb Canyon Gneiss where is has thick amphibolite layers.

The Mount Owen Quartz Monzonite is named from exposures on the slopes of Mount Owen and is described as an irregular pluton of light-colored quartz monzonite and associated pegmatite that underlies much of the central Teton Range (Reed and Zartman 1973). Typically the Mount Owen Quartz Monzonite is a medium- to fine-grained light-colored rock consisting of 30–40% quartz, 20–30% K (potassium)-feldspar, 25–35% Na (sodium)-plagioclase (oligoclase), 5% or less biotite, and trace amounts of muscovite (Reed and Zartman 1973). Associated pegmatite bodies range in thickness from several cm (a few inches) to several tens of meters or feet throughout the main body of the Mount Owen Quartz Monzonite. The pegmatites contain irregular masses of quartz, oligoclase, microcline, and muscovite; a few pegmatites contain garnet crystals up to 15 cm (6 in) in diameter (Reed and Zartman 1973). Reed and Zartman (1973) designated the type locality as the more easily accessible exposures along the trail in the South Fork of Cascade Canyon at an elevation of 2,700 m (8,880 ft), 3.1 km (1.9 mi) due west of the summit of Mount Owen, Grand Teton 7.5' quadrangle, Wyoming (Figure 12).

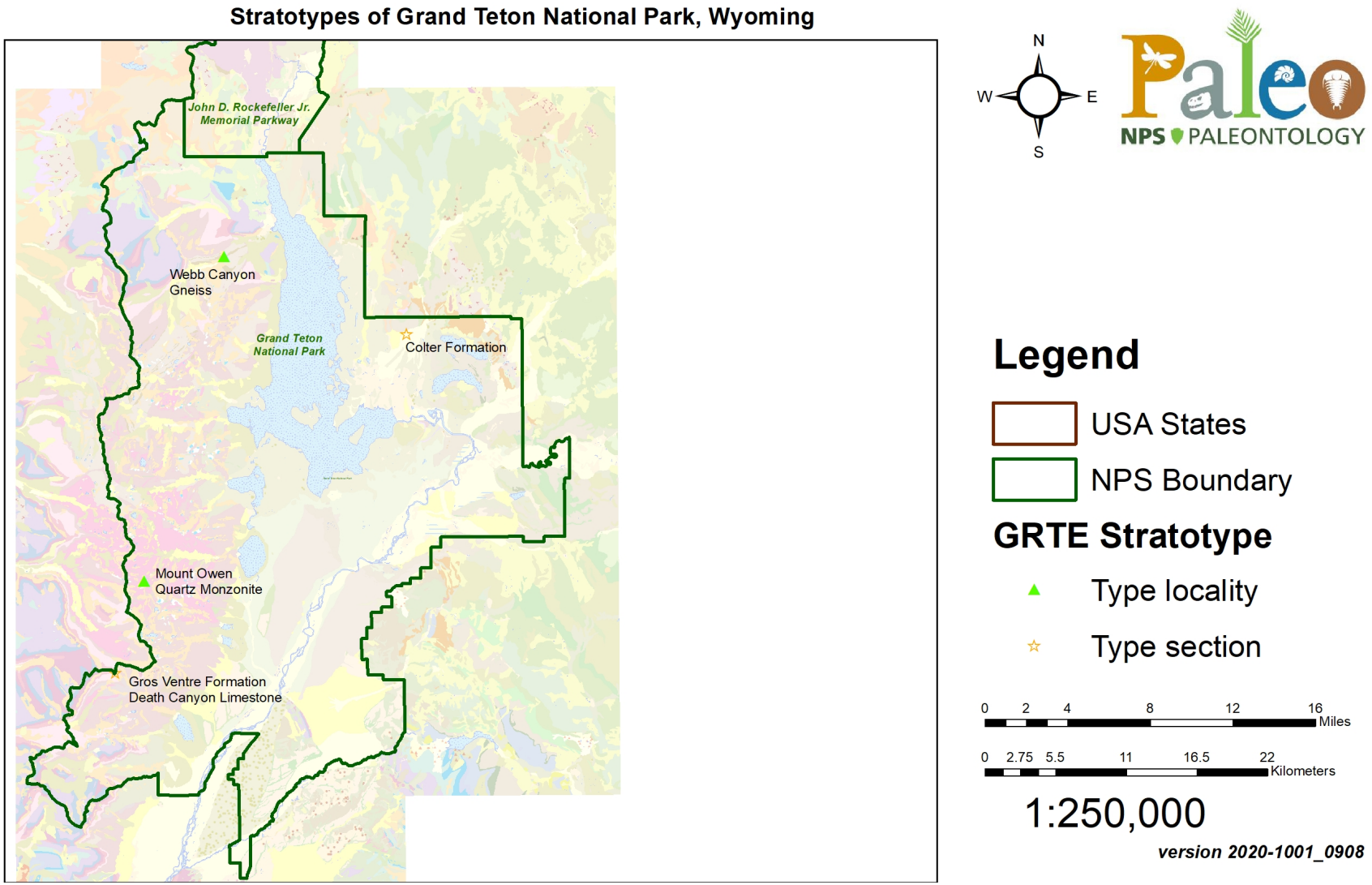


Figure 12. Modified geologic map of GRTE showing stratotype locations. The transparency of geologic units has been increased.

The oldest type section unit of GRTE is the Cambrian Death Canyon Limestone Member of the Gros Ventre Formation. The Death Canyon Limestone Member occurs stratigraphically above the Wolsey Shale and beneath the Park Shale, and consists largely of thin-bedded, fine-grained, dark-gray, brown and black mottled limestone separated by argillaceous seams (Figure 13; Miller 1936; Shaw 1957). Miller (1936) designated the type section location as being along the divide between the South Fork of Teton Canyon and Death Canyon in the Teton Range, about 3 km (2 mi) south of Buck Mountain (Figure 12). At the type occurrence the limestone is approximately 86.9 m (285 ft) thick and forms a prominent, double-rimmed scarp (Figure 14).

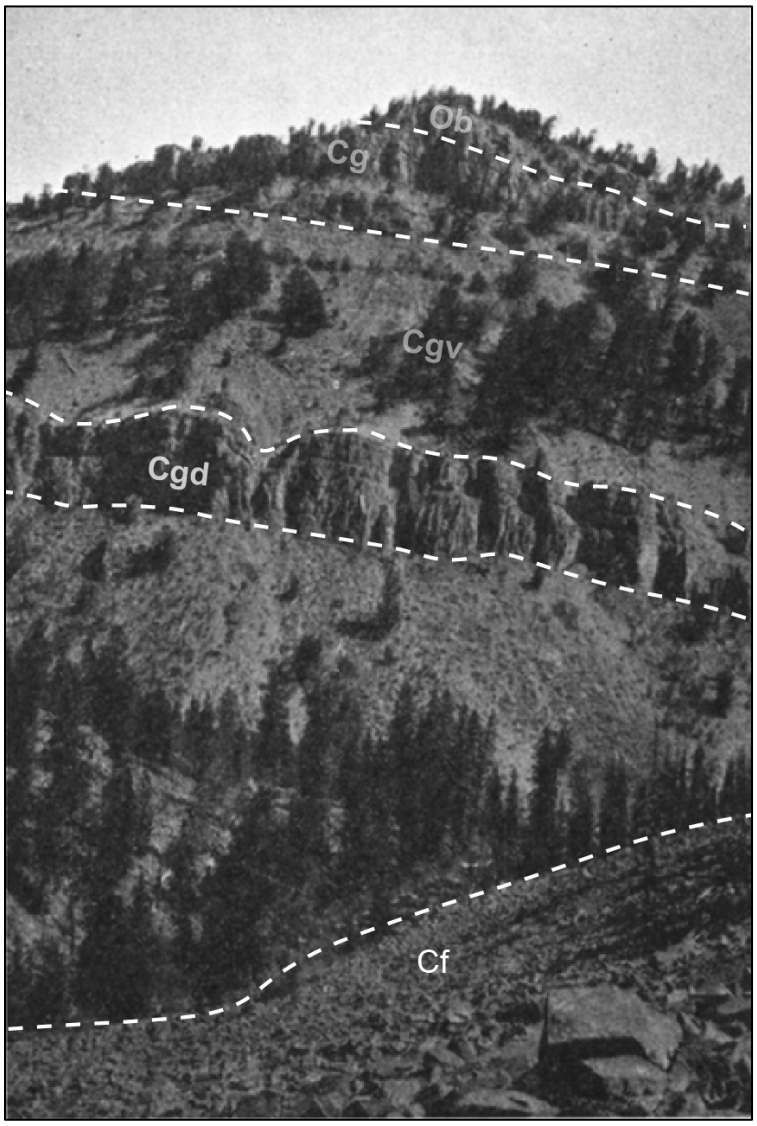


Figure 13. Section along Warm Springs Creek in the Teton Range, Wyoming. The blocks in the foreground are Flathead Sandstone (Cf); the prominent lower cliff is the upper part of the Death Canyon Limestone Member of the Gros Ventre Formation (Cgd). The contact between the Gros Ventre Formation (Cgv) and Gallatin Limestone (Cg) is just above the base of the second cliff above the Death Canyon Limestone; the Gallatin Limestone–Bighorn Dolomite (Ob) contact is in the middle part of the cliff capping the hill. Figure modified from Miller (1936) (figure courtesy David Rowley/Journal of Geology).



Figure 14. Type section of the Death Canyon Member of the Gros Ventre Formation, 3 km (2 mi) south of Buck Mountain, in the South Fork of Teton Canyon, GRTE. The double-rimmed scarp is the Death Canyon Member (Cgd) atop the shaly slopes of the lower Gros Ventre Formation (Cgv); the blocks in the foreground are at the top of the Flathead Sandstone (Cf). Figure modified from Miller (1936) (figure courtesy David Rowley/Journal of Geology).

The second GRTE type section is the Miocene-age Colter Formation, which is based on a 2,100-m (7,000-ft) sequence of gray, green, and brown pyroclastic rock, sandstone, and claystone near Colter Bay, Wyoming (Love 1956). The Colter Formation is characterized by abundant lithic fragments consisting of red, black, and green angular- to sub-rounded basalt found in tuffs and conglomerates (Love 1956). Deposits of the formation were later classified as pyroclastic flow, lahar, surge, and coarse air-fall deposits that were erupted from vents mainly in the northwest part of Jackson Hole (Barnosky 1984; Barnosky and Labar 1989). Love (1956) described the type section location as extending eastward from the east face of Pilgrim Peak across Pilgrim Creek for a distance of about a mile, within Sections 20, 21, and 22, and 27, 28, and 29, Township 46 North, Range 114 West, in Teton County, Wyoming. Exposures in the vicinity of the type section on Pilgrim Creek are the thickest, where 2,100 m (7,000 ft) of strata were measured with the exception of the basal part of the formation, which was distorted by intrusions and landslides (Figure 12; Love 1956). Barnosky (1984) defined type sections of the Crater-Tuff Breccia Member and Pilgrim Conglomerate Member of the Colter Formation, stating that the composite of the two member type sections is the type section reported by Love (1956) for the Colter Formation.

In addition to the designated stratotypes located within GRTE, a list of stratotypes located within 48 km (30 mi) of park boundaries is included here for reference. These nearby stratotypes include the Eocene Hominy Peak Formation (type section) and the Devonian Darby Formation (type section).

John D. Rockefeller, Jr. National Memorial Parkway

John D. Rockefeller, Jr. National Memorial Parkway (JODR), located in Teton County, Wyoming, was authorized by Congress on August 25, 1972 to commemorate Rockefeller's philanthropy and significant contributions to the establishment of several national parks: GRTE, Acadia National Park (ACAD), Great Smoky Mountains National Park (GRSM), and Virgin Islands National Park (VIIS). Congress also named the highway from GRTE's south boundary to West Thumb in YELL in honor of Rockefeller (Anderson 2017). The 132 km (81 mi) parkway encompasses 9,622 hectares (23,777 acres) of remote and largely uninhabited land that provides a natural link between GRTE and YELL (Figure 9).

The parkway is a mountainous region with moderate to steep slopes situated between the volcanic plateaus of YELL and the jagged fault-block mountains of GRTE. The geology of the parkway largely reflects influences of extra-regional origin and contains geothermal, glacial, and volcanic features of particular interest (Figures 15 and 16; KellerLynn 2010). Jurassic and Cretaceous sandstone and shale are present, but more recent lava and ash from Yellowstone volcanism blanket much of the older Cretaceous bedrock. The most prominent volcanic event was the caldera eruption that created Yellowstone Lake 600,000 years ago, which deposited thick layers of rhyolite in the parkway (Rodman et al. 1992; KellerLynn 2010). The Teton fault, so significant for GRTE, has also uplifted the topography and influenced seismic activity within the parkway. Glaciers originating in YELL entirely covered the parkway during the Pleistocene Epoch (2.6 million to 11,700 years ago), creating its gouged valleys and rounded mountains (Rodman et al. 1992).

The Grand Teton National Park and John D. Rockefeller, Jr. Memorial Parkway Foundation Document (2017) references the following fundamental resources and values identified for GRTE and JODR: "*Geologic Features and Processes. Powerful ongoing geologic forces shape the park, parkway, and nearby Yellowstone National Park. Regional heat from the earth's mantle combined with local heat from the plume of magma under Yellowstone have lifted and cracked the earth's crust. Earthquakes generated along one of these cracks–the Teton fault–tilted the Teton Range skyward while dropping the valley of Jackson Hole. As the mountains were rising, massive glaciers flowed south from Yellowstone and alpine glaciers carved out U-shaped canyons and piedmont lakes ringed by glacial moraines. The glaciers melted, washing soil from the valley floor, and leaving behind an outwash plain covered with cobbles and carving terraces that step down to the modern Snake River. Today, small earthquakes occasionally shake the region, suggesting the power of future mountain-building. Remnant glaciers serve as reminders of the powerful and massive glaciers that shaped the landscape. All the while, rainfall and freeze-thaw cycles cause landslides and rockfalls.*"

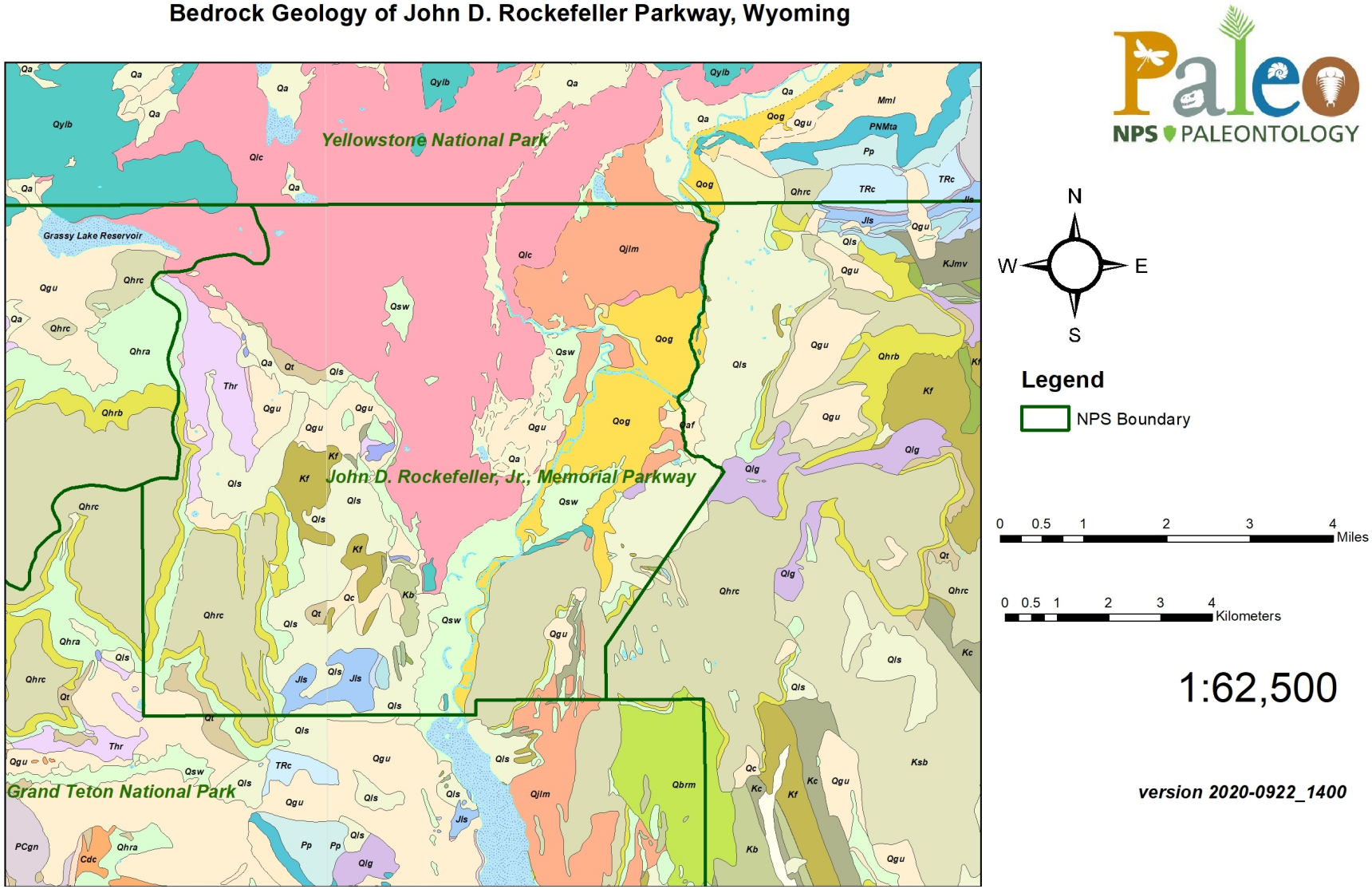


Figure 15. Bedrock geologic map of JODR, Wyoming.

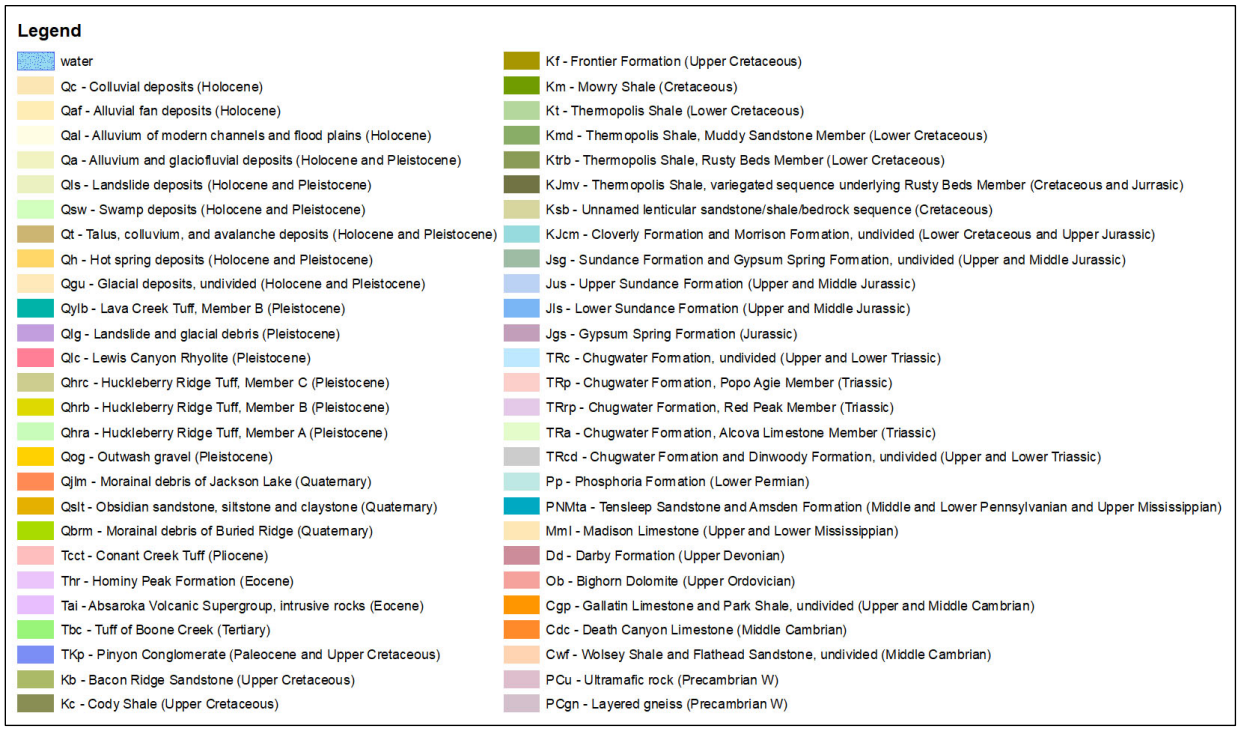


Figure 16. Bedrock geologic map legend of JODR, Wyoming.

JODR contains one type section and one type area, both of which are associated with Yellowstone volcanism (Table 2; Figure 17). The one type section of JODR is the Pleistocene-age Huckleberry Ridge Tuff, the oldest ash-flow sheet of the Yellowstone Group, dating to approximately 2.1 Ma. The Huckleberry Ridge Tuff consists mainly of welded ash-flow tuff that is predominantly devitrified, containing major phenocrysts of quartz, sanidine, and sodic plagioclase with minor phenocrysts of oxides, clinopyroxene, fayalite, zircon, hornblende, allanite, and chevkinite (Christiansen and Blank 1972). Christiansen and Blank (1972) designated the Huckleberry Ridge Tuff type section as the cliff exposure at the head of a large landslide 1.8 km (1.1 mi) N10° E of the Snake River bridge at Flagg Ranch along the John D. Rockefeller highway about 3 km (2 mi) south of the South Entrance of YELL (Figure 17). The type section is approximately 170 m (560 ft) thick and consists of welded phenocryst-rich rhyolitic ash-flow tuff overlying Cretaceous sandstones and shales (Figure 18; Christiansen and Blank 1972).

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

Unit Name (map symbol)	Reference	Stratotype Location	Age
Lewis Canyon Rhyolite (Qlc)	Christiansen & Blank 1972	Type area: north side of Glade Creek between Snake River and east end of Grassy Lake Reservoir	Pleistocene
Huckleberry Ridge Ruff (Th)	Christiansen & Blank 1972	Type section: cliff exposure at head of large landslide 1.8 km (1.1 mi) north of Snake River bridge along the parkway	Pleistocene

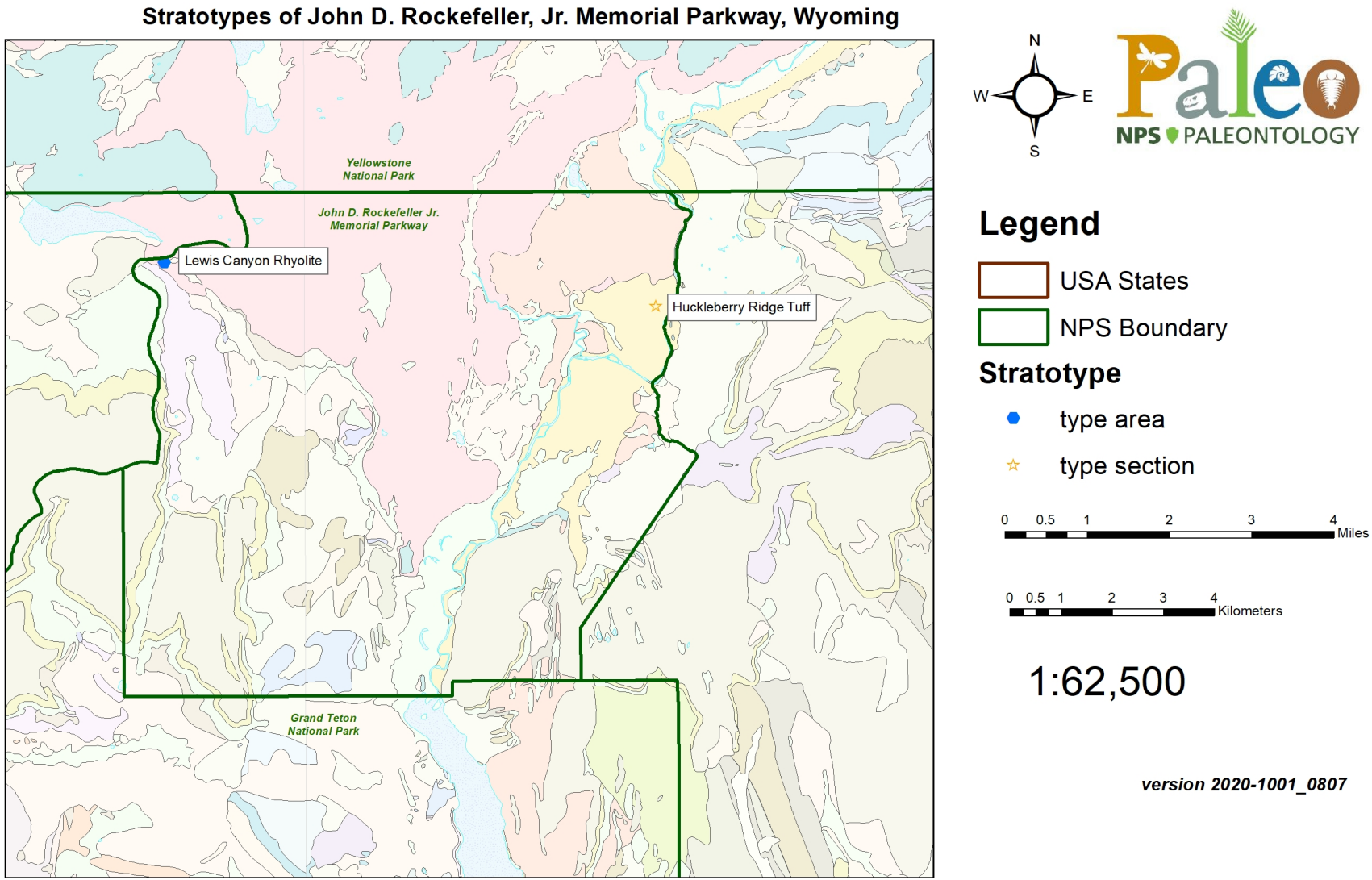


Figure 17. Modified geologic map of JODR showing stratotype locations. The transparency of geologic units has been increased.

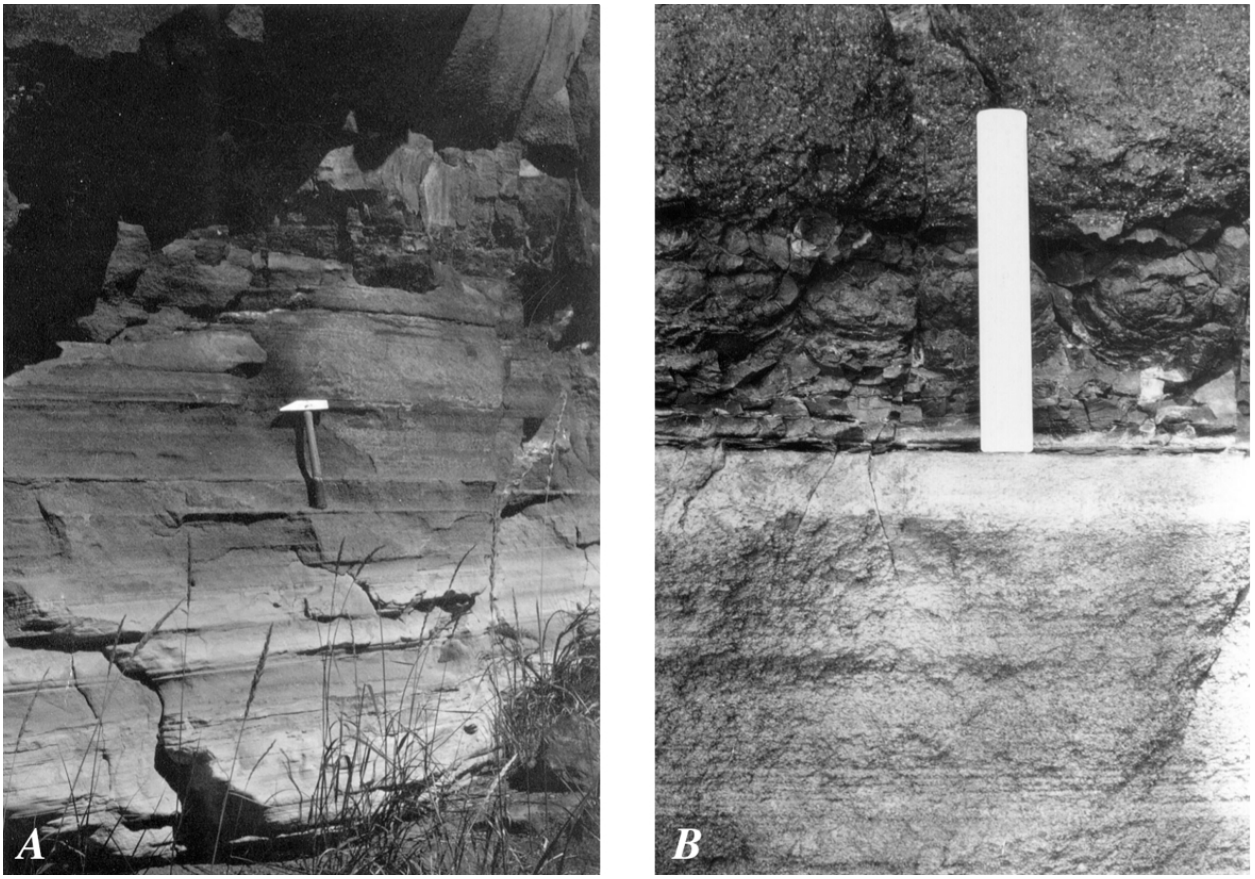


Figure 18. Basal fallout ash of Huckleberry Ridge Tuff, Mount Everts, YELL. A: continuous planar bedding of fallout tuff; lower, lighter colored part is relatively fine-grained, darker upper part is coarser grained. B: fused tuff at top of basal fallout, overlain by vitrophyric welded ash-flow tuff. Fallout-ash flow contact is about 7 cm (3 in) below top of scale (20 cm or 8 in long); base of scale is at base of fused zone. Figure from Christiansen (2001).

Ash flows of the Huckleberry Ridge Tuff type section are divided into three members due to significant changes in welding and minor variations in phenocryst content (Christiansen 1979; Christiansen and Blank 1972). The oldest member (A) is approximately 45 m (150 ft) thick and contains abundant (40–50%) phenocrysts at its base that become less abundant in the upper 15 m (50 ft). The middle member (B) is approximately 30 m (100 ft) thick and has a thin, phenocryst-poor base with a zone of abundant large phenocrysts above it (Christiansen and Blank 1972). The top of member B contains distinct dark crystallized pumice that is overlain sharply by member C (Christiansen and Blank 1972). Member C is approximately 95 m (310 ft) thick and is characterized by smaller, moderately abundant phenocrysts than the other underlying members (Christiansen and Blank 1972).

The one geologic type area of JODR is for the Pleistocene-age Lewis Canyon Rhyolite. Stratigraphically, the Lewis Canyon Rhyolite overlies the Huckleberry Ridge Tuff and consists of several bulbous, non-stratiform rhyolitic lava flows dated to approximately 0.85 Ma (850,000 years ago) (Christiansen and Blank 1972; Christiansen 2001). The rhyolite is characterized as containing

30–40% phenocrysts, including abundant sodic oligoclase with smaller, less abundant phenocrysts of quartz, sanidine, clinopyroxene, and opaque oxides (Christiansen and Blank 1972). Christiansen and Blank (1972) designated the type area as the north side of Glade Creek, between the Snake River and the east end of Grassy Lake Reservoir (Figure 17). In this area the Lewis Canyon Rhyolite is represented by well-exposed, 200 m (660 ft) thick flows that occur along the meadows on the north side of Glade Creek. The type area rhyolite overlies the Huckleberry Ridge Tuff and Cretaceous sedimentary rocks and is overlain by the Lava Creek Tuff (Christiansen and Blank 1972).

Yellowstone National Park

Yellowstone National Park (YELL) is located in parts of Wyoming, Montana, and Idaho (Figure 19). Established on March 1, 1872, YELL is the first and oldest national park in the United States and spans an area of 898,317.5 hectares (2,219,791 acres) (Anderson 2017). YELL forms the core of the Greater Yellowstone Ecosystem–one of the largest nearly intact temperate-zone ecosystems on Earth, home to elk, bison, bighorn sheep, wolves, grizzly bears, and more than 1,000 species of native plants. Old Faithful Geyser, Grand Prismatic Spring, Mammoth Hot Springs, and some 10,000 other geothermal features make this park the greatest geyser area on the planet (Anderson 2017). The vast natural wealth of YELL also includes lakes, waterfalls, high mountain meadows, and the Grand Canyon of the Yellowstone. YELL has been designated as both a Biosphere Reserve in 1976 and World Heritage Site in 1978.

YELL represents one of the most geologically dynamic areas on Earth, with a landscape that has been shaped by a variety of processes. Large areas of the park have been buried by multiple cycles of Tertiary and Quaternary volcanism associated with the Yellowstone hotspot in addition to Pleistocene glacial deposits (Figures 20–23). Older Paleozoic and Mesozoic rocks are exposed in a few areas where erosion and glacial scouring has uncovered these units (Santucci 1998). Precambrian through Upper Cretaceous strata are exposed in the Gallatin Range. Jurassic rocks and a thick section of Cretaceous strata are exposed on Mount Everts. Precambrian and Paleozoic units outcrop in the northeast corner of the park. Paleozoic rocks are also exposed in the Birch Hills and Snake River areas along the southern boundary of Yellowstone (Santucci 1998).

The Yellowstone National Park Foundation Document (2014) references the following significance statement, "*Yellowstone National Park was set aside because of its geothermal wonders — the planet's most active, diverse, and intact collection of geothermal, geologic, and hydrologic features and systems and the underlying volcanic activity that sustains them.*"

The following geological fundamental resources and values have been identified for YELL:

1) Geothermal wonders. YELL contains an unparalleled collection of more than 10,000 thermal features, including geysers, hot springs, mud pots, and fumaroles, which are fed by underground geothermal and hydrothermal systems. They provide habitats for microorganisms and other wildlife, and unique opportunities for research.

2) Dynamic geologic processes and features. YELL's dramatic landscapes, including the Grand Canyon of the Yellowstone, Overhanging Cliff, and Obsidian Cliff, were shaped by volcanism, glaciation, erosion, and seismic activity. These processes have resulted in exposed and hidden geology and produce a varied landscape that provides unique habitat for many species.

YELL contains a total of 31 stratotypes that can be subdivided into three type sections, three reference sections, five type localities, and 20 type areas (Table 3; Figure 24).

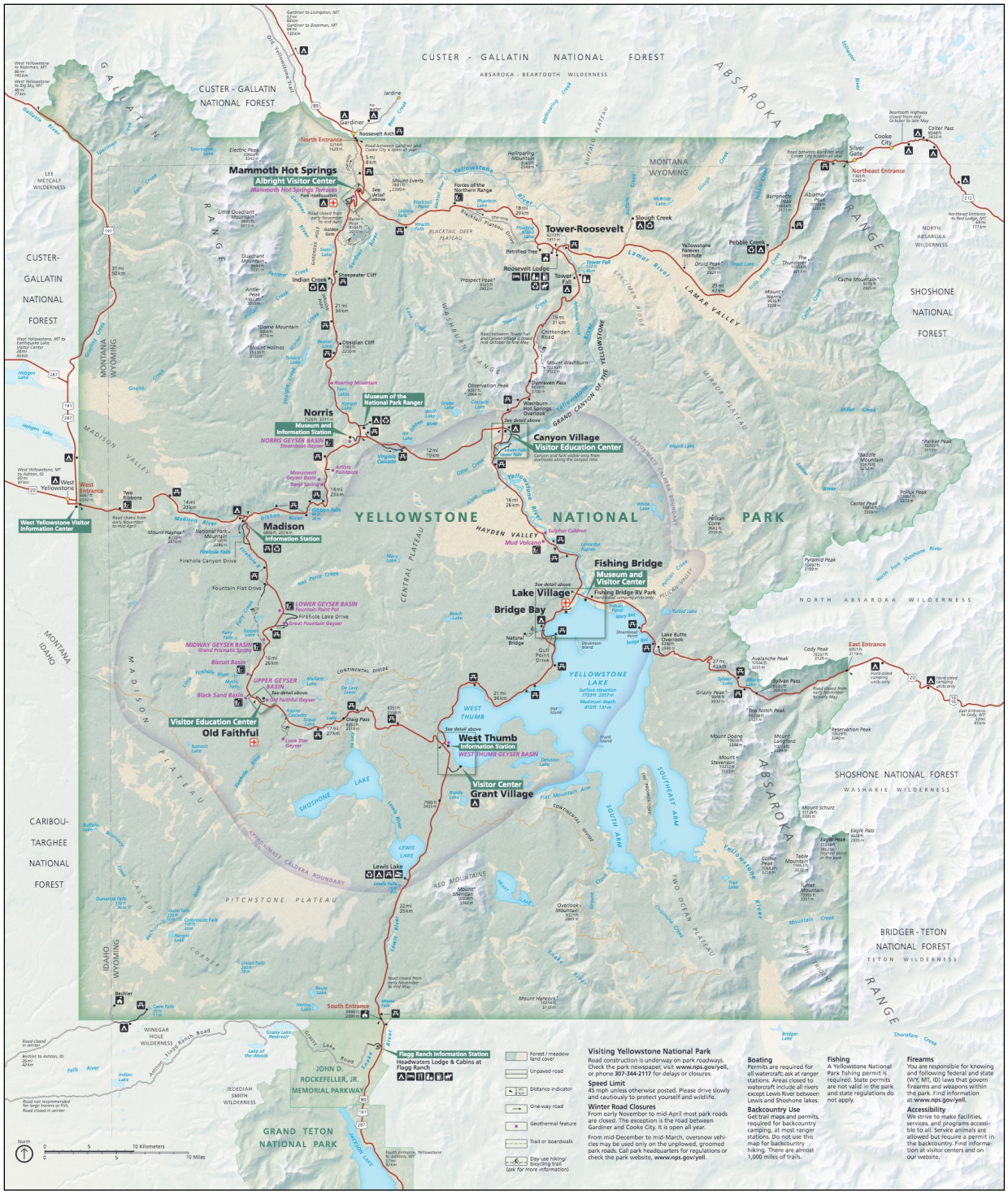


Figure 19. NPS park map of YELL, Wyoming–Idaho–Montana (NPS).

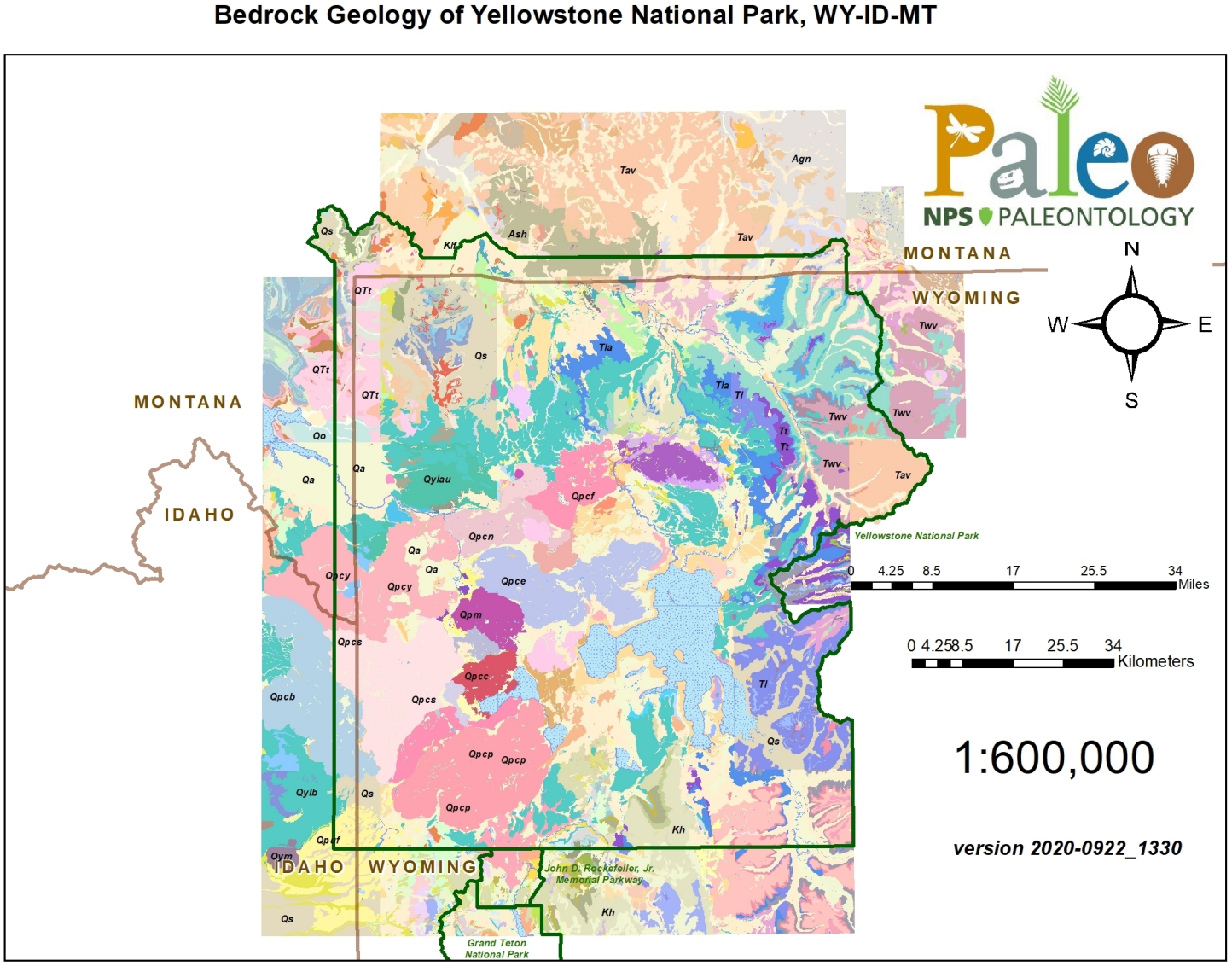


Figure 20. Bedrock geologic map of YELL, Wyoming–Idaho–Montana.



Figure 21a. Bedrock geologic map legend of YELL, Wyoming–Idaho–Montana.



Figure 21b. Bedrock geologic map legend of YELL, Wyoming–Idaho–Montana.

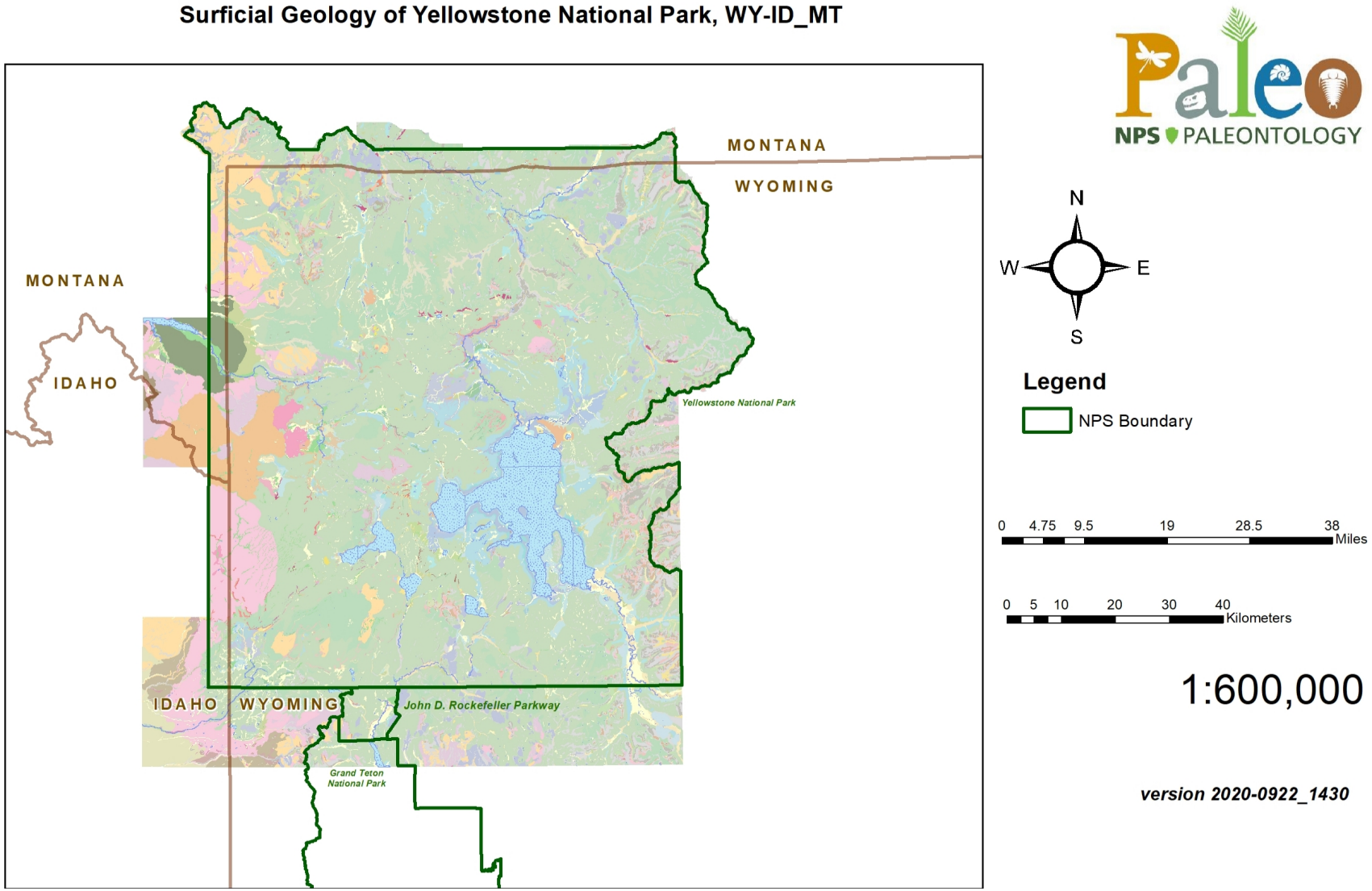


Figure 22. Surficial geologic map of YELL, Wyoming–Idaho–Montana.



Figure 23. Surficial geologic map legend of YELL, Wyoming–Idaho–Montana.

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

Unit Name (map symbol)	Reference	Stratotype Location	Age
Plateau Rhyolite, Central Plateau Member (Qpcp)	Christiansen & Blank 1972	Type area: the Central Plateau, located in the middle of the Yellowstone Caldera	Pleistocene
Osprey Basalt (Qob)	Pierce et al. 1970	Type section: cliff on west side of Sheepeater Canyon, north of Osprey Falls	Pleistocene
Mallard Lake Flow (Qpm)	Christiansen & Blank 1972	Type area: Mallard Lake, ~5 km (3 mi) northeast of Old Faithful	Pleistocene
Madison River Basalt (Qmr)	Christiansen & Blank 1972	Type area: uplands west of south end of Gallatin Range, south of Maple Creek	Pleistocene
Plateau Rhyolite, Roaring Mountain Member (Qpr)	Christiansen & Blank 1972	Type area: Roaring Mountain in northwest YELL	Pleistocene
Plateau Rhyolite, Obsidian Creek Member (Qpo)	Christiansen & Blank 1972	Type area: Obsidian Creek in northwest YELL	Pleistocene
Plateau Rhyolite, Upper Basin Member (Qpud)	Christiansen & Blank 1972	Type area: in the Upper Geyser Basin	Pleistocene
Falls River Basalt (Qpuf)	Christiansen & Blank 1972	Type locality: west rim of the valley of Falls River, below Cave Falls	Pleistocene
Swan Lake Flat Basalt (Qpusl)	Christiansen & Blank 1972	Type area: Sheepeater Cliffs, on east side of Gardner River, southeast of Bunsen Peak	Pleistocene
Lava Creek Tuff, Member B (Qylb)	Christiansen & Blank 1972; Christiansen 2001	Reference section: east wall of Sheepeater Canyon on the Gardner Canyon ~1 km (0.6 mi) northeast of Osprey Falls	Pleistocene
Lava Creek Tuff, Member A (Qyla)	Christiansen & Blank 1972; Christiansen 2001	Reference section: south-facing cliff of Purple Mountain above an old gravel pit ~1 km (0.6 mi) east of Madison Junction	Pleistocene
Lava Creek Tuff (Qylu)	Christiansen & Blank 1972	Type area: upper canyon of Lava Creek and its tributary in Arrow Canyon	Pleistocene
Undine Falls Basalt (Qufb)	Christiansen & Blank 1972	Type locality: cliff on north side of Lava Creek Canyon, just west of Undine Falls	Pleistocene
Mount Jackson Rhyolite (Qjf)	Christiansen & Blank 1972	Type area: the Madison Canyon near Mount Jackson	Pleistocene
Junction Butte Basalt (Qj)	Christiansen & Blank 1972	Type locality: west side of the Grand Canyon of the Yellowstone opposite the mouth of Deep Creek	Pleistocene

Table 3 (continued). List of YELL stratotype units sorted by age with associated reference publications and locations.

Unit Name (map symbol)	Reference	Stratotype Location	Age
Heart Lake Conglomerate (QTh)	Love & Keefer 1969	Type section: south-facing headwall at the base of steep slopes that rise to the top of Mount Sheridan	Pliocene–Pleistocene
Absaroka Volcanics Supergroup (Tav)	Smedes & Prostka 1972	Type area: Absaroka volcanic field and vicinity	Eocene
Two Ocean Formation (Tto)	Smedes & Prostka 1972	Type area: along the east edge of Two Ocean Plateau	Eocene
Langford Formation, Promontory Member (Tlpm)	Smedes & Prostka 1972	Type area: the Promontory, a peninsula between the South Arm and Southeast Arm of Yellowstone Lake	Eocene
Langford Formation (Tl)	Smedes & Prostka 1972	Type area: Mount Langford	Eocene
Mount Wallace Formation, Slough Creek Tuff Member (Tms)	Smedes & Prostka 1972	Type area: west of Slough Creek 3 km (2 mi) south of northern YELL boundary	Eocene
Lamar River Formation (Tlr)	Smedes & Prostka 1972	Type area: along valley walls of the Lamar River and its tributaries	Eocene
Sepulcher Formation, Fortress Mountain Member (Tsf)	Smedes & Prostka 1972	Type area: Bighorn Peak	Eocene
Sepulcher Formation, Daly Creek Member (Tsd)	Smedes & Prostka 1972	Type area: headwaters of Daly Creek	Eocene
Sepulcher Formation, Lost Creek Tuff Member (Tslc)	Smedes & Prostka 1972	Type area: near Lost Creek, northwest of Tower Junction	Eocene
Sepulcher Formation (Tse)	Smedes & Prostka 1972	Type area: Sepulcher Mountain	Eocene
Harebell Formation (Kh)	Love 1956, 1973	Type section: extends from Snake River south along the top of Big Game Ridge; Type locality: extends from the head of Snake River gorge south over Big Game Ridge ~3 km (2 mi) east of Mount Hancock and across Wolverine Creek to Pinyon Peak	Upper Cretaceous
Everts Formation (Ke)	Fraser et al. 1969	Type area: west half of Mount Everts	Upper Cretaceous
Quadrant Sandstone (PNq)	Weed 1896	Type locality: bluff encircling Quadrant Mountain in southern Gallatin Range	Pennsylvanian
Bighorn Dolomite (Ob)	Ruppel 1972	Reference section: Three Rivers Peak, at the head of the Gallatin River	Ordovician

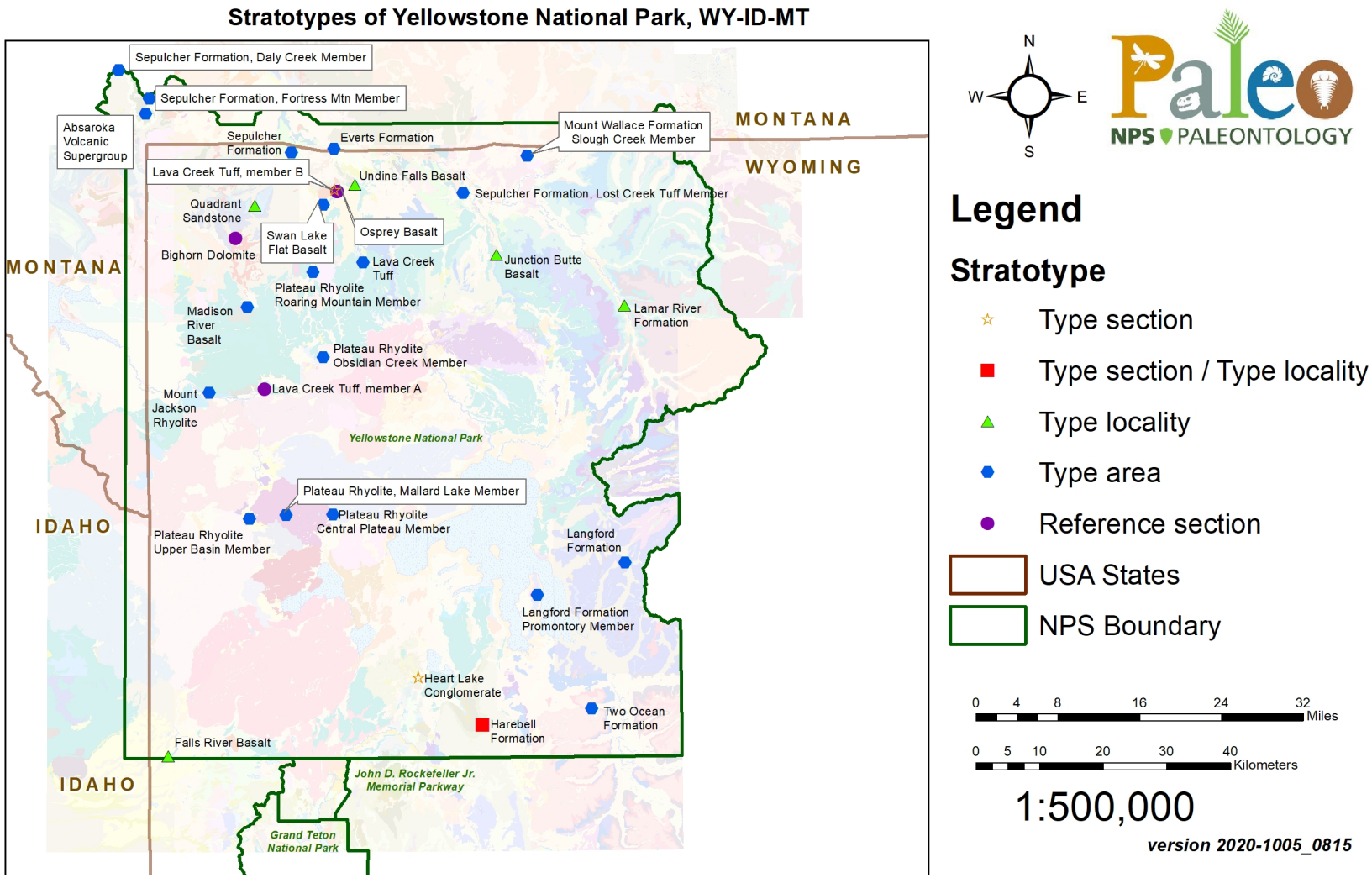


Figure 24. Modified geologic map of YELL showing stratotype locations. The transparency of geologic units has been increased.

The oldest stratotype unit for YELL is the Ordovician Bighorn Dolomite. Originally named by Darton (1904) after exposures in the Bighorn Mountains, the formation is described as a massive, light-brownish-gray dolomite that weathers pale yellowish brown to light gray and has a distinctive irregular or pitted surface (Figure 25; Darton 1904; Ruppel 1972). Texturally, the dolomite is very fine- to fine-grained, partly laminated, and contains light gray to yellowish-orange chert lenses that are as much as 3 cm (0.1 ft) thick and 1.5 m (5 ft) long (Ruppel 1972). Ruppel (1972) designated the reference section after 30.5 m (100 ft)-thick exposures on Three Rivers Peak at the head of the Gallatin River (Figure 24).

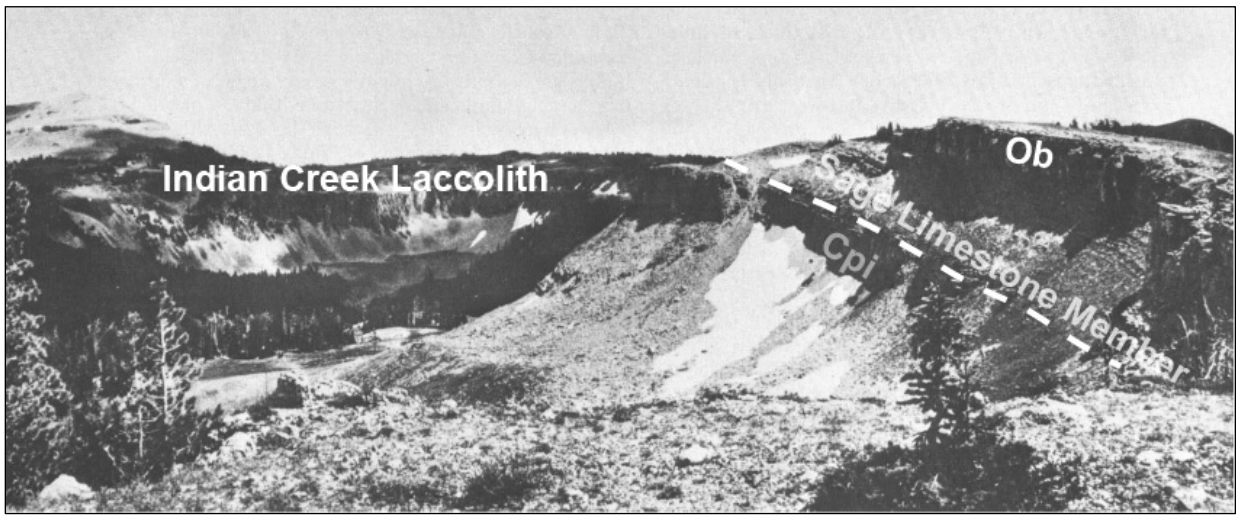


Figure 25. View southward from Bighorn Pass, Gallatin Range. On right, lower cliff is Cambrian Pilgrim Limestone (Cpi); middle platy beds are Cambrian Sage Limestone Member of Snowy Range Formation; upper cliff is Ordovician Bighorn Dolomite (Ob). Cliffs in cirque headwall (center left) are part of Indian Creek laccolith. Figure modified from Ruppel (1972).

The Pennsylvanian Quadrant Sandstone was originally named by Peale (1893) from the Quadrant Mountains in the Gallatin Range in the northwest corner of YELL, Wyoming. The unit is described as consisting of brown, cross-bedded sandstone and white, yellowish, and occasionally pink beds of quartzite, with intercalated beds of drab saccharoidal limestones (Weed 1896; Sando et al. 1985). The type locality is designated in the Quadrant Mountains where the formation averages 122 m (400 ft) thick and forms a picturesque bluff encircling the mountain (Figure 24; Weed 1896).

The Upper Cretaceous Everts Formation was first described by Fraser et al. (1969) as the upper Cretaceous strata that overlie the Eagle Sandstone and unconformably underlie the Landslide Creek Formation on Mount Everts southeast of Gardiner. The formation is characterized by interbedded light-colored, fine-grained, lenticular sandstone and medium to light-gray mudstone. Fraser et al. (1969) described the type area as the west half of the northern projection of Mount Everts, where it extends northward about 4 km (2.5 mi) from the Wyoming–Montana border nearly to the Yellowstone River (Figure 24). Type area exposures of the Everts Formation measured on Mount Everts reach a thickness of approximately 381 m (1,250 ft).

The Upper Cretaceous Harebell Formation represents the oldest type section unit of the park and was named after Harebell Creek along the south boundary of YELL. Love (1956) used the name to describe a 1,524 m (5,000 ft) succession of quartzite pebble conglomerate, olive-drab to gray sandstone, drab-colored siltstone, claystone, and shale unconformably overlying older Cretaceous rocks and unconformably overlain by Paleocene and younger Tertiary rocks (Figure 26). The type locality was first described as extending from the head of the Snake River gorge southward over Big Game Ridge, about 3 km (2 mi) east of Mount Hancock, and on across Wolverine Creek to the north base of Pinyon Peak (Love 1956). Love (1973) later designated a type section extending from the Snake River southward along the top of Big Game Ridge (Figures 24 and 27). The basal type section is exposed in the bottom of Snake River Canyon about 1.6 km (1 mi) southwest of Barlow Peak, in southern YELL and the top is exposed at the head of a north-facing cirque wall on the divide between Wolverine and Fox creeks, 5.6 km (3.5 mi) south of the park boundary (Love 1973).

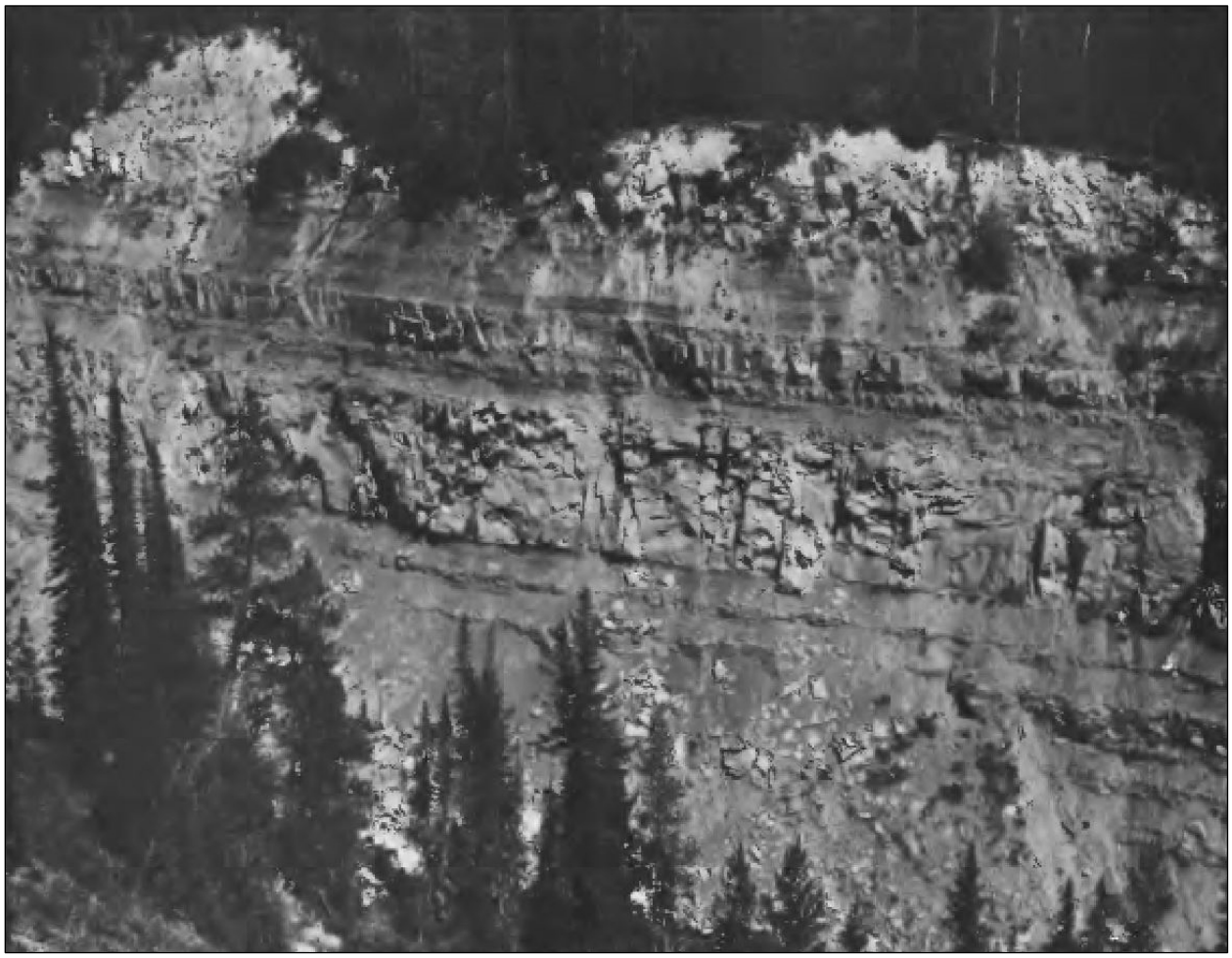


Figure 26. Fine-grained facies in lower part of Harebell Formation, consisting of evenly bedded sandstone, siltstone, shale, and claystone, near Whetstone Falls, Wyoming. Thickness of visible section is about 36.6 m (120 ft). Figure from Love (1973).

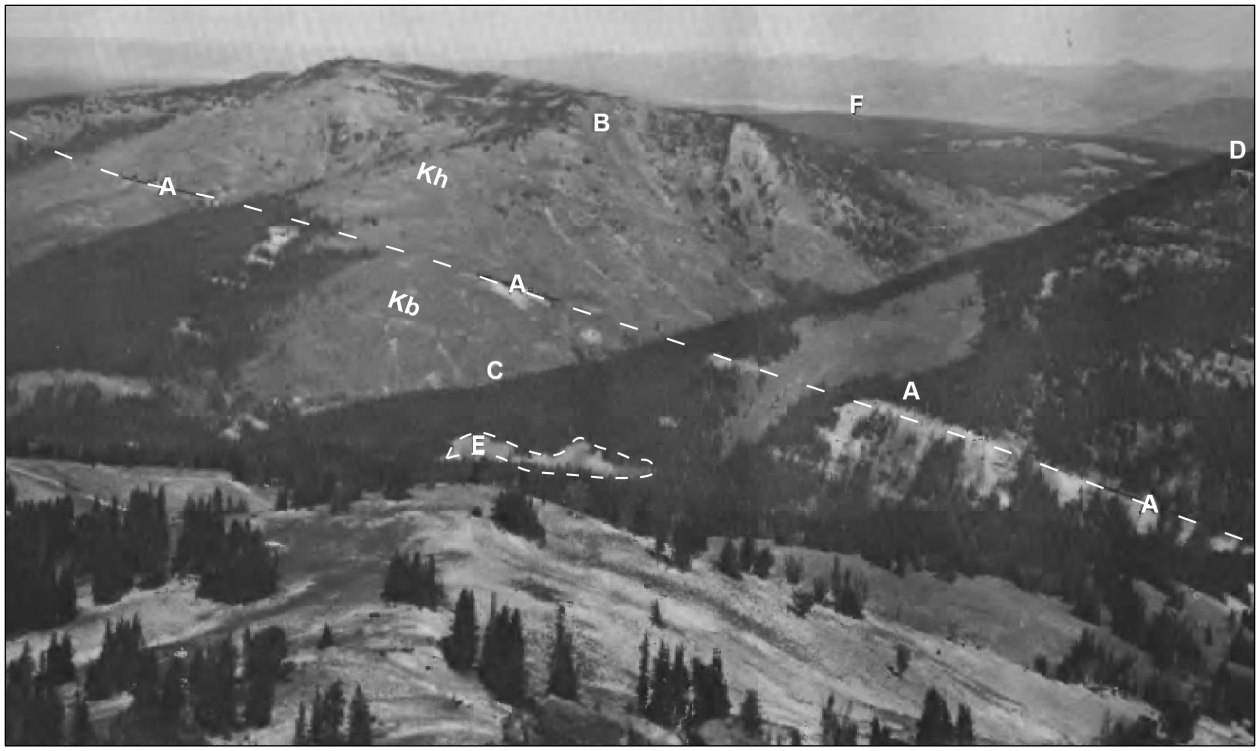


Figure 27. View looking northeast from top of Mount Hancock showing, at extreme right margin, the basal part of the type section of the Harebell Formation. Indicated are the unconformable contact between the Bacon Ridge Sandstone (Kb) and Harebell Formation (Kh) (A), Chicken Ridge and exposure of 914 m (3,000 ft) of Harebell (B), Sickle Creek (C), Barlow Peak and exposure of 823 m (2,700 ft) of Harebell (D), Cody Shale (E), and Southeast Arm of Yellowstone Lake (F). Figure modified from Love (1973).

The Eocene Sepulcher Formation, and the associated Lost Creek, Daly Creek, and Fortress Mountain Members, all occur in northwestern and north-central YELL and were proposed by Smedes and Prostka (1972). The formation is named for the type area of Sepulcher Mountain, where a nearly complete section is exposed in the cliffs on the north face (Figure 24; Smedes and Prostka 1972). Type area exposures are more than 914 m (3,000 ft) thick and consist of coarse alluvial facies that grade upward into vent facies rock (Figure 28; Smedes and Prostka 1972). Andesite lava flows and flow breccias constitute the upper 366 m (1,200 ft) of section.



Figure 28. Thin-bedded, fine-grained alluvial facies volcanic sandstone, siltstone, and air-fall tuff of the Sepulcher Formation found near Quartz Creek, on the west side of Specimen Ridge, YELL. Figure from Smedes and Prostka (1972).

The Lost Creek Tuff Member of the Sepulcher Formation was formally named by Howard (1937) to describe scattered outcrops of buff- to yellow-weathering purple and gray welded tuff found in the Tower Junction area of YELL. The unit is named after typical exposures that occur in the meadow of Lost Creek. Stratigraphically, the Lost Creek Tuff Member overlies the Elk Creek Basalt Member and is overlain by the Daly Creek Member in the vicinities of Sepulcher Mountain and Crescent Hill. The member is characterized as a sequence of yellowish-gray rhyodacite welded ash-flow sheets containing abundant phenocrysts of sanidine, andesine, and biotite with minor amounts of hornblende (Smedes and Prostka 1972). Flattened pumice fragments and bits of charred wood are common (Brown 1961; Smedes and Prostka 1972). The type area is located near Lost Creek, northwest of Tower Junction where exposures are about 107 m (350 ft) thick and thicken westward to a maximum 305 m (1,000 ft) north of Sepulcher Mountain (Figure 24; Smedes and Prostka 1972).

The Daly Creek Member represents the lower part of the Sepulcher Formation in the Bighorn Peak region of the Gallatin Range and is characterized by Smedes and Prostka (1972) as a sequence of light-colored andesitic volcaniclastic strata consisting of vent and alluvial facies. Stratigraphically, the Daly Creek Member unconformably overlies highly deformed rocks of Late Cretaceous or Paleocene age and underlies the Fortress Mountain Member (Smedes and Prostka 1972). The type area is defined as the headwaters region of Daly Creek in the northwest corner of YELL, where the

unit consists of 244 m (800 ft) of vent facies near the mouth of Specimen Creek and grades northward to 122 m (400 ft) of fine-grained alluvial facies on the ridge at the head of Daly Creek (Figure 24; Smedes and Prostka 1972).

Smedes and Prostka (1972) proposed the Fortress Mountain Member after the upper, dark-gray coarse alluvial facies of andesitic volcaniclastic rocks of the Sepulcher Formation. The type area is located at Bighorn Peak, where the member is divided into three informal units that are well-exposed on the south slope (Figure 24; Smedes and Prostka 1972). Exposures in the type area consist of upper and lower dark-gray cliff-forming units of crudely bedded, poorly sorted conglomerate, and a middle unit of light-gray poorly resistant conglomerate with multi-colored clasts in an ashy matrix (Smedes and Prostka 1972). All three informal units contain tuffaceous sandstone, siltstone, and mudstone with an abundant concentration of petrified trees in more than 30 distinct fossil horizons; some trees exceed 1.2 m (4 ft) in diameter and are preserved in their upright growth position (Smedes and Prostka 1972).

The Eocene Lamar River Formation was named after exposures found along the rugged valley walls of the Lamar River and its tributaries (Smedes and Prostka 1972). Sections of the Lamar River Formation found in the valley walls show nearly all of the lithologic variation of the formation, which led Smedes and Prostka (1972) to designate this region the type area (Figure 24). The formation is unconformably overlain by the Langford Formation and unconformably overlies the Sepulcher Formation. The unit is characterized as a sequence of medium-brown andesitic lavas and volcaniclastic rocks with minor mafic lava flows (Smedes and Prostka 1972). The well-bedded coarse alluvial facies volcanic conglomerates, breccias, and tuffs of the Lamar River Formation are known to contain some of the most impressive and best-preserved fossil forests in YELL (Figure 29; Smedes and Prostka 1972). Concentrated in at least 27 horizons, these fossil forests include hundreds of petrified tree trunks, and thousands of fossilized leaves, twigs, needles, cones, and seeds of more than 100 species of plants (Smedes and Prostka 1972).

The Eocene Slough Creek Tuff Member of the Mount Wallace Formation was named by Smedes and Prostka (1972). The unit is exposed in only two areas of the park: 1) in the type area west of Slough Creek 3 km (2 mi) south of the northern YELL boundary (Figure 24); and 2) along Buffalo Creek (Smedes and Prostka 1972). At the type area the unit is approximately 213 m (700 ft) thick and underlies mafic lava flows (Smedes and Prostka 1972). The tuff is characterized as a composite sheet of rhyodacite welded ash-flow tuff. Ash flows of the member contain variable proportions of quartz, sanidine, biotite phenocrysts, as well as abundant basaltic and andesitic fragments of the Mount Wallace Formation (Smedes and Prostka 1972).

The Eocene Langford Formation was named after well-exposed 610 m (2,000 ft)-sections that occur in the type area at Mount Langford (Figure 24; Smedes and Prostka 1972). The Langford Formation overlies the Trout Peak Trachyandesite and is unconformably overlain by the Two Ocean Formation in the east-central region of YELL. Smedes and Prostka (1972) described the unit as a thick section of light-colored andesitic volcaniclastic strata and lava flows of vent and alluvial facies (Figure 30). The Promontory Member of the Langford Formation is named for several eastward-thinning tongues of dark massive volcanic conglomerate and breccia found interbedded with the more typical lighter

colored strata of the Langford Formation (Smedes and Prostka 1972). Well-exposed 183 m (600 ft)-thick sections of the Promontory Member occur in the type area of the Promontory, a peninsula separating the Southeast Arm and South Arm of Yellowstone Lake (Figure 24; Smedes and Prostka 1972).

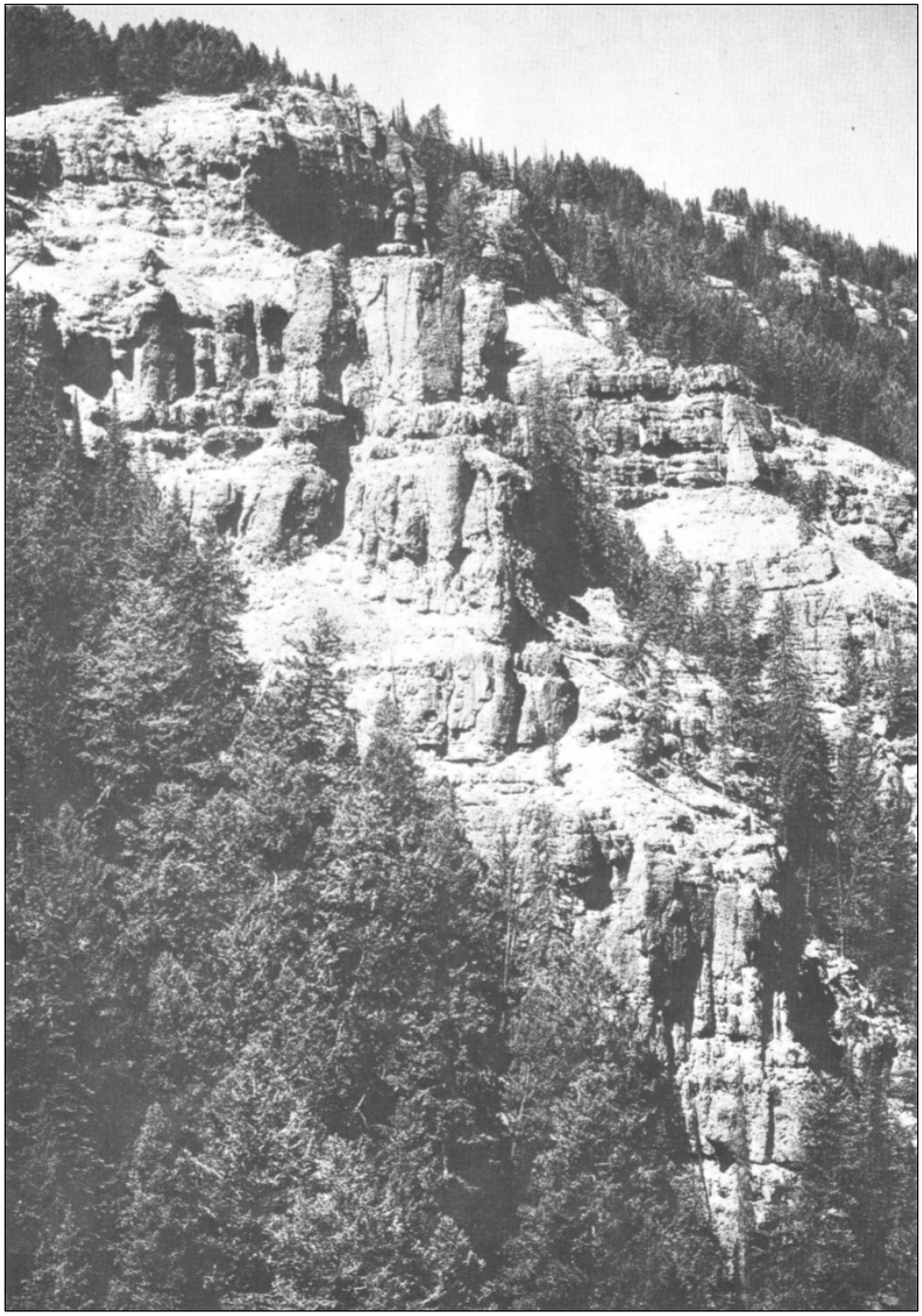


Figure 29. Well-bedded coarse alluvial facies, volcanic conglomerates, sandstones, breccias and air-fall tuff of the Lamar River Formation in the Fossil Forest, along the northeast side of Specimen Ridge, YELL. Figure from Smedes and Prostka (1972).

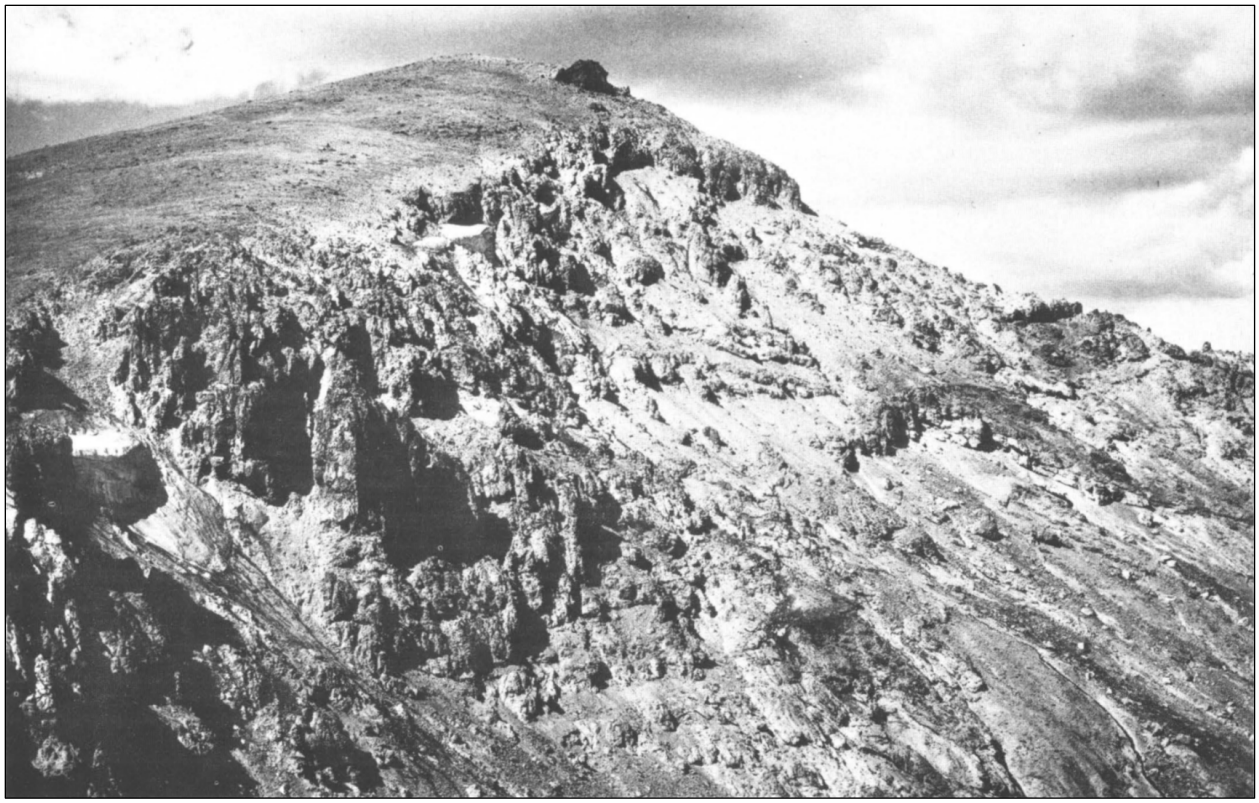


Figure 30. Chaotic, indistinctly bedded vent facies rocks of the Langford Formation, along the east ridge of Plentycoups Peak, YELL. About 152 m (500 ft) of relief is shown. Figure from Smedes and Prostka (1972).

The Eocene Two Ocean Formation was proposed by Smedes and Prostka (1972) for a sequence of dark-colored thick-bedded coarse andesitic volcaniclastic rock of alluvial and vent facies which overlie the Langford Formation in the southeastern park of YELL. Named for the type area designated along the precipitous east edge of Two Ocean Plateau, the exposed sections occur in prominent dark cliffs between the light-colored less resistant Langford Formation below and Wiggins Formation above (Figure 24; Smedes and Prostka 1972). In the Eagle Peak region, the Two Ocean Formation reaches a maximum thickness of approximately 610 m (2,000 ft).

Volcanic rocks of the Absaroka Volcanic Supergroup in the YELL region are of Early, Middle and possibly Late Eocene age and consist of deeply eroded andesitic and basaltic strata (Smedes and Prostka 1972). The name and type area were designated by Smedes and Prostka (1972) after the Absaroka volcanic field of northwestern Wyoming and southwestern Montana (Figure 24).

The Pliocene–Pleistocene age Heart Lake Conglomerate is characterized as a distinctive conglomerate that overlaps Mesozoic rocks and the Pinyon Conglomerate and underlies Pleistocene rhyolitic sequences in the Mount Sheridan area. The conglomerate has distinctive features that include: lithic fragments ranging in size from sand to boulders 0.9 m (3 ft) in diameter, most of which were derived from the Mississippian Madison Limestone; an abundance of waxy talc and chloritic claystone fragments; and an increased abundance of rhyolitic debris in the middle and upper

parts (Love and Keefer 1969). The type section location is described as the east and south slopes of Mount Sheridan, where the strata are exposed on a steep south-facing headwall at the base of the great bare precipitous slope that rises 518 m (1,700 ft) to the top of the mountain (Figures 24 and 31; Love and Keefer 1969). The type section of the Heart Lake Conglomerate is approximately 100 m (330 ft) thick.

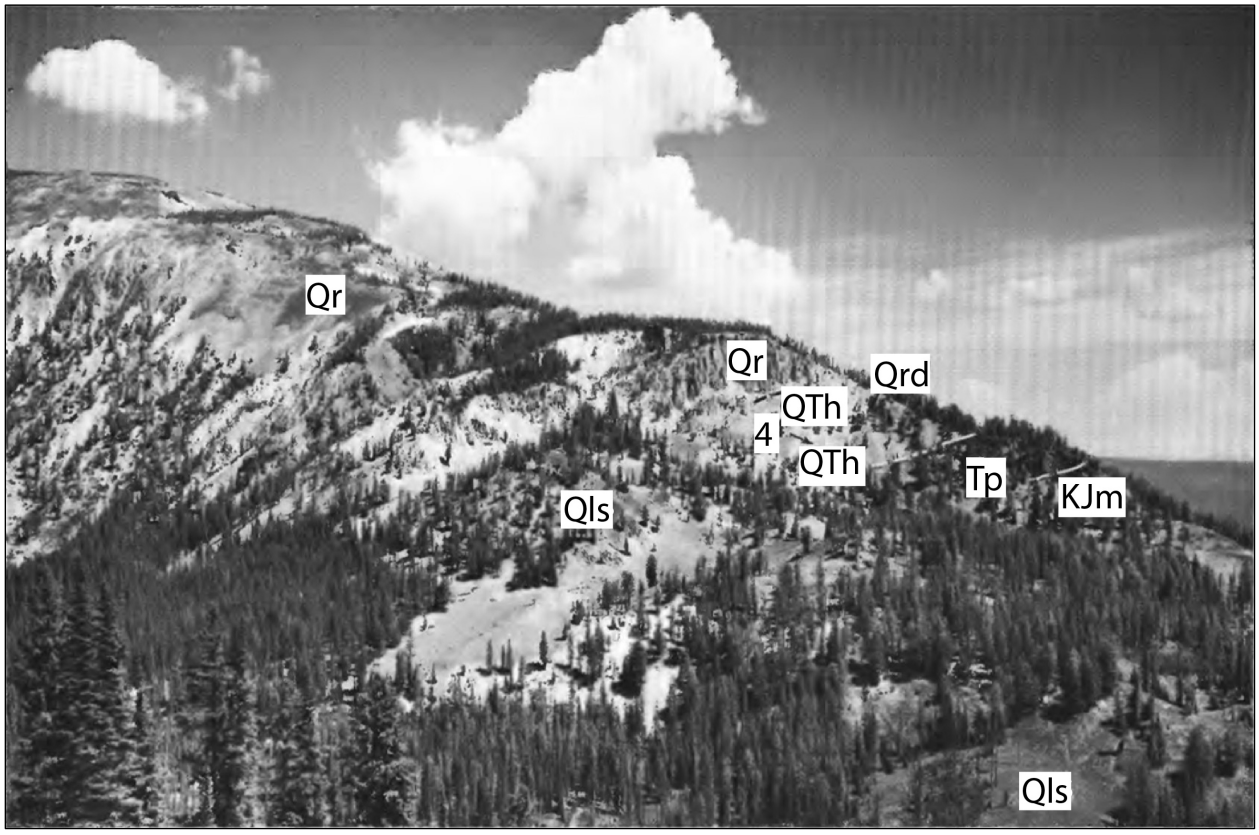


Figure 31. View north across Basin Creek toward the type section of the Heart Lake Conglomerate, YELL. Indicated are the main mass of rhyolite welded tuff (Qr) on Mount Sheridan, the Heart Lake Conglomerate (QTh), marker bed (4) described in measured section of Love and Keefer (1969), Pinyon Conglomerate (Tp), Cloverly and Morrison(?) Formations (KJm), dike of rhyolite mixed with Pinyon Conglomerate (Qrd), and landslide debris (Qls). Figure modified from Love and Keefer (1969).

The Pliocene Junction Butte Basalt was originally named by Howard (1937) after the prominent butte separating the Yellowstone and Lamar rivers. Stratigraphically, the Junction Butte Basalt conformably underlies the Huckleberry Ridge Tuff and is considered the oldest unit associated with the first volcanic cycle of the rhyolite plateau in YELL (Christiansen and Blank 1972; Christiansen 2001). The basalt is characterized as being aphanitic with sparse to abundant phenocrysts of labradorite plagioclase and an abundant olivine groundmass (Christiansen 2001). Although outcrops of Junction Butte Basalt occur in the Yellowstone River valley and on adjacent uplands from Deep Creek to Blacktail Deer Creek and Mount Everts, the type locality is designated as the west side of the Grand Canyon of the Yellowstone opposite the mouth of Deep Creek (Figure 24; Christiansen and Blank 1972). Christiansen and Blank (1972) state that the type locality basalt section is

approximately 90 m (300 ft) thick, consists of three or four thick flows, and is overlain unconformably by the Wapiti Lake flow of the Mount Jackson Rhyolite and by the Lava Creek Tuff. A few kilometers downstream, the Junction Butte Basalt is exposed in the Overhanging Cliff flow, a spectacular roadside cliff north of Tower Creek where the flow is characterized by well-developed two-tiered columnar jointing (Figure 32; Christiansen and Blank 1972; Christiansen 2001).

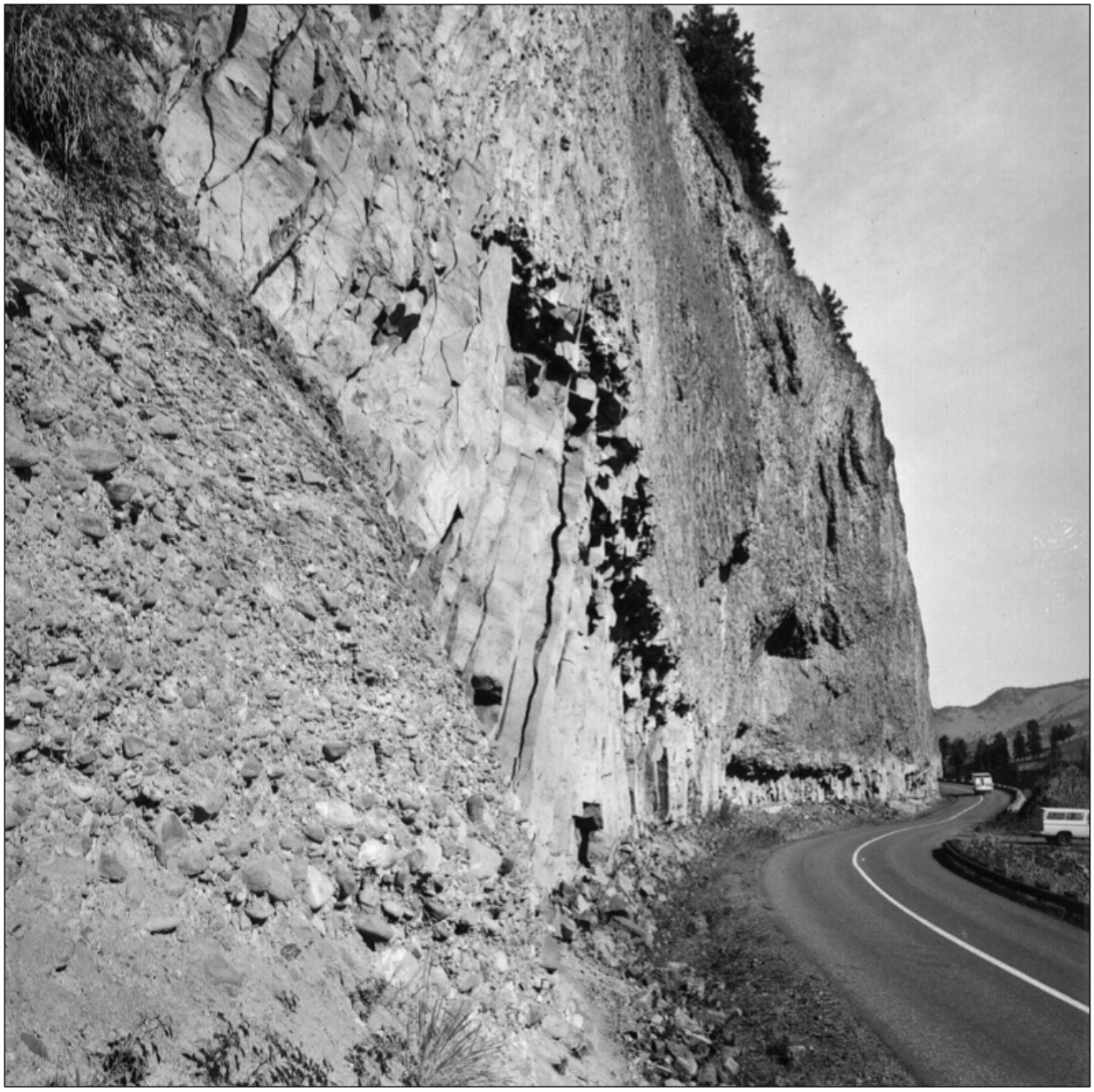


Figure 32. Overhanging Cliff flow of the Junction Butte Basalt located just north of Tower Falls, YELL. Basal columnar jointing is approximately 3 m (10 ft) thick. Figure from Christiansen (2001).

The Pleistocene Mount Jackson Rhyolite was named by Christiansen and Blank (1972) after exposures high in the cliffs forming the north wall of the Madison Canyon 5.5 km (3.4 mi) west of

Madison Junction, YELL. The type area is designated as the Madison Canyon near Mount Jackson (Figure 24; Christiansen and Blank 1972). In the type area the base of the Mount Jackson Rhyolite lava flows are not exposed, but the formation is conformably overlain by the Lava Creek Tuff (Christiansen and Blank 1972). The formation is characterized as consisting of rhyolitic lava flows that are quite varied in appearance, typically containing 30–50% large phenocrysts of quartz, sanidine, plagioclase, and minor opaque oxides and clinopyroxenes (Christiansen and Blank 1972).

The Quaternary Undine Falls Basalt was named by Christiansen and Blank (1972) for the waterfall on Lava Creek near the Mammoth–Tower Junction Road just south of Mount Everts, Yellowstone National Park, Wyoming. The Undine Falls Basalt erupted during the third volcanic cycle of the Yellowstone Plateau and conformably underlies the Lava Creek Tuff and overlies lower Tertiary intrusive dacite and Cretaceous sedimentary rocks (Christiansen and Blank 1972; Christiansen 2001). Christiansen and Blank (1972) designated the type locality as the cliff on the north side of Lava Creek canyon just west of the falls (Figure 24). The type locality basalt section measures 6 m (20 ft) thick and consists of several thin basaltic flows. Flows of the Undine Falls Basalt in and near the type locality originated from unknown vents located north and northwest of the Washburn Range and flowed down deeply eroded valleys that follow the present courses of the Gardner and Yellowstone Rivers (Christiansen 2001).

The Pleistocene Lava Creek Tuff represents the upper ash-flow sheet of the Yellowstone Group that overlies the Huckleberry Ridge Tuff and is overlain by most of the younger units of the third volcanic cycle in and near YELL (Christiansen and Blank 1972). The unit was named by Christiansen and Blank (1972) after the type area in the upper canyon walls of Lava Creek and its tributary, Arrow Creek (Figure 24). Type area exposures overlie the Huckleberry Ridge Tuff and consist of a 210 m (689 ft)-thick section.

Two distinct members of the Lava Creek Tuff, A and B, were described by Christiansen and Blank (1972) and Christiansen (2001). The two members are separated by a zone of strongly jointed but weakly welded crystal ash and have a noticeable difference in the welding-density profile of the tuff, with lower member A representing a less densely welded section than upper member B (Figures 33–35; Christiansen and Blank 1972; Christiansen 2001). Christiansen and Blank (1972) designated the reference section for member A as the south-facing cliff of Purple Mountain above an old gravel pit about 1 km (0.6 mi) east of Madison Junction (Figure 24). The 180 m (590 ft) thick exposures overlie the Mount Jackson Rhyolite, are overlain by member B, and contain conspicuous collapsed pumice and an abundance of rhyolitic lithic inclusions (Christiansen and Blank 1972). The reference section for member B is on the east wall of Sheepeater Canyon on the Gardner River, 1 km (0.6 mi) northeast of Osprey Falls (Figure 24). The well-exposed section is 140 m (459 ft) thick, overlies the Undine Falls Basalt, and is overlain by the Swan Lake Flat Basalt (Christiansen and Blank 1972).

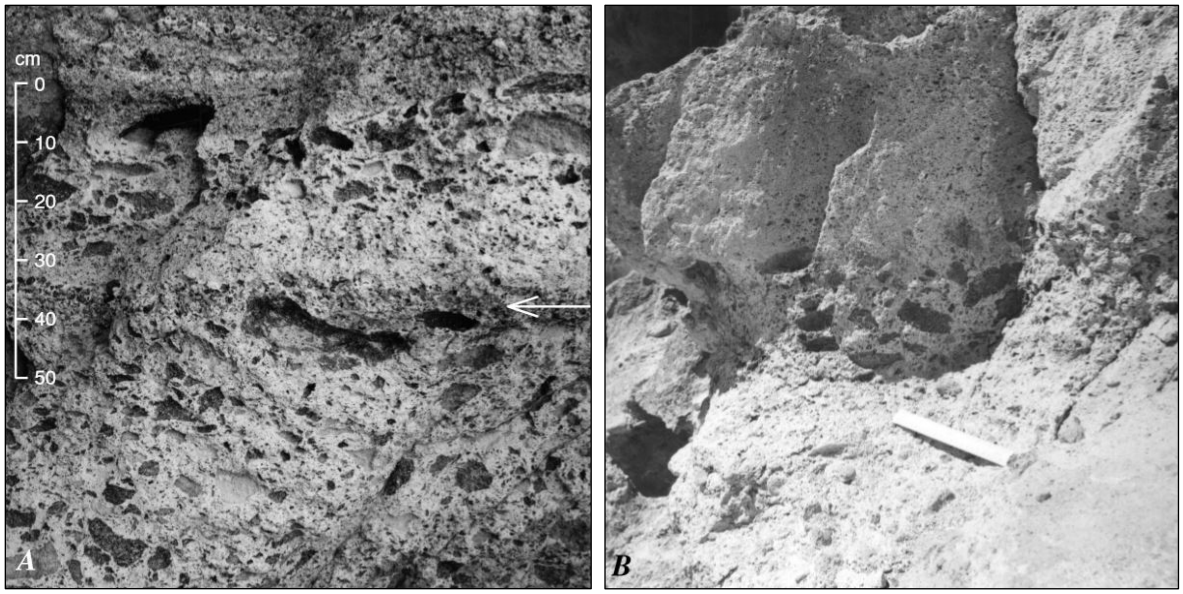


Figure 33. Lava Creek Tuff, at Tuff Cliff, base of Purple Mountain 400 m (1,300 ft) northeast of Madison Junction, YELL. All the tuff has undergone vapor-phase crystallization. A) Two pumice-rich ash flows of lower member A separated by sorted layer (arrow); note fine-grained base of upper ash flow. Additional sorted layers at top. B) Contact between two ash flows, showing abundant large pumice clasts concentrated at top of lower ash flow. Scale is 20 cm (7.9 in). Figure from Christiansen (2001).

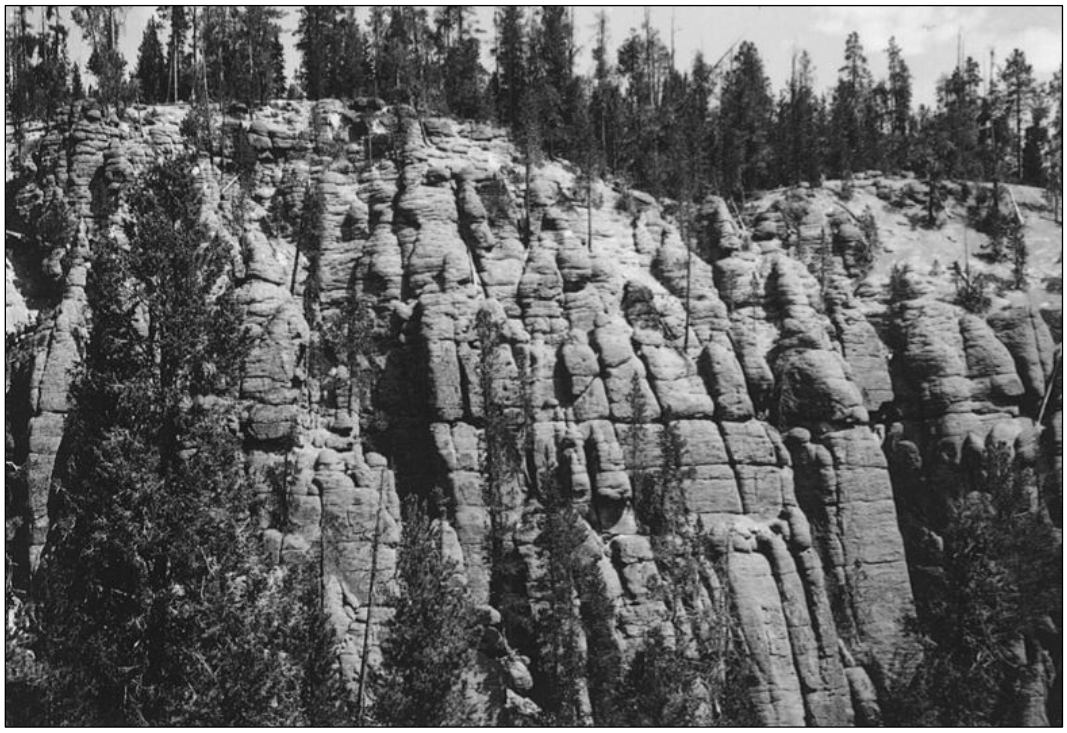


Figure 34. Typical outcrop of upper part of member A, Lava Creek Tuff, on cliffs just south of Monument Geyser Basin, YELL. The upper part of member A characteristically forms steep bluffs with large rounded joint columns. Figure from Christiansen (2001).



Figure 35. Basal fallout ash of member B, Lava Creek Tuff, showing sharp contact between finer-grained part below and coarser-grained part above. Grand Canyon of the Yellowstone, 1.5 km (0.9 mi) southeast of Tower Falls, YELL. Scale is 20 cm (7.9 in). Figure from Christiansen (2001).

The Pleistocene Swan Lake Flat Basalt was introduced by Christiansen and Blank (1972) to describe basalts younger than the Lava Creek Tuff but older than an unconformity that represents the first major period of canyon cutting into the Lava Creek in the area north of Obsidian Cliff, YELL. Christiansen and Blank (1972) named the unit after a valley partly surrounded and largely underlain by lavas about 8 km (5 mi) southwest of Mammoth. The type area of the Swan Lake Flat Basalt is designated as the Sheepeater Cliffs, on the east side of the canyon of the Gardner River southeast of Bunsen Peak (Figure 24; Christiansen and Blank 1972). Exposures in the type area are from the lower part of the sequence and conformably overlie the Lava Creek Tuff and are locally overlain by flows of the Plateau Rhyolite (Christiansen and Blank 1972; Christiansen 2001).

The Pleistocene Falls River Basalt was originally described by Christiansen and Blank (1972) to include all basalts younger than the Lava Creek Tuff and older than the Central Plateau Member of the Plateau Rhyolite in the southwest corner of YELL. The unit takes its name from the Falls River that drains the nearby area. The Falls River Basalt is characterized as a moderate gray basalt that forms dense, thin flows with vesicular tops (Christiansen and Blank 1972). Lithologically, the basalts contain sparse phenocrysts of plagioclase approximately 0.5–1.0 cm (0.2–0.4 in) in diameter. The type locality is designated as the west rim of the valley of Falls River just below Cave Falls, where

the basalt exposures conformably overlie the Lava Creek Tuff and are overlain by upper Pleistocene glacial deposits (Figure 24; Christiansen and Blank 1972).

The Pleistocene Upper Basin Member of the Plateau Rhyolite was defined by Christiansen and Blank (1972) to include early post-caldera rhyolitic lava flows and associated pyroclastic deposits that erupted within the Yellowstone caldera after resurgent doming. Christiansen and Blank (1972) named the member after its type area in the Upper Geyser Basin of YELL, where outcrops of the unit are widely distributed among the sediments and hydrothermal deposits that blanket the floor of the basin (Figure 24). Lava flows of the Upper Basin Member in the type area overlie the Mallard Lake Member and underlie the Central Plateau Member of the Plateau Rhyolite (Christiansen and Blank 1972). The member is characterized by abundant plagioclase phenocrysts, commonly containing oligoclase that is highly embayed (Christiansen and Blank 1972).

The Pleistocene-age Obsidian Creek Member of the Plateau Rhyolite was named by Christiansen and Blank (1972) for a series of isolated, extracaldera rhyolitic lava flows and domes located along Obsidian Creek, YELL. The type area consists of the mixed lavas of Gardner River and Grizzly Lake, as well as the eruptive domes of Paintpot Hill, Willow Park, Apollinaris Spring, Landmark, Gibbon Hill, and Geyser Creek (Figure 24; Christiansen and Blank 1972). The mixed lavas and domes occur in a north-trending belt that parallels Obsidian Creek between the Norris Geyser Basin area and the Gardner River (Christiansen and Blank 1972).

The Pleistocene Roaring Mountain Member of the Plateau Rhyolite was designated by Christiansen and Blank (1972) for four, isolated rhyolitic lava flows north of Yellowstone caldera near Roaring Mountain, YELL. The member consists of the Crystal Spring, Obsidian Cliff, Cougar Creek, and Riverside flows, which Christiansen and Blank (1972) designated as the type area (Figure 24). The lava flows of the Roaring Mountain Member are characterized as phenocryst-free or phenocryst-poor rhyolitic lava flows which contain abundant, fresh black obsidian as well as crystallized and partly crystallized material (Christiansen and Blank 1972).

The Pleistocene Madison River Basalt was designated by Christiansen and Blank (1972) to describe scattered patches of post-Lava Creek basalts that occur in the area south and west of the Gallatin Range near West Yellowstone. The type area is located in the basalt-covered uplands west of the south end of the Gallatin Range, south of upper Maple Creek (Figure 24; Christiansen and Blank 1972). Type area exposures lie on an eroded surface on the Lava Creek Tuff and are deeply mantled by upper Pleistocene glacial deposits and till of Bull Lake age (Christiansen and Blank 1972).

The Pleistocene Mallard Lake Member of the Plateau Rhyolite was defined by Christiansen and Blank (1972) and consists of a single rhyolitic lava flow (the Mallard Lake flow) that is approximately 120 m (390 ft) thick. The unit is named after the type area around Mallard Lake, a small lake about 5 km (3 mi) northeast of Old Faithful geyser (Figure 24; Christiansen and Blank 1972). A complex, northwest-trending graben system has uplifted and faulted the rhyolitic flow on the resurgent Mallard Lake dome (Christiansen and Blank 1972; Christiansen 2001). Christiansen and Blank (1972) report that the base of the Mallard Lake Member is obscure in outcrop and no complete sections are exposed.

The Pleistocene Osprey Basalt was named by Pierce et al. (1970) after Osprey Falls and described as a sequence of interlayered basalts and gravels which fill or partly fill the paleotopography cut in, or through both the upper part of the Yellowstone Tuff and conformably overlying basalts in the northern region of YELL. Christiansen and Blank (1972) redefined the Osprey Basalt to include basalts and interlayered gravels that are younger than the Swan Lake Flat Basalt and Lava Creek Tuff. The type section of the formation is described as the cliff exposure on the west side of Sheepeater Canyon, 975 m (3,200 ft) almost due north of Osprey Falls and just east of the closest approach in this vicinity of the Bunsen Peak Road to the rim of the canyon (Figure 24; Pierce et al. 1970). The type section exposure is approximately 61 m (200 ft) thick and consists of six flows of columnar-jointed basalt, several of which are separated by as much as 6 m (20 ft) of gravel in the lower part of the section (Pierce et al. 1970). The type section basalt rests above an eroded Eocene intrusive body which forms Bunsen Peak (Pierce et al. 1970).

The Pleistocene Central Plateau Member of the Plateau Rhyolite was named by Christiansen and Blank (1972) after the type area designation of the Central Plateau, located in the middle of the Yellowstone Caldera (Figure 24). Lava flows of the member form the Madison, Pitchstone, Central, and Solfatara plateaus, constituting the greatest portion of the total volume of the Plateau Rhyolite (Christiansen and Blank 1972). Eighteen separate lava flows have been mapped as parts of the member, with some flows measured at over 300 m (984 ft) thick. The flows are described as containing abundant phenocrysts, generally consisting of quartz and sanidine with no plagioclase (Christiansen and Blank 1972).

In addition to the designated stratotypes located within YELL boundaries, a list of stratotypes located within 48 km (30 mi) of park boundaries is included here for reference. These nearby stratotypes include the Cambrian Snowy Range Formation (type locality); Permian Shedhorn Sandstone (type section); Paleocene–Eocene Pinyon Conglomerate (reference section); Eocene-age units of the Wapiti Formation (type section), Cathedral Cliffs Formation (type section), Hyalite Peak Volcanics (reference section), Mount Wallace Formation (type area), and Trout Peak Trachyandesite Pacific Creek Tuff Member (type area); and Pleistocene-age units of the Gerrit Basalt (type area) and Island Park Rhyolite Mesa Falls Tuff Member (type section & reference section).

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 GRYN Geologic Type Section Inventory report is finalized, the NPS Geologic Resources Division will schedule a briefing for the staff of the GRYN network and respective network parks.

3) 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.

4) The NPS Geologic Resources Division should work with park and network staff, the U.S. Geological Survey, state geological surveys, academic geologists, and other partners to formally assess potential new stratotypes as to their significance (international, national, or state-wide), based on lithology, stratigraphy, fossils or notable features using procedural code outlined by the North American Commission on Stratigraphic Nomenclature.

5) 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.

6) 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.

7) The NPS Geologic Resources Division should ensure the park-specific Geologic Type Section Inventory Reports are widely distributed and available online.

8) 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.

9) 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.

10) 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.

11) 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).

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Appendix A: Source Information for GRI Maps of GRYN Parks

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YELL

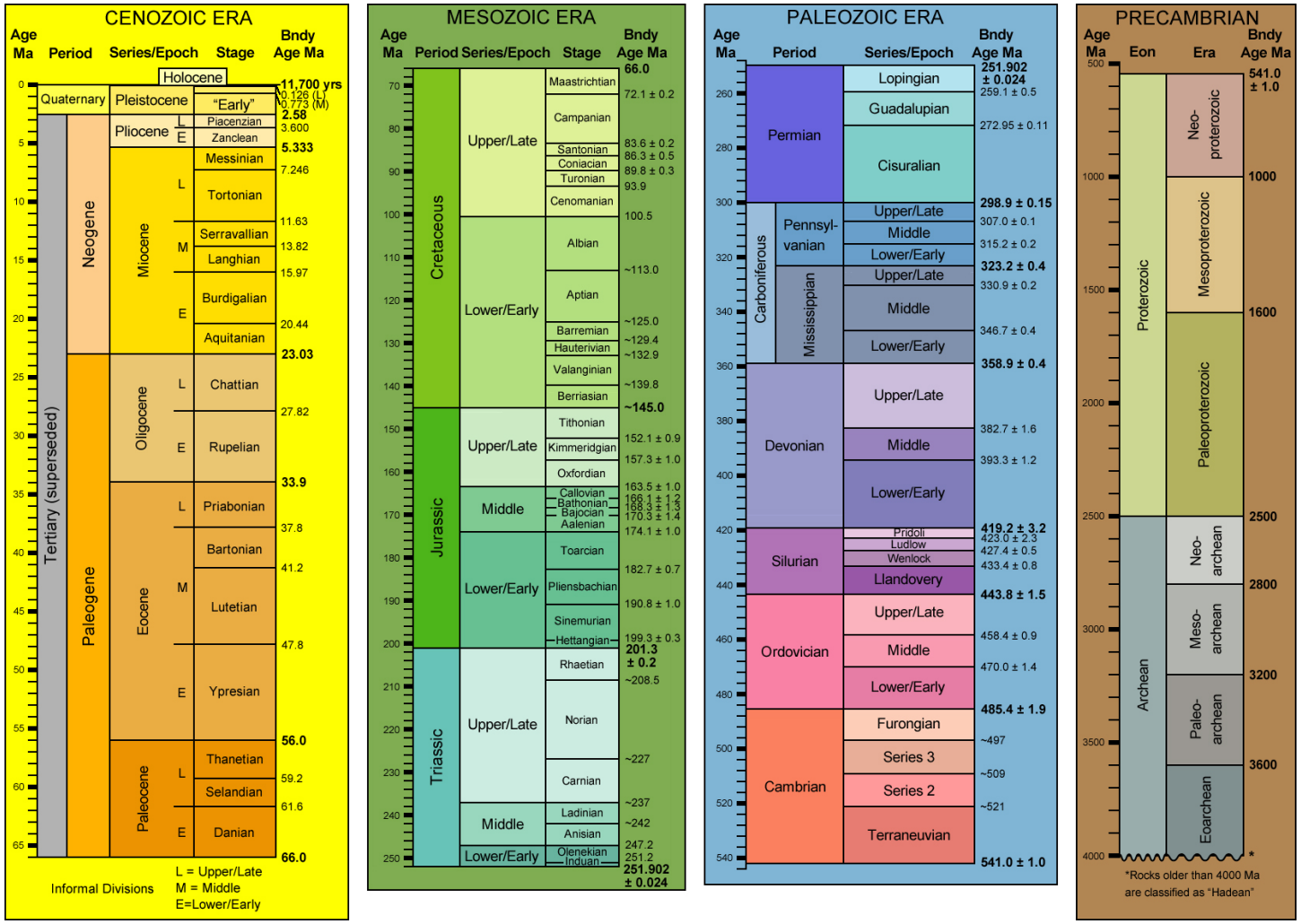
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Appendix B: Geologic Time Scale



Ma=Millions of years old. **Bndy Age**=Boundary Age. Modified from 1999 Geological Society of America Time Scale (https://www.geosociety.org/documents/gsa/timescale/timescl-1999.pdf). Dates and additional information from International Commission on Stratigraphy update 2019/05 (https://stratigraphy.org/chart) and USGS Fact Sheet 2007-3015 (https://pubs.usgs.gov/fs/2007/3015/).

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

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