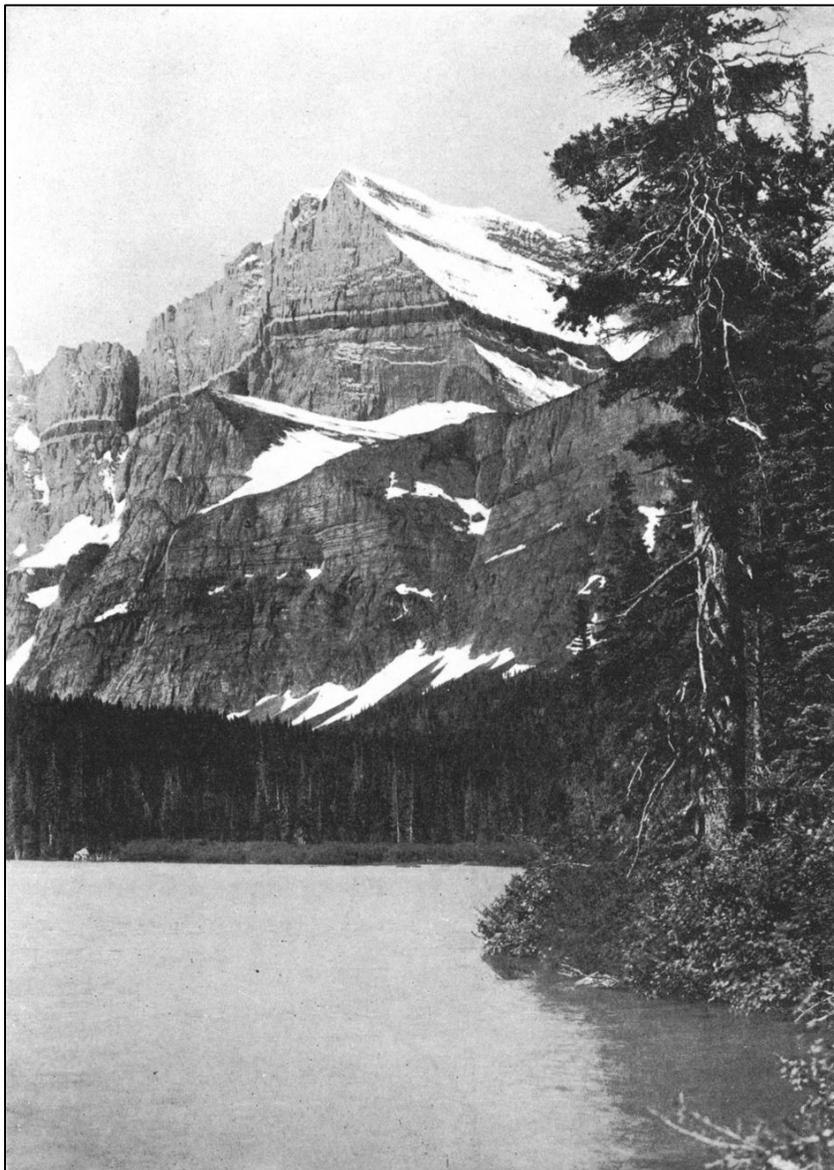




# National Park Service Geologic Type Section Inventory

## *Rocky Mountain Inventory & Monitoring Network*

Natural Resource Report NPS/ROMN/NRR—2020/2215



**ON THE COVER**

Southwest view of Mount Gould from the south fork of Swiftcurrent Lake, Glacier National Park. The upper cliffs are comprised of the Helena and Empire Formations, with lower cliffs consisting of the Grinnell Formation; dark band consists of intrusive diorite. Plate 46 from Willis (1902).

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

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

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# Contents

	Page
Figures.....	v
Tables.....	vii
Photographs.....	vii
Executive Summary .....	ix
Acknowledgments.....	xi
Dedication .....	xiii
Introduction.....	1
Geology and Stratigraphy of the Rocky Mountain I&M Network Parks .....	3
Precambrian.....	4
Paleozoic .....	5
Mesozoic .....	5
Cenozoic.....	5
National Park Service Geologic Resource Inventory .....	7
GRI Products .....	7
Geologic Map Data.....	8
Geologic Maps.....	8
Source Maps .....	8
GRI GIS Data .....	8
GRI Map Posters .....	9
Use Constraints.....	9
Methods.....	11
Methodology.....	11
Definitions .....	16
Florissant Fossil Beds National Monument (FLFO).....	17
Glacier National Park (GLAC) .....	21
Grant-Kohrs Ranch National Historic Site (GRKO) .....	39

# Contents (continued)

	Page
Great Sand Dunes National Park and Preserve (GRSA).....	43
Little Bighorn Battlefield National Monument (LIBI) .....	47
Rocky Mountain National Park (ROMO).....	51
Recommendations.....	57
Literature Cited .....	59
Appendix A: Source Information for GRI Maps of ROMN Parks .....	63
Appendix B: Geologic Time Scale .....	65

# Figures

	Page
<b>Figure 1.</b> Map of Rocky Mountain Network parks, including: Florissant Fossil Beds National Monument (FLFO), Glacier National Park (GLAC), Grant-Kohrs Ranch National Historic Site (GRKO), Great Sand Dunes National Park and Preserve (GRSA), Little Bighorn Battlefield National Monument (LIBI), and Rocky Mountain National Park (ROMO) (NPS).....	4
<b>Figure 2.</b> Screenshot of digital geologic map of Glacier National Park showing mapped units.....	12
<b>Figure 3.</b> GEOLEX search result for the Mount Shields Formation.....	13
<b>Figure 4.</b> Stratotype inventory spreadsheet of the ROMN displaying attributes appropriate for geolocation assessment. ....	15
<b>Figure 5.</b> Park map of FLFO, Colorado (NPS).....	17
<b>Figure 6.</b> Geologic map of FLFO, Colorado.....	19
<b>Figure 7.</b> Park map of GLAC, Montana (NPS).....	22
<b>Figure 8.</b> Geologic map of GLAC, Montana. ....	23
<b>Figure 9.</b> Modified geologic map of GLAC showing stratotype locations.....	25
<b>Figure 10.</b> Type locality exposures of the Altyn Formation in the lower slopes of Appekunny Mountain, northeast of Many Glacier Hotel, GLAC.....	26
<b>Figure 11.</b> Northwest view of Singleshot Mountain, GLAC; type locality of the Singleshot Member of the Appekunny Formation (Annotated USGS photo). ....	27
<b>Figure 12.</b> Southwest view of Appistoki Peak, GLAC, consisting entirely of the Appekunny Formation and the type locality exposures of the Appistoki Peak Member (USGS photo).....	28
<b>Figure 13.</b> View of Mount Gould from the south fork of Swiftcurrent Lake, looking southwest, GLAC.....	29
<b>Figure 14.</b> Grinnell Formation in GLAC. ....	29
<b>Figure 15.</b> Type locality exposures of the Piegan Group of the Belt Supergroup, Piegan Mountain, GLAC. ....	31
<b>Figure 16.</b> Rocks of the Helena Formation. ....	32
<b>Figure 17.</b> Spur of Mount Cleveland, GLAC, consisting entirely of the Helena Formation and type locality exposures of the Goathaunt Member.....	33

## Figures (continued)

	Page
<b>Figure 18.</b> Upper surfaces of two large colonies of <i>Collenia</i> sp. from the Granite Park Member of the Helena Formation, Hole-in-the-Wall cirque, GLAC.....	34
<b>Figure 19.</b> Hole-in-the-Wall basin, looking west at location of the Snowslip Formation reference section, GLAC. ....	35
<b>Figure 20.</b> Rhythmic, fining-upward sequences in member 5 of the Snowslip Formation reference section located at Hole-in-the-Wall basin, GLAC. ....	36
<b>Figure 21.</b> Regional map of GRKO, Montana (NPS). ....	40
<b>Figure 22.</b> Geologic map of GRKO, Montana. ....	41
<b>Figure 23.</b> Park map of GRSA, Colorado (NPS). ....	44
<b>Figure 24.</b> Geologic map of GRSA, Colorado. ....	45
<b>Figure 25.</b> Park map of LIBI, Montana (NPS). ....	47
<b>Figure 26.</b> Geologic map of LIBI, Montana. ....	49
<b>Figure 27.</b> Park map of ROMO, Colorado (NPS). ....	52
<b>Figure 28.</b> Geologic map of ROMO, Colorado. ....	53
<b>Figure 29.</b> Modified geologic map of ROMO showing stratotype locations. ....	55
<b>Figure 30.</b> View west from Tanina Peak of Fourth, Spirit, and Verna Lakes, scoured by ice in bedrock of the upper canyon of East Inlet. ....	56

## Tables

	Page
<b>Table 1.</b> List of GLAC stratotype units sorted by age with associated reference publications and locations.....	24
<b>Table 2.</b> List of ROMO stratotype units sorted by age with associated reference publications and locations.....	54

## Photographs

	Page
Joe Gregson, retired NPS geologist standing next to Precambrian stromatolites at Glacier National Park (JOE GREGSON).....	xiii



## Executive Summary

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

There are several different categories of geologic or stratigraphic units (supergroup, group, formation, member, bed) which represent a hierarchical system of classification. The mapping of stratigraphic units involves the evaluation of lithologies, bedding properties, thickness, geographic distribution, and other factors. If a new mappable geologic unit is identified, it may be described and named through a rigorously defined process that is standardized and codified by the professional geologic community (North American Commission on Stratigraphic Nomenclature 2005). In most instances when a new geologic unit such as a formation is described and named in the scientific literature, a specific and well-exposed section of the unit is designated as the type section or type locality (see Definitions). The type section is an important reference section for a named geologic unit which presents a relatively complete and representative profile for this unit. The type or reference section is important both historically and scientifically, and should be recorded such that other researchers may evaluate it in the future. Therefore, this inventory of geologic type sections in NPS areas is an important effort in documenting these locations in order that NPS staff recognize and protect these areas for future studies.

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

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

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

The goal of this project is to consolidate information pertaining to geologic type sections which occur within NPS-administered areas, in order that this information is available throughout the NPS to inform park managers and to promote the preservation and protection of these important geologic landmarks and geologic heritage resources. The review of stratotype occurrences for the ROMN shows there are currently no designated stratotypes for Florissant Fossil Beds National Monument (FLFO), Grant-Kohrs Ranch National Historic Site (GRKO), Great Sand Dunes National Park and Preserve (GRSA), and Little Bighorn Battlefield National Monument (LIBI); Glacier National Park (GLAC) has two type sections, fourteen type localities, and one reference section; and Rocky Mountain National Park (ROMO) has one lithodeme reference locality.

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

## Acknowledgments

Many individuals were consulted in the preparation of this report on the geologic type sections for the national parks of the Rocky Mountain Inventory & Monitoring Network. We first want to extend our sincere appreciation to Randy Orndorff, Nancy Stamm and David Soller (U.S. Geological Survey) for their assistance with this geologic type section inventory and other important NPS projects. Randy, Nancy and David manage the National Geologic Map Database for the United States (NGMDB, [https://ngmdb.usgs.gov/ngmdb/ngmdb\\_home.html](https://ngmdb.usgs.gov/ngmdb/ngmdb_home.html)) and the U.S. Geologic Names Lexicon (“GEOLEX”, <https://ngmdb.usgs.gov/Geolex/search>), critical sources of geologic map information for science, industry and the American public. We also extend our appreciation to Katie McDonald (Montana Bureau of Mines and Geology) and Matthew Morgan (Colorado School of Mines).

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.

Thanks to our NPS colleagues in the Rocky Mountain Inventory & Monitoring Network and various network parks including: Erin Borgman, Paula Capece, Sonya Daw; Kristin Long, Billy Schweiger, and Kirk Sherrill (ROMN); Therese Johnson, Seth Maile, and Herb Meyer (FLFO); Mark Biel, Tara Carolin, and Richard Menicke (GLAC); Jason E. Smith (GRKO); Fred Bunch and Andrew Valdez (GRSA); Marian Doane and James Yelton (LIBI); and Chris Clatterbuck, Scott Esser, and Koren Nydick (ROMO). Additional thanks to Michael Bozek, Brendan Moynahan, and Don Weeks for continued support for this and other important geology projects in the Intermountain Region of the NPS.

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## Dedication

This Rocky Mountain Inventory & Monitoring Network Geologic Type Section Inventory is dedicated to Joe Gregson, retired geologist in the National Park Service Inventory & Monitoring Program. Joe was instrumental in ensuring that geologic mapping, geologic resource inventories, and GIS were part of the original twelve natural resource inventories undertaken by the NPS. The parks and the NPS Geologic Resources Division continue to benefit from Joe's important and foundational work.



Joe Gregson, retired NPS geologist standing next to Precambrian stromatolites at Glacier National Park (JOE GREGSON).



## 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 I&M 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 (1) systematically report the assigned stratotypes that occur within national park boundaries, (2) provide detailed descriptions of the stratotype exposures and their locations, and (3) reference the stratotype assignments from published literature. It is important to note that this project cannot verify a stratotype for a geologic unit if one has not been formally assigned and/or published. Additionally, numerous stratotypes are located geographically outside of national park boundaries, but only those within 48 km (30 mi) of park boundaries will be presented in this report.

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

This inventory fills a current void in basic geologic information not currently compiled by the NPS 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 whether a particular type section is geographically located within or outside NPS administered boundaries. Below are the primary considerations that warrant this inventory of NPS geologic type sections.

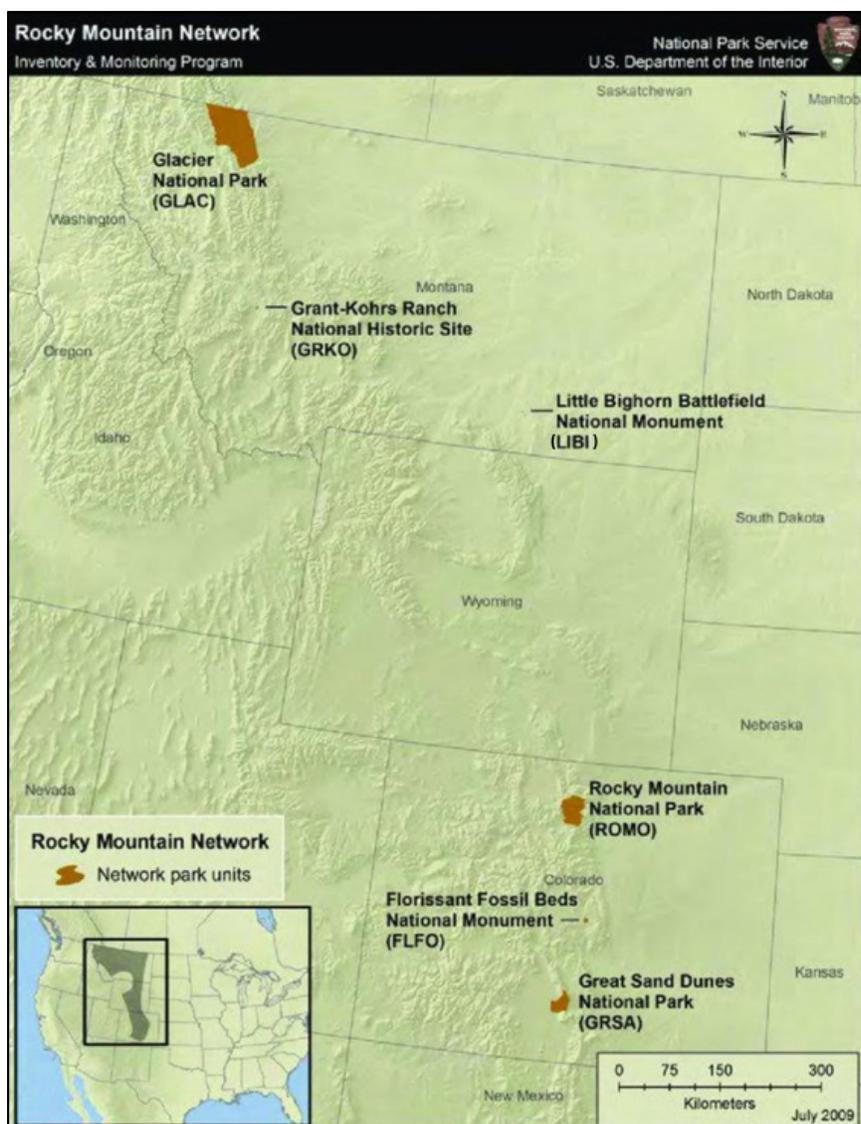
- Geologic type sections are a part of our national geologic heritage and are a cornerstone of the scientific value used to define the societal significance of geoheritage sites (<https://www.nps.gov/articles/scientific-value.htm>);
- Geologic type sections are important geologic landmarks and reference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

The Rocky Mountain Inventory & Monitoring Network (ROMN) consists of six parks located within the central and northern Rocky Mountain region of the United States in the states of Colorado and Montana (Figure 1). Glacier National Park (GLAC) is the northernmost of the network parks and lies along the U.S.–Canadian international border and incorporates the Lewis and Livingston ranges. Florissant Fossil Beds National Monument (FLFO) and Rocky Mountain National Park (ROMO) are associated with the Front Range in Colorado. Great Sand Dunes National Park and Preserve (GRSA) is part of the Sangre de Cristo Range, also in Colorado. The Continental Divide is a prominent feature which extends along the Rocky Mountain Cordillera within Glacier National Park and Rocky Mountain National Park. Florissant Fossil Beds National Monument, Great Sand Dunes National Park and Preserve, and Little Bighorn Battlefield National Monument (LIBI) all are located on the plains east of the Continental Divide, while Grant-Kohrs Ranch National Historic Site (GRKO) is located just west of the divide. The highest point of elevation in the Rocky Mountain I&M Network is 4,346 m (14,259 ft) above sea level on top of Longs Peak within ROMO. The lowest point of elevation is 933 m (3,061 ft) above sea level at LIBI.

Geologically, the parks of the Rocky Mountain I&M network are diverse and heavily influenced by orogenic (mountain-building) events, exhibiting varying degrees of metamorphism, deformation, overthrusting, folding and faulting. The geology of GLAC consists predominantly of Mesoproterozoic-age metasedimentary rocks that have undergone low-grade metamorphism. ROMO is dominated by granite intrusions and metamorphic rock complexes that have been highly deformed. The bedrock of the other network parks consists of sedimentary deposits shed from uplifted mountains into intermountain basins or along the flanks of the mountain ranges. Past and present glacial activity defines the landscape and associated ecosystems in both GLAC and ROMO.

This network of parks includes a broad range of climatic zones, habitat types, elevation profiles, and encompasses great biological and geological diversity. These parks 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 Rocky Mountain Network parks, including: Florissant Fossil Beds National Monument (FLFO), Glacier National Park (GLAC), Grant-Kohrs Ranch National Historic Site (GRKO), Great Sand Dunes National Park and Preserve (GRSA), Little Bighorn Battlefield National Monument (LIBI), and Rocky Mountain National Park (ROMO) (NPS).

## Precambrian

Precambrian basement rocks are the foundation for the three ROMN parks in Colorado (see Appendix B for a geologic time scale). The Pikes Peak Granite (Mesoproterozoic) underlies the fossiliferous Eocene formations at FLFO. Surrounding the intermountain basin of GRSA are metamorphic gneiss (Paleoproterozoic) and intrusive igneous quartz monzonite (Paleoproterozoic and Mesoproterozoic) forming a barrier to the famous wind-blown sands accumulated into great 230 m (750 ft) high dunes. The alpine landscape of ROMO is dominated by massive igneous and metamorphic complexes (Paleoproterozoic and Mesoproterozoic) with dozens of peaks standing above 3,657 m (12,000 ft) above sea level. One of the more notable Precambrian units in ROMO is

the 1.664 billion-year-old Boulder Creek batholith. This massive igneous body was one of a series of intrusives which served as a heat source for regional metamorphism.

The most extensive Precambrian record is exposed in GLAC. The Waterton Formation is the basement unit upon which lies a thick sequence of Mesoproterozoic formations recording a long geologic history, now uplifted by tectonics and cut by glaciers. The backbone of the northern Rocky Mountains is constructed of at least 13 Mesoproterozoic geologic formations, one of the most extensive Precambrian sequences in the NPS. Similar-aged, well-preserved and un-altered sections of old sedimentary rock are also exposed in the Grand Canyon.

### **Paleozoic**

A long interval of erosion followed the igneous intrusive and metamorphic events of the Precambrian in the northern Rockies. This erosional period removed thousands of feet of rock, producing a major unconformity. Late Paleozoic mountain building during the Pennsylvanian (approximately 300 million years ago) formed the Ancestral Rocky Mountains, which were elevated along some of the faults in the crystalline Precambrian basement. GRSA is situated just west of the ancestral Front Range (Apashapa block) within the central Colorado trough and contains sediments shed from the actively uplifted Sangre de Cristo Formation. The Paleozoic geologic record is preserved in only two of the ROMN parks. Devonian igneous intrusive rocks are documented in ROMO. More extensive Paleozoic strata are exposed at GRSA, spanning from the Early Ordovician through the Permian.

### **Mesozoic**

The Mesozoic geologic record for the ROMN parks is best represented by Upper Cretaceous marine and terrestrial sedimentary strata mapped in LIBI, ROMO, and most extensively in GLAC. The Cretaceous Interior Seaway influenced middle to late Cretaceous deposition in the area now represented by the ROMN.

Beginning during the Late Cretaceous, approximately 75 million years ago, a mountain building event referred to as the Laramide Orogeny dramatically altered the landscape of western North America. A series of tectonic events resulted in the uplift and deformation of crust on the central craton with a corresponding retreat of the Interior Seaway. This orogenic event gave birth to the Rocky Mountains extending north to south from Canada into Mexico, and significantly reshaped the landscape of the ROMN parks.

### **Cenozoic**

The Laramide Orogeny continued into the Cenozoic and further uplifted the Rocky Mountains into a chain of high-elevation mountain peaks and subsiding intermountain basins. Large volumes of rocks and sediments were eroded during and after this major mountain building event. The sediments, along with the products of periodic volcanism, accumulated in the intermountain basins and to the plains directly to the east. The Denver–Cheyenne and North Park sedimentary basins flank ROMO and contain vast sediments shed from uplifted rock associated with the Laramide orogeny.

A transition from Laramide-related compression to Neogene extension led to the development of the Rio Grande Rift. The San Luis Basin contains GRSA and is one the most dramatic grabens of the Rio

Grande Rift. The abrupt topographic relief along the active San Luis Basin boundary has effectively trapped the famous sands of the park where they remain today.

Eocene and Oligocene sedimentary and volcanoclastic units record the post-Laramide period in many of the ROMN parks. These units include the Wall Mountain Tuff and the Florissant Formation at FLFO, the Troublesome Formation and some igneous intrusives at ROMO, the Renova Formation at GRKO, and the Kishenehn Formation at GLAC. One of the world's largest volcanic fields is the Oligocene-age San Juan volcanic field, located west of GRSA. Detritus from the San Juan field is the main source of sand captured at the dunes.

During the Pleistocene, alpine and continental glaciation reshaped and modified the geomorphology and surficial features in the parks of the ROMN. This Pleistocene and Holocene glacial activity was most pronounced at GLAC and ROMO and continues today, although greatly diminished due to the retreat and disappearance of some glaciers due to climate change.

# 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 ROMN parks:

- ROMO: August 12, 1998
- GRSA: August 21, 1998
- FLFO: October 21, 1998 and August 11, 1999
- GRKO: August 19, 2002
- GLAC: August 20–23, 2002
- LIBI: May 18, 2005 (scoped peripherally with BICA session)

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 all of the parks in the ROMN. 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 a principal deliverable of the GRI program. GRI GIS data produced for the ROMN parks as part of this inventory project 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.

Posters display the data over imagery of the park and surrounding area. Complete GIS data associated with this report 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 ROMN 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 ROMN 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 FLFO, GLAC, and GRSA were compiled using data model version 2.3, and GRKO and ROMO were compiled using 2.1; versions 2.0+ are available at <https://www.nps.gov/articles/gri-geodatabase-model.htm>; the data for LIBI are based on an older data model (1.3.1) 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 FLFO, GLAC, GRKO, GRSA, LIBI, or ROMO 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 here. 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 ROMN. This report is part of a more extensive inventory of geologic type sections throughout the National Park System. Therefore, the methods, definitions, and challenges identified here pertain not only to the parks of the ROMN, but also to other inventory and monitoring networks and parks.

There are a number of considerations to be addressed throughout this inventory. The most up-to-date information available is necessary, either found online or in published articles and maps. Occasionally, there is a lack of specific information 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.

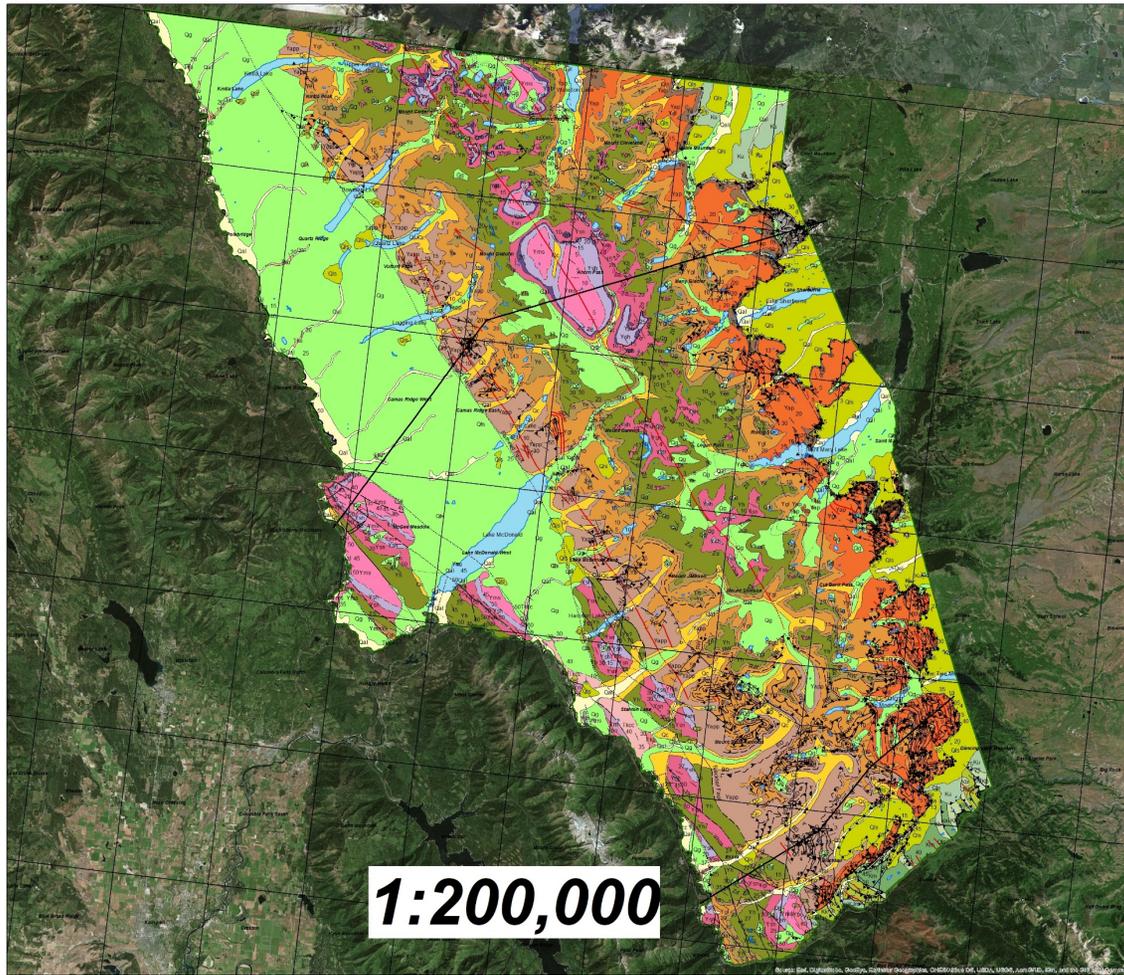
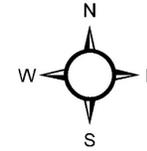
The lack of a designated and formal type section or inadequate and vague geospatial information associated with a type section limits the ability to capture precise information for this inventory. The available information related to the geologic type sections is included in this report.

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).

# Geology of Glacier National Park, Montana



### Legend

- NPS boundary
- known or certain
- - - approximate
- ⋯ concealed
- ⋯ queried
- · - approximate and queried
- ⋯ concealed and queried
- map boundary
- water or shoreline
- ⋯ subaqueous (inferred)
- Water
- Qal - Alluvium (Holocene and upper Pleistocene)
- Qc - Colluvium (Holocene and upper Pleistocene)
- Qg - Till (Holocene and upper Pleistocene)
- Qls - Landslide deposit (Holocene and upper Pleistocene)
- Tku - Kishenehn Formation, undivided (Oligocene and Eocene)
- Tkp - Kishenehn Formation, Conglomerate Member of Pinchot Creek (Eocene)
- Tkcc - Kishenehn Formation, Lacustrine Member of Coal Creek (Eocene)
- Km - Marias River Shale (Upper Cretaceous)
- Kb - Blackleaf Formation (Upper(?) and Lower Cretaceous)
- Kbk - Blackleaf and Kootenai Formations, undivided (Upper(?) and Lower Cretaceous)
- Kk - Kootenai Formation (Lower Cretaceous)
- Ku - Sedimentary rocks, undivided (Cretaceous)
- KJm - Mount Pablo & Morrison Fms. & Ellis Group, undivided (Lower Cretaceous & Upper-Middle Jurassic)
- Zd - Diorite, diabase, and gabbro sills and dikes (Late Proterozoic?)
- Ym - McNamara Formation (Middle Proterozoic)
- Ybo - Bonner Quartzite (Middle Proterozoic)
- Yms - Mount Shields Formation (Middle Proterozoic)
- Ysh - Shepard Formation (Middle Proterozoic)
- Ypb - Purcell Lava (Middle Proterozoic)
- Ysn - Snowslip Formation (Middle Proterozoic)
- Yh - Helena Formation (Middle Proterozoic)
- Yhcs - Helena Formation, conophyton stromatolite zone (Middle Proterozoic)
- Ye - Empire Formation (Middle Proterozoic)
- Ygl - Grinnell Formation (Middle Proterozoic)
- Yap - Appekunny Formation (Middle Proterozoic)
- Yapa - Appekunny and Altyn Formations, undivided (Middle Proterozoic)
- Yapp - Appekunny and Prichard Formation, undivided (Middle Proterozoic)
- Ya - Altyn Formation (Middle Proterozoic)
- Yae - Altyn Formation, Eastern facies (Middle Proterozoic)
- Ywt - Waterton Formation (Middle Proterozoic)

**1:200,000**



v2020-0806\_1500

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

Each map unit name is then queried in the U.S. Geologic Names Lexicon online database (“GEOLEX”, a national compilation of names and descriptions of geologic units) at <https://ngmdb.usgs.gov/Geolex/search>. Information provided by GEOLEX includes unit name, stratigraphic nomenclature usage, geologic age, published stratotype location descriptions, and the database provides a link to significant publications as well as the USGS Geologic Names Committee Archives (Wilmarth 1938; Keroher et al. 1966). Figure 3 below presents GEOLEX search results from the Mount Shields Formation.

The screenshot displays the GEOLEX search results for the Mount Shields Formation. At the top, there are logos for USGS (science for a changing world) and AASG (Association of American State Geologists), along with navigation links for USGS HOME, CONTACT USGS, and SEARCH USGS. Below this is a horizontal menu with tabs for Home, Catalog, Lexicon, MapView, New Mapping, Standards, and Comments. The main heading is "National Geologic Map Database" with a sub-heading "Geolex—Unit Summary".

The search results for the "Geologic Unit: Mount Shields" are as follows:

- Usage:** Mount Shields Formation of Missoula Group of Belt Supergroup (ID\*,MT\*)  
Mount Shields Formation of Belt Supergroup (MT)  
Originally called Shields.
- Geologic age:** Middle Proterozoic\*
- Type section, locality, area and/or origin of name:**  
Type section: along ridge between Mount Shields and Blacktail Mountain, Flathead Co., MT. Named from Mount Shields Mountain (Childers, 1963).  
Reference section: along crest of ridge parallel to and northwest of Camp Creek, in secs. 22, 28, and 33, T. 20 N., R. 12 W., Lewis and Clark Range, Powell Co., MT (McGill and Sommers, 1967).
- AAPG geologic province:** Northern Rocky Mountain region\*

Additional features include a "Significant Publications" icon, a box with links for "Correlation charts", "GNC Archives", "N.A. Stratigraphic Code", and "More Resources", and a footer with accessibility and privacy information, social media icons, and the USA.gov logo.

**Figure 3.** GEOLEX search result for the Mount Shields Formation.

Published GEOLEX stratotype spatial information is provided in three formats: (1) descriptive, using distance from nearby points of interest; (2) latitude and longitude coordinates; or (3) Township/Range/Section (TRS) coordinates. TRS coordinates are based upon subdivisions of a single 93.2 km<sup>2</sup> (36 mi<sup>2</sup>) township into 36 individual 2.59 km<sup>2</sup> (1 mi<sup>2</sup>) sections, and were converted into Google Earth (.kmz file) locations using Earth Point (<https://www.earthpoint.us/TownshipsSearchByDescription.aspx>). The most accurate GEOLEX descriptions using TRS coordinates can help locate features within 0.1618 km<sup>2</sup> (0.0625 mi<sup>2</sup>). Once

stratotype locality information provided for a given unit is geolocated using Google Earth, a GRI digital geologic map of the national park is draped over it. This step serves two functions: to improve accuracy in locating the stratotype, and validating the geologic polygon for agreement with GEOLEX nomenclature. Geolocations in Google Earth are then converted into an ArcGIS format using a “KML to Layer” conversion tool in ArcMap.

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

AutoSave Off ROMN Type Section Inventory.xlsx - Excel Henderson, Timothy C

File Home Insert Page Layout Formulas Data Review View Help Search

Clipboard Font Alignment Number Styles Cells Editing

Calibri 11

General

Share Comments

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	A	B	C	D	E	F	G	H	I	J	K
	Formation	Type Section Not Designated?	Type section in NPS boundary?	QC on GoogleEarth	Non-NPS type section locality	Publication	Desc. Geospatial Info	Coordinate Geospatial Info	Geologic Age_Era	Geologic Age_Period	Heirarchy
13	MISSOULA GROUP		NO		Type locality: slopes east and we	Fenton and Fenton 1937					
14	McNamara Formation		NO		Type section: along Blackfoot Riv	Clapp and Deiss, 1931; McGill and Sommers, 1967	Reference section: Camp Creek secti		Precambrian	Middle Proterozoic	Belt Super
15	Bonner Quartzite		NO		Type locality: In Lolo National Fo	Nelson and Dobell, 1961; McGill and Sommers, 1967	Reference section: Camp Creek secti		Precambrian	Middle Proterozoic	Belt Super
16	Mount Shields Formation		YES - GLAC	YES	Reference section: along crest of	Childers, 1963; McGill and	Type section: along ridge between Mount Shields and Blacktail M		Precambrian	Middle Proterozoic	Belt Super
17	Shepard Formation		YES - GLAC	YES		Fenton and Fenton, 1937	Type locality: Cliffs of Lewis Range near Shepard Glacier, Glacier N		Precambrian	Middle Proterozoic	Belt Super
18	Purcell Lava	X	NO				<b>Not designated.</b> Named from exposures in the McGillivray, Galtc		Precambrian	Middle Proterozoic	Belt Super
19	Snowslip Formation		YES - GLAC	YES	Reference section 1) Camp Creek	Childers, 1963; McGill and	Sommers, 1967; Whipple an	Type section: on ridge between Sno	Precambrian	Middle Proterozoic	Belt Super
20	PIEGAN GROUP		YES - GLAC	YES		Fenton and Fenton 1937	Type locality: Piegan Mountain, Glacier National Park. Well expos		Precambrian	Middle Proterozoic	
21	Helena Formation (formerly Siyeh)		YES - GLAC	YES		Walcott, 1899; Willis 1902;	Type locality (Siyeh Fm): stated being at Mt. Siyeh, Glacier Natio		Precambrian	Middle Proterozoic	Belt Super
22	Helena Formation, Granite Park Member		YES - GLAC	YES		Fenton and Fenton 1937	Type locality: Cliffs of the Continental Divide southeastward from		Precambrian	Middle Proterozoic	Belt Super
23	Helena Formation, Goathaunt Member		YES - GLAC	YES		Fenton and Fenton 1937	Type locality: south wall of cirque between Mount Goat Haunt ar		Precambrian	Middle Proterozoic	Belt Super
24	Empire Formation		NO		Type localities are on ridge north	Walcott, 1899; Knopf, 1950; Fenton and Fenton 1937			Precambrian	Middle Proterozoic	Belt Super
25	RAVALLI GROUP		NO		Type locality: Hills along the Jock	Fenton and Fenton 1937					
26	Grinnell Formation		YES - GLAC	YES		Willis, 1902	Type locality: Mount Grinnell, at head of Swift Current Valley, G		Precambrian	Middle Proterozoic	Belt Super
27	Grinnell Formation, Rising Bull Formation		YES - GLAC	YES		Fenton and Fenton, 1937	Type locality: Upper cliffs of Mt. Rockwell (Rising Bull of the Black		Precambrian	Middle Proterozoic	Belt Super
28	Grinnell Formation, Red Gap Member		YES - GLAC	YES		Fenton and Fenton, 1937	Type locality: mountain between Red Gap and Ptarmigan Wall, G		Precambrian	Middle Proterozoic	Belt Super
29	Grinnell Formation, Rising Wolf Member		YES - GLAC	YES		Fenton and Fenton, 1937	Type locality : Southern slopes of Rising Wolf Mountain, Glacier ?		Precambrian	Middle Proterozoic	Belt Super
30	Appekunny Formation		YES - GLAC	YES		Willis, 1902; Fenton and Fe	Type locality: Appekunny Mountain, north of Swiftcurrent Valley		Precambrian	Middle Proterozoic	Belt Super
31	Appekunny Formation, Scenic Point Member		YES - GLAC	YES		Fenton and Fenton, 1937	Type locality: Scenic Point, overlooking Two Medicine Valley, sou		Precambrian	Middle Proterozoic	Belt Super
32	Appekunny Formation, Appistoki Member		YES - GLAC	YES		Fenton and Fenton, 1937	Type locality: Appistoki Peak, near Two Medicine Lake, Glacier Ne		Precambrian	Middle Proterozoic	Belt Super
33	Appekunny Formation, Singleshot Member		YES - GLAC	YES		Fenton and Fenton, 1937	Type locality: at Singleshot Mountain, near St. Mary Lake, in east		Precambrian	Middle Proterozoic	Belt Super
34	Appekunny and Altyn Formations, undivided								Precambrian	Middle Proterozoic	
35	Appekunny and Prichard Formation, undivided								Precambrian	Middle Proterozoic	
36	Prichard Formation		NO		Type area: in the Coeur d'Alene n	Calkins, 1908; Cresswell 1989			Precambrian	Middle Proterozoic	Belt Super
37	Altyn Formation		YES - GLAC	YES		Willis, 1902; Fenton and Fe	Type locality: basal cliffs of Appekunny Mountain, about a mile n		Precambrian	Middle Proterozoic	Belt Super
38	Altyn Formation, Carthew Member		NO		Type locality: Eastern cliffs of Car	Fenton and Fenton 1937			Precambrian	Middle Proterozoic	Belt Super
39	Altyn Formation, Hell Roaring Member		NO		Type locality: Hell Roaring Falls ir	Fenton and Fenton 1937			Precambrian	Middle Proterozoic	Belt Super
40	Altyn Formation, Eastern facies								Precambrian	Middle Proterozoic	
41	Waterton Formation		NO		(Waterton Member of Altyn) - Tw	Daly, 1912; Fenton and Fe	<b>Not designated.</b> Named from exposures near Waterton Lake. Bri		Precambrian	Middle Proterozoic	Belt Super

Ready

**Figure 4.** Stratotype inventory spreadsheet of the ROMN displaying attributes appropriate for geolocation assessment. Pink highlighted cells represent geologic units that were not included in the stratigraphic unit listing for the GRI map of GLAC.

## 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.

# Florissant Fossil Beds National Monument (FLFO)

Florissant Fossil Beds National Monument (FLFO) is located in central Colorado and was established August 20, 1969 to preserve one of the richest and most diverse fossil deposits in the world (Figure 5). FLFO encompasses 2,427 hectares (5,998 acres) of land that have yielded spectacular fossils of finely preserved insects, spiders, beetles, ants, dragonflies, butterflies, flies, fish, plants, ferns, leaves, pollen, flowers, mammals, and birds, as well as redwood stumps up to 4.3 m (14 ft) wide. Significant research of FLFO includes the study and interpretation of more than 40,000 fossil specimens from a 34-million-year-old Eocene ecosystem which furnishes critical evidence of biologic and climatic change during a period of tectonic uplift (KellerLynn 2006).

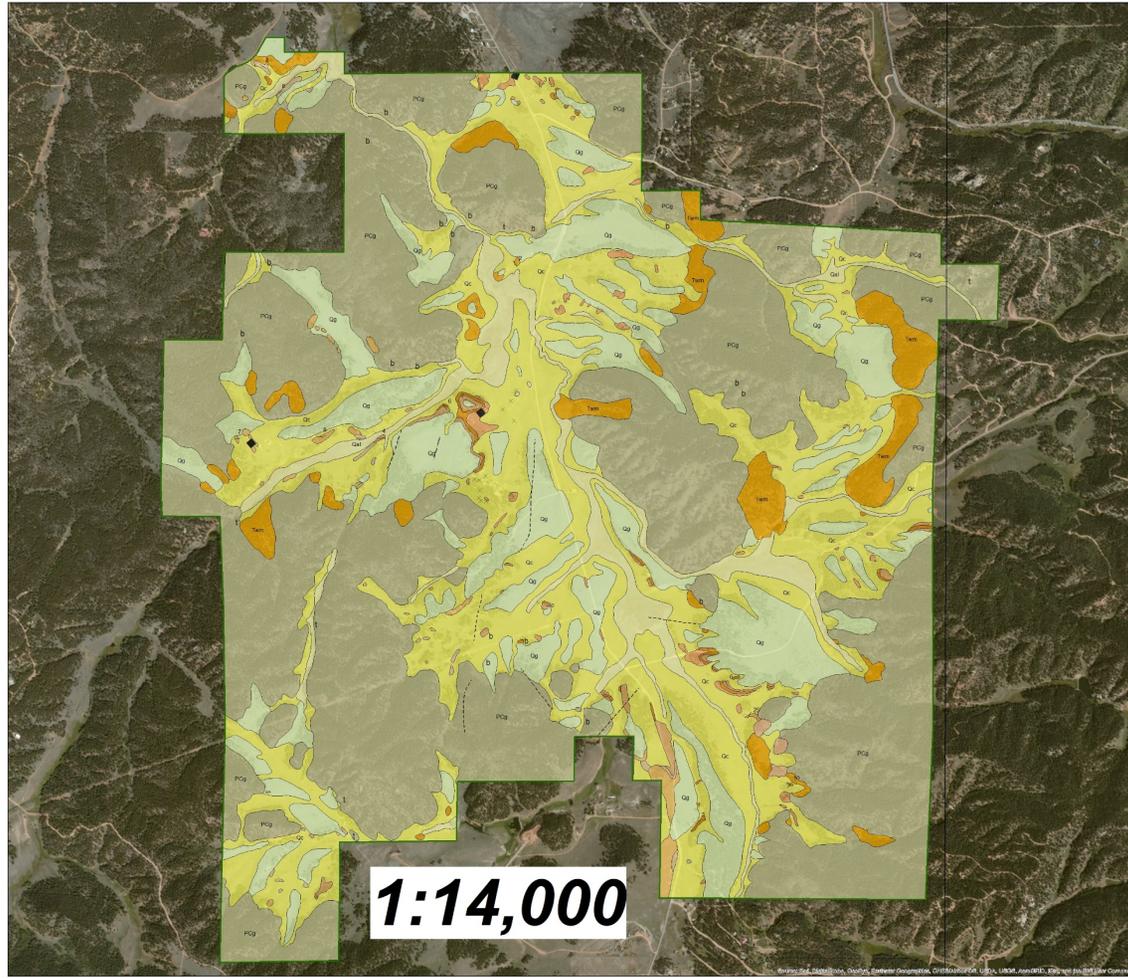
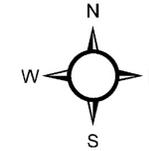


Figure 5. Park map of FLFO, Colorado (NPS).

The geologic story of FLFO is intimately linked to the existence of the rare and delicate fossil specimens which are completely absent or extremely rare in most paleontological sites. Strata of the Florissant valley were deposited on the eroded surface of the Precambrian-age Pikes Peak Granite, dated at 1.08 billion years old (Wobus 2001). Geologic units consist of lava flows, massive pumiceous tuffs, river gravels, agglomerates, and finely laminated, fossiliferous paper shales which form the most prominent outcrops (Figure 6). The Florissant Formation was deposited within a valley that was episodically blocked by volcanic debris flows (lahar deposits) that dammed the streams and formed Lake Florissant (KellerLynn 2006). Evanoff et al. (2001) interpreted the Florissant Formation as probably recording two episodes of lake generation: the first represented by the lower shale unit; the second represented by the middle and upper shale units, which are divided by a caprock conglomerate unit throughout most of FLFO. The lacustrine deposits were eventually buried by pumice gravel and lahars from the Thirtynine Mile volcanic field.

As of the writing of this paper, there are no designated type formations identified within the boundaries of FLFO. The Florissant Formation of FLFO deserves stratotype designation (see “Recommendations” below). A list of stratotypes located within 48 km (30 mi) of park boundaries is included here for reference. These nearby stratotypes include the Cambrian–Ordovician Manitou Limestone (type section), Ordovician Harding Sandstone (type locality), Eocene Wall Mountain Tuff (type locality), and Oligocene Antero Formation (type area).

# Geology of Florissant Fossil Beds National Monument, Colorado



## Legend

- NPS boundary
- | strike and dip of inclined beds
- | strike of vertical beds
- horizontal beds
- ◆ average trend of crossbedding
- b rock/boulder
- × fossil stump(s)
- t tor(s)
- known or certain
- map boundary
- - - - - unknown offset/displacement, inferred
- Qal - Holocene alluvium (Holocene)
- Qc - Quaternary colluvium (Pleistocene to Holocene)
- Qg - Pleistocene gravels (Pleistocene)
- Tf5 - Florissant Formation, unit 5 (Eocene)
- Tf4 - Florissant Formation, unit 4 (Eocene)
- Tf3 - Florissant Formation, unit 3 (Eocene)
- Tf2 - Florissant Formation, unit 2 (Eocene)
- Tf1 - Florissant Formation, unit 1 (Eocene)
- Tb - Eocene boulder conglomerate (Eocene)
- Twm - Wall Mountain Tuff (Eocene)
- PCg - Pikes Peak Granite (Precambrian)

**1:14,000**



v2020-0806\_1346

Figure 6. Geologic map of FLFO, Colorado.



## Glacier National Park (GLAC)

Glacier National Park (GLAC), located in Flathead and Glacier counties, northern Montana, was established May 11, 1910 and is renowned for its spectacular glacial landscapes, sparkling lakes, and a diverse ecoregion home to an array of plant and animal species (Figure 7). The National Historic Landmark Going-to-the-Sun Road bisects the park and provides breathtaking alpine views and access to remote wild land enjoyed by more than 2 million visitors per year (Anderson 2017). GLAC encompasses 410,078 hectares (1,013,324 acres) of land. It was authorized as part of the Waterton-Glacier International Peace Park in 1932, designated a Biosphere Reserve in 1976, and designated a World Heritage Site in 1995 (Anderson 2017).

As the name suggests, GLAC contains some of the most spectacular glacial geomorphology on the planet. The story of GLAC involves a complex interplay of geology, water, ice, tectonic forces, and climate. Geological processes established the groundwork that initiated complex responses that led to rock formations, mountains and valleys, waterfalls and lakes (Thornberry-Ehrlich 2004).

Compressive tectonic forces along the Lewis Overthrust fault have uplifted older rocks on top of younger ones, with ancient sea beds forming mountainous regions (Figure 8). Subsequent erosion due to streams and glaciers has shaped the landscape visible today. Park stewardship and protection of the architectural elegance of GLAC has become a concern as human influence has noticeably modified its geologic system, and glacial retreat has rapidly increased since the mid-1800s.

GLAC contains seventeen stratotype designations, all of which are part of the Mesoproterozoic Belt Supergroup (~1.5–1.25 billion years ago). These stratotypes can be broken down into two type sections, fourteen type localities, and one reference section (Figure 9; Table 1).

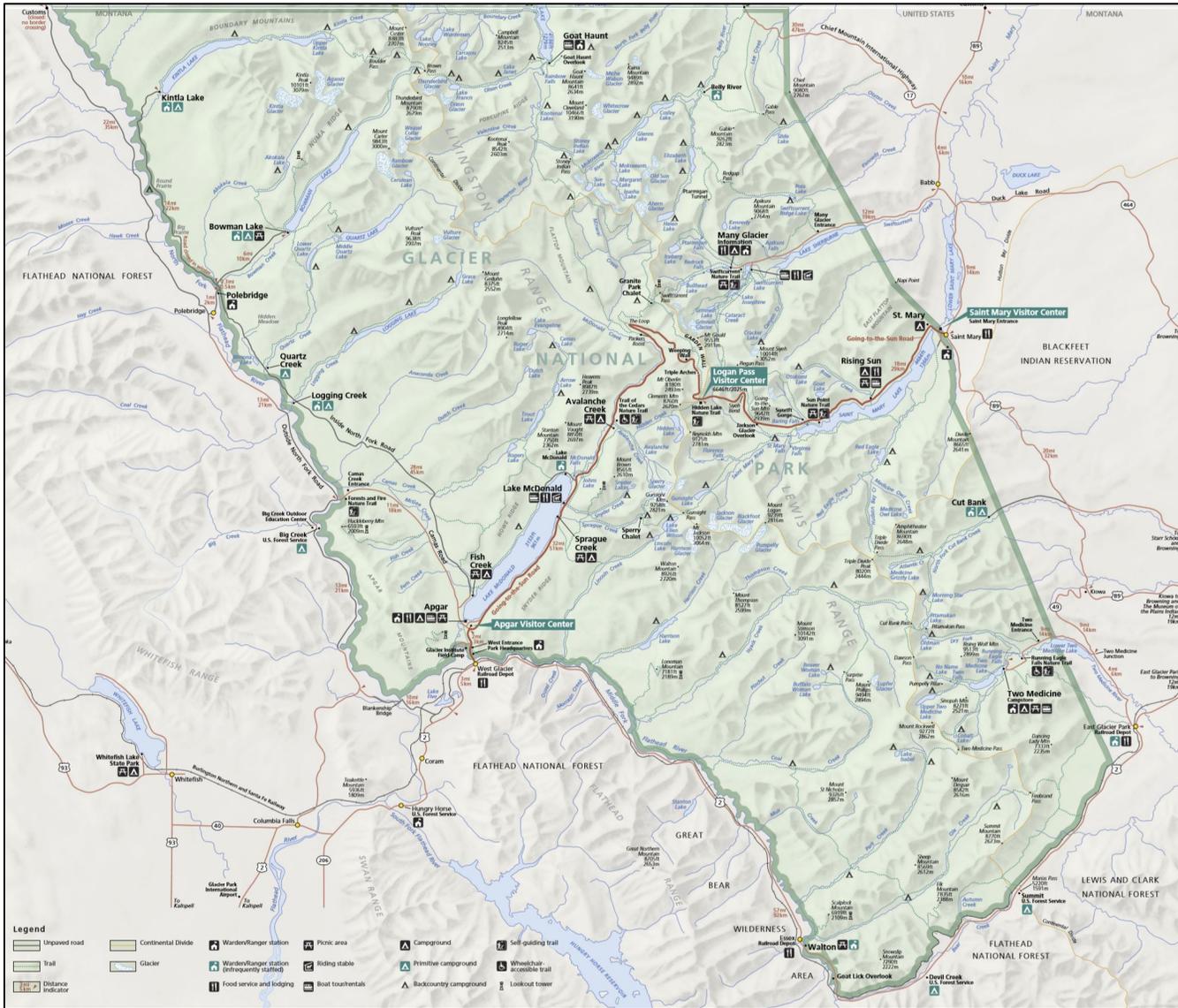
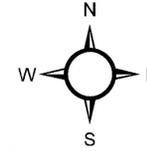


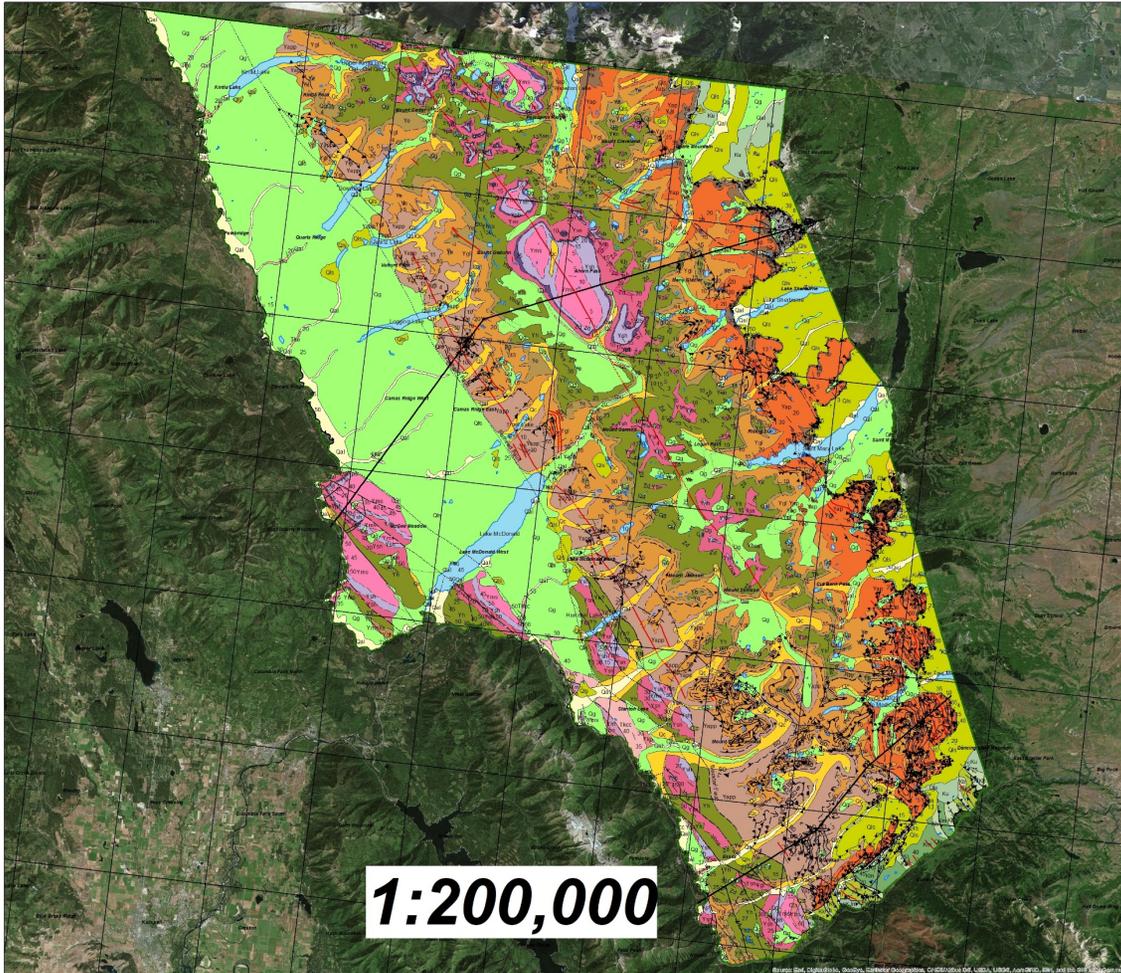
Figure 7. Park map of GLAC, Montana (NPS).

# Geology of Glacier National Park, Montana



## Legend

- NPS boundary
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- approximate
- concealed
- queried
- approximate and queried
- concealed and queried
- map boundary
- water or shoreline
- subaqueous (inferred)
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- Qg - Till (Holocene and upper Pleistocene)
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- Ku - Sedimentary rocks, undivided (Cretaceous)
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- Ybo - Bonner Quartzite (Middle Proterozoic)
- Yms - Mount Shields Formation (Middle Proterozoic)
- Ysh - Shepard Formation (Middle Proterozoic)
- Ypb - Purcell Lava (Middle Proterozoic)
- Ysn - Snowslip Formation (Middle Proterozoic)
- Yh - Helena Formation (Middle Proterozoic)
- Yhcs - Helena Formation, conophyton stromatolite zone (Middle Proterozoic)
- Ye - Empire Formation (Middle Proterozoic)
- Ygl - Grinnell Formation (Middle Proterozoic)
- Yap - Appekunny Formation (Middle Proterozoic)
- Yapa - Appekunny and Altyn Formations, undivided (Middle Proterozoic)
- Yapp - Appekunny and Prichard Formation, undivided (Middle Proterozoic)
- Ya - Altyn Formation (Middle Proterozoic)
- Yae - Altyn Formation, Eastern facies (Middle Proterozoic)
- Ywt - Waterton Formation (Middle Proterozoic)



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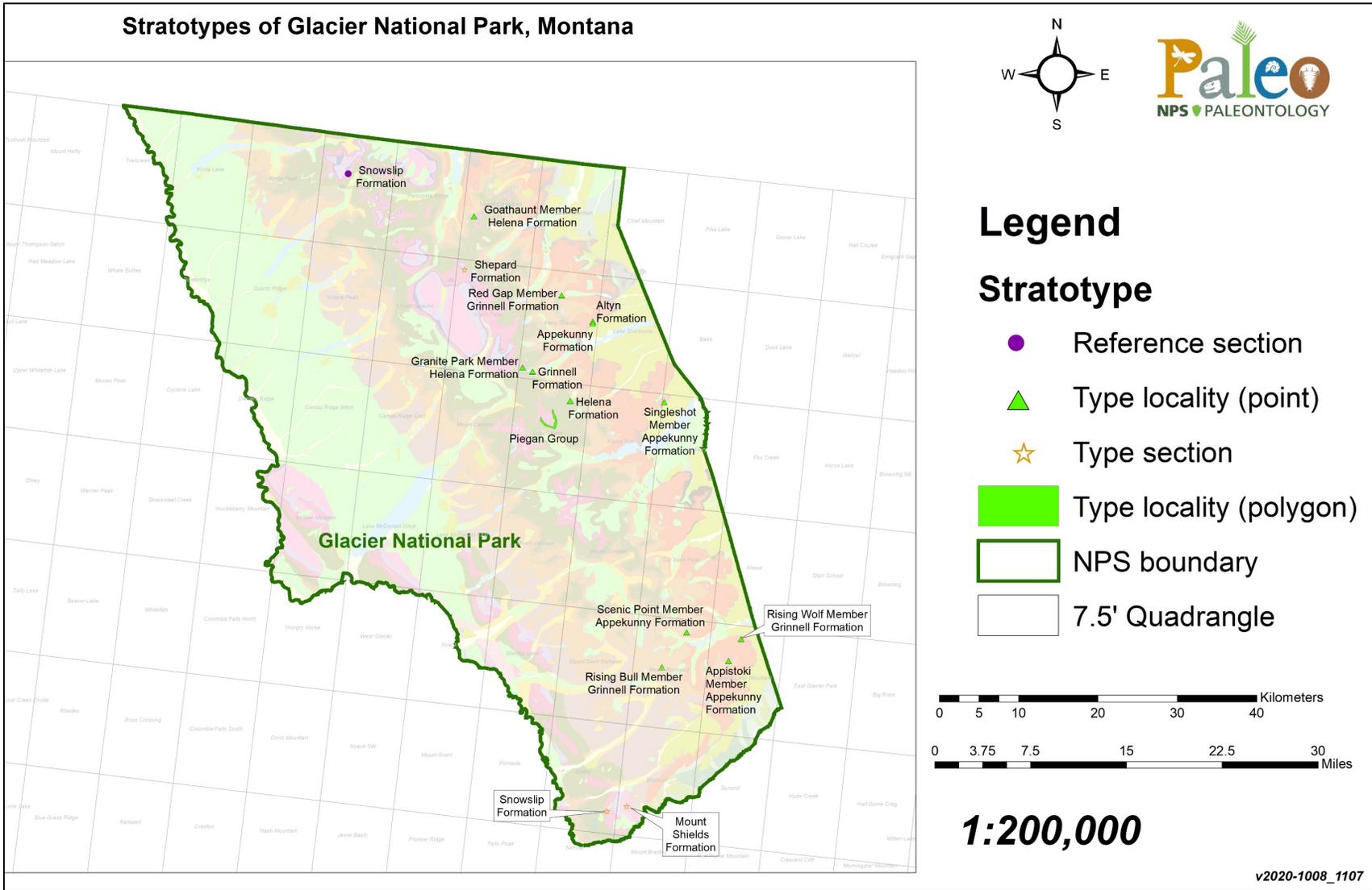


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Figure 8. Geologic map of GLAC, Montana.

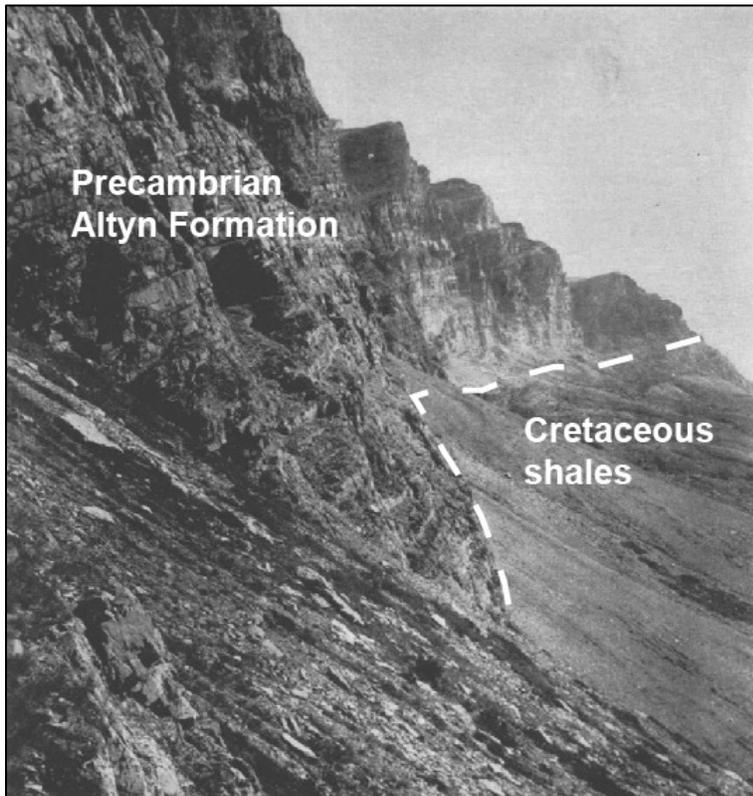
**Table 1.** List of GLAC stratotype units sorted by age with associated reference publications and locations.

Unit Name (map symbol)	Reference	Stratotype Location	Age
Mount Shields Formation (Yms)	Childers 1963	Type section: along ridge between Mount Shields and Blacktail Mountain	Mesoproterozoic
Shepard Formation (Ysh)	Fenton and Fenton 1937	Type locality: cliffs of Lewis Range near Shepard Glacier	Mesoproterozoic
Snowslip Formation (Ysn)	Childers 1963; Whipple and Johnson 1988	Type section: on ridge between Snowslip Mountain and Mount Shields Reference section: east wall of Hole-in-the-Wall cirque	Mesoproterozoic
Helena Formation, Granite Park Member	Fenton and Fenton 1937	Type locality: cliffs of the Continental Divide southeastward from Granite Park	Mesoproterozoic
Helena Formation, Goathaunt Member	Fenton and Fenton 1937	Type locality: south wall of cirque between Mount Goat Haunt and Mount Cleveland	Mesoproterozoic
Helena Formation (Yh)	Willis 1902	Type locality (former Siyeh Formation): Mount Siyeh	Mesoproterozoic
Belt Supergroup, Piegan Group	Fenton and Fenton 1937	Type locality: Piegan Mountain	Mesoproterozoic
Grinnell Formation, Rising Bull Member	Fenton and Fenton 1937	Type locality: upper cliffs of Mount Rockwell, south of Two Medicine Lake	Mesoproterozoic
Grinnell Formation, Red Gap Member	Fenton and Fenton 1937	Type locality: mountain between Red Gap and Ptarmigan Wall	Mesoproterozoic
Grinnell Formation, Rising Wolf Member	Fenton and Fenton 1937	Type locality: southern slopes of Rising Wolf Mountain	Mesoproterozoic
Grinnell Formation (Ygl)	Willis 1902	Type locality: Mount Grinnell, at the head of Swiftcurrent Valley	Mesoproterozoic
Appekunny Formation, Scenic Point Member	Fenton and Fenton 1937	Type locality: Scenic Point, overlooking Two Medicine Lake	Mesoproterozoic
Appekunny Formation, Appistoki Member	Fenton and Fenton 1937	Type locality: Appistoki Peak, near Two Medicine Lake	Mesoproterozoic
Appekunny Formation, Singleshot Member	Fenton and Fenton 1937	Type locality: at Singleshot Mountain, near St. Mary Lake	Mesoproterozoic
Appekunny Formation (Yap)	Fenton and Fenton 1937	Type locality: Appekunny Mountain, north of Swiftcurrent Valley	Mesoproterozoic
Altyn Formation (Ya)	Willis 1902; Fenton and Fenton 1937	Type locality: basal cliffs of Appekunny Mountain, in Swiftcurrent Valley NE of Many Glacier Hotel	Mesoproterozoic



**Figure 9.** Modified geologic map of GLAC showing stratotype locations. The transparency of geologic units has been increased.

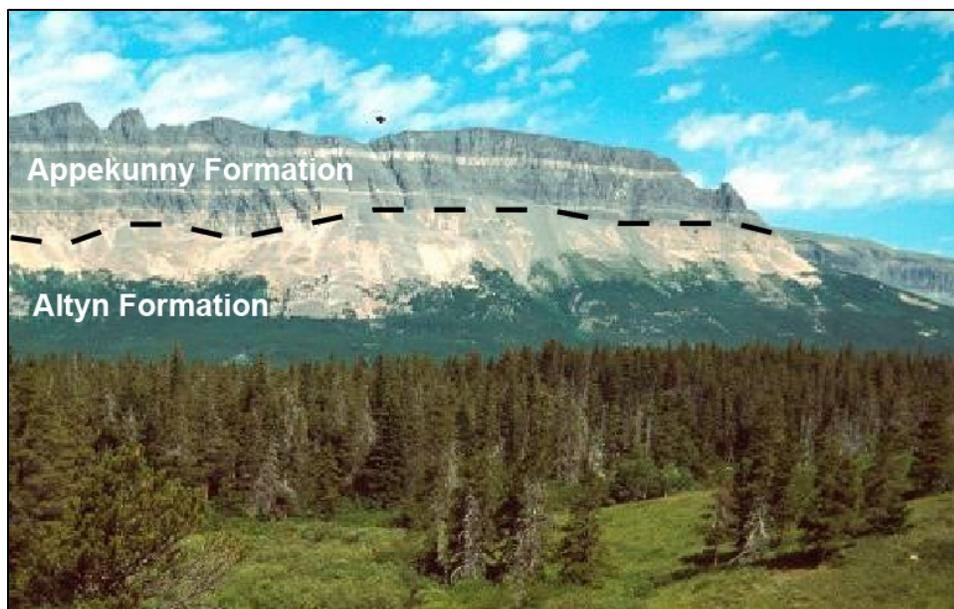
The Mesoproterozoic Altyn Formation occurs only on the east side of GLAC and was named by Willis (1902) for its type locality in the basal cliffs at the foot of Apikuni Mountain north of Altyn in Swiftcurrent Valley (Figures 9 and 10; Table 1). Type locality exposures are approximately 244 m (800 ft) thick (Willis 1902). Originally characterized as a limestone unit, it was later described by Pratt (2017) as consisting of sandy grainstone, intraclastic rudstone, stromatolite patch reefs, laminated silty mudstone, and oolite.



**Figure 10.** Type locality exposures of the Altyn Formation in the lower slopes of Appekunny Mountain, northeast of Many Glacier Hotel, GLAC. The Lewis overthrust is at the base of the cliffs (white dashed line), and the smooth slopes below are underlain by Cretaceous-age shale. Figure modified from Willis (1902: Figure 2).

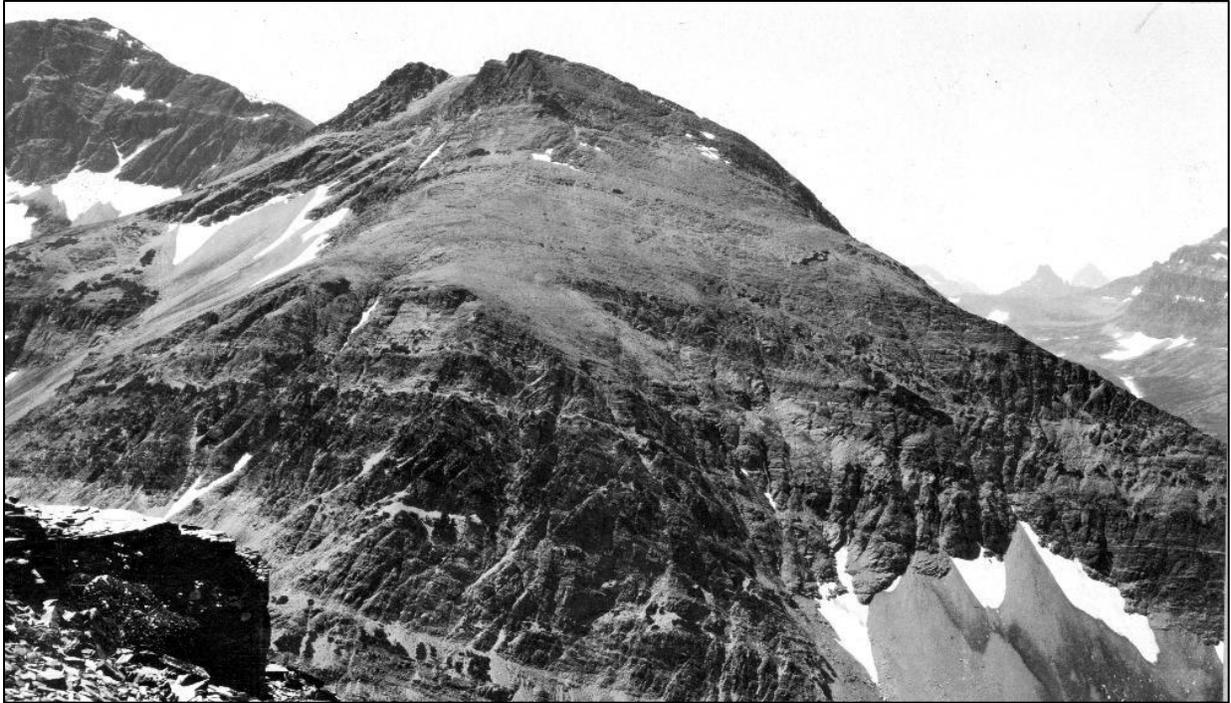
The Mesoproterozoic Appekunny Formation was originally named the Appekunny argillite by Willis (1902) after notable exposures in the northeastern spur of Appekunny Mountain, GLAC. Fenton and Fenton (1937) later designated these ~183 m (600 ft)-thick cliff exposures as the type locality for the formation (Figure 9; Table 1). The Appekunny Formation is characterized as a remarkably uniform succession of laminated mudstone, argillaceous siltstone, and very fine-grained sandstone, with an upper part that consists of laminated claystone, siltstone, and intraclastic siltstone (Fenton and Fenton 1937; Pratt 2017). Common sedimentary structures include ripple cross-lamination, low-relief hummocky cross-stratification, mud cracks, and soft-sediment deformation features (Willis 1902; Fenton and Fenton 1937; Pratt 2017).

The Singleshot Member of the Appekunny Formation was named by Fenton and Fenton (1931, 1937) after its type locality at Singleshot Mountain near St. Mary Lake, GLAC (Figures 9 and 11; Table 1). The unit is described as a 91–122 m (300–400 ft) thick succession of argillites and quartzites interbedded with siliceous dolomite and dolomitic sandstone that contains abundant mud cracks, ripple marks, and abundant mud breccias (Fenton and Fenton 1937). Besides the type locality, the Singleshot Member has notable exposures on the western slope of Goat Haunt Mountain and on the northern face of Gable Mountain, GLAC (Fenton and Fenton 1937).



**Figure 11.** Northwest view of Singleshot Mountain, GLAC; type locality of the Singleshot Member of the Appekunny Formation (Annotated USGS photo).

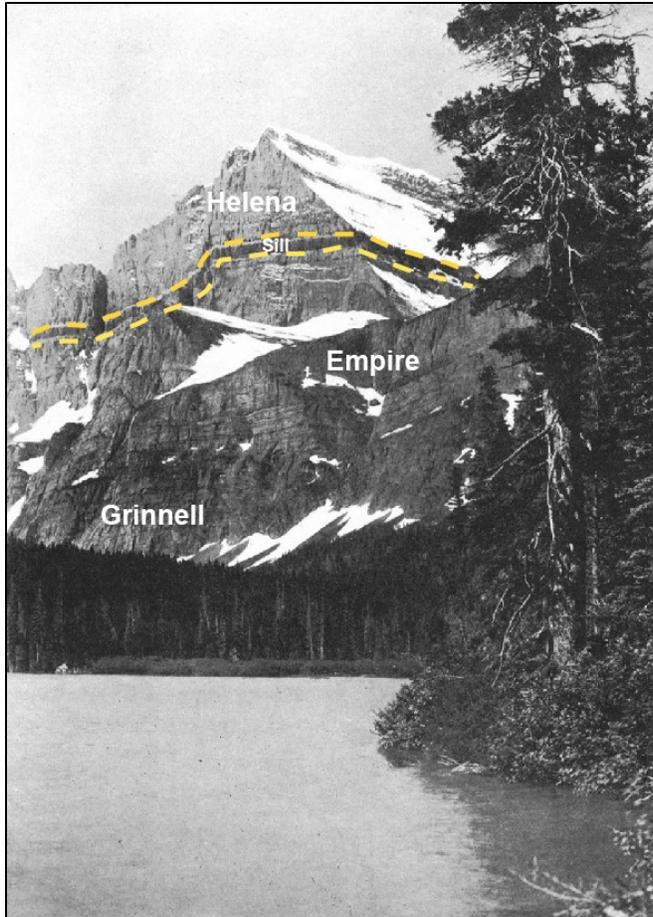
The Appistoki Member of the Appekunny Formation was designated by Fenton and Fenton (1931, 1937) after type locality exposures at Appistoki Peak, near Two Medicine Lake, GLAC (Figures 9 and 12; Table 1). The Appistoki Member is characterized as gray, green, olive-brown, and rusty-gray argillites that are interbedded with stratified green, white, or pink quartzites (Fenton and Fenton 1937). Common sedimentary features include pebble breccias, mud cracks, and abundant ripple marks. In some layers rain and sleet prints are present (Fenton and Fenton 1937). In the region of Two Medicine Lake, the Appistoki Member consists primarily of finely laminated argillites with pebble breccias that consist of small blue and green pebbles embedded in a darker-green, gritty matrix (Fenton and Fenton 1937).



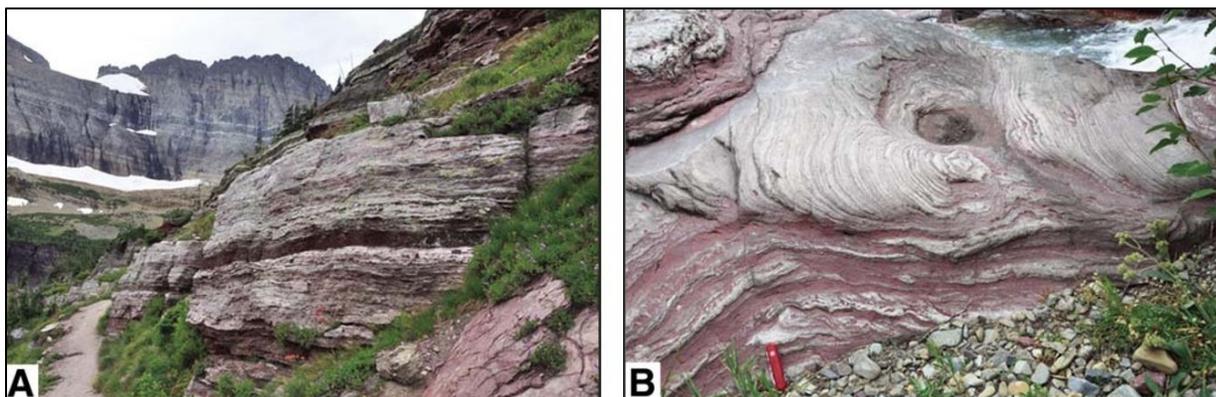
**Figure 12.** Southwest view of Appistoki Peak, GLAC, consisting entirely of the Appekunny Formation and the type locality exposures of the Appistoki Peak Member (USGS photo).

The Scenic Point Member of the Appekunny Formation was named by Fenton and Fenton (1937) for its type locality exposures at Scenic Point, overlooking Two Medicine Valley, GLAC (Figure 9; Table 1). Fenton and Fenton (1937) describe the type locality exposures as consisting of micaceous to earthy, green, red, buff, and brown argillites that contain mud cracks, with interbedded coarse, friable sandstones. In the region of Two Medicine Valley, the Scenic Point Member forms cliffs at Twin Falls and below Upper Two Medicine Lake. Thick ledges consisting of the member are exposed along the trail to Cobalt Lake. At Many Glacier, the member is characterized as thickly bedded, coarsely mud-cracked argillites that are green or purplish-green, with a few dull, dark red interbeds that form resistant ledges near lakes and streams (Fenton and Fenton 1937).

The Mesoproterozoic Grinnell Formation was originally named the Grinnell argillite by Willis (1902) after the type locality occurrence at Mount Grinnell where the unit is 550 m (1,800 ft) thick at the head of Swiftcurrent Valley, GLAC (Figure 9; Table 1). Willis (1902) states that the Grinnell Formation is also well-exposed along the eastern side of Appekunny and Robertson Mountains. Stratigraphically, the Grinnell Formation conformably underlies the Empire Formation and overlies the Appekunny Formation (Figure 13). The unit is comprised of strikingly red- to maroon-colored strata, consisting of laminated mudstone and claystone with sporadic beds of white, cross-laminated sandstone or quartzite (Figures 14A and 14B; Pratt 2017). Common sedimentary structures include ripple marks and mud cracks.



**Figure 13.** View of Mount Gould from the south fork of Swiftcurrent Lake, looking southwest, GLAC. The upper cliffs are comprised of the Helena and Empire Formations, with lower cliffs consisting of the Grinnell Formation; dark band outlined by orange dashed lines consists of intrusive diorite sill. Thickness of rock exposures from lake to summit is 1,423 m (4,670 ft). Figure modified from Willis (1902: Plate 46).



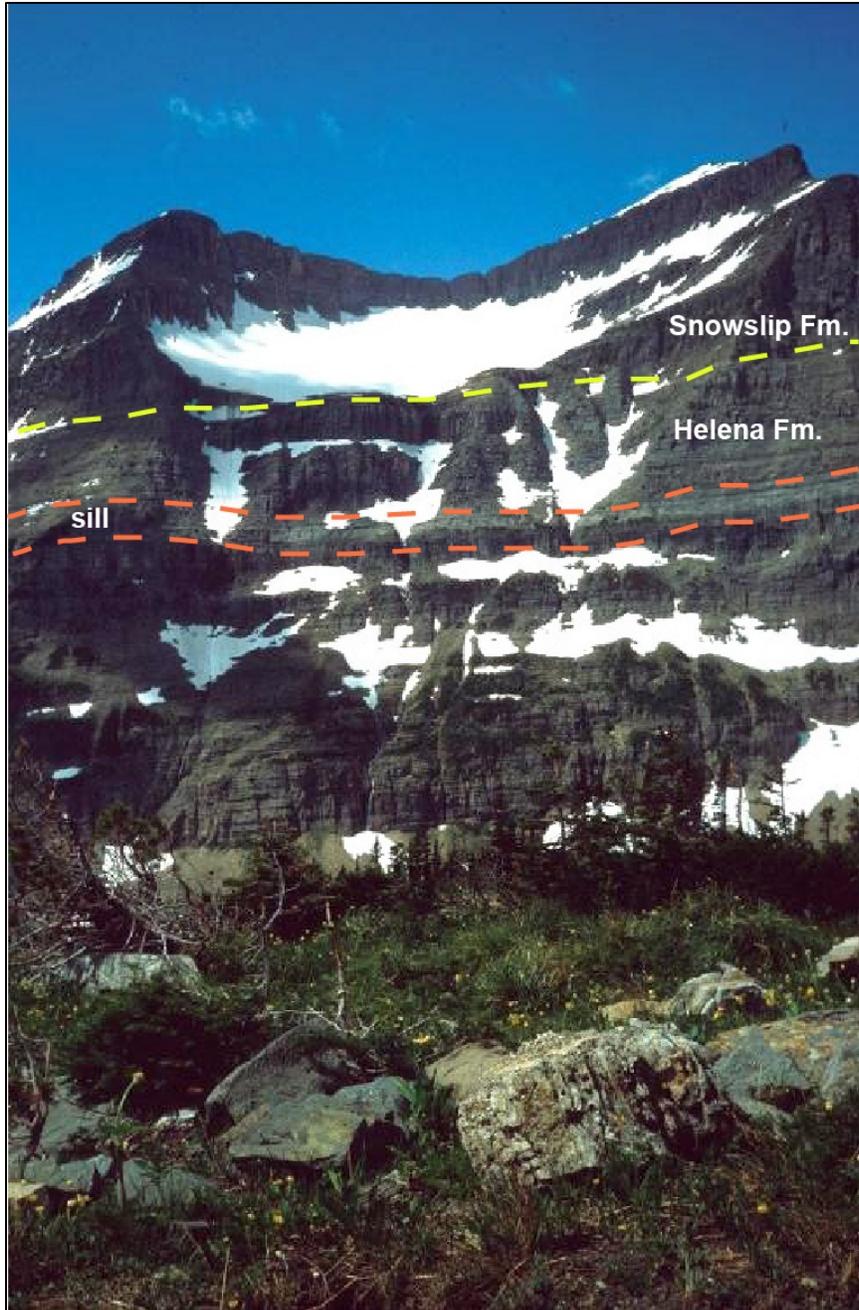
**Figure 14.** Grinnell Formation in GLAC. (A) Exposures along the Grinnell Glacier trail, showing red mudstone and interbedded white quartzite. Black band halfway up the exposure is diorite sill with contact-metamorphosed carbonate on either side. (B) Baring Creek exposure showing oblique view of red mudstone with interbedded thin lenses of quartzite containing blocky claystone intraclasts, capped by a bed of cross-laminated quartzite. Figure from Pratt (2017: Figure 7).

The Rising Wolf Member of the Grinnell Formation was named by Fenton and Fenton (1937) after its type locality exposures on the southern slopes of Rising Wolf Mountain, GLAC (Figure 9; Table 1). Fenton and Fenton (1937) designated the Rising Wolf Member as the basal member of the formation and characterized the unit as a series of alternating white and pink quartzites interbedded with dark red argillites. Common sedimentary features of the member include symmetrical and asymmetrical ripple marks, mud cracks, cross-bedding, mud breccias, and mud balls (Fenton and Fenton 1937).

The Red Gap Member of the Grinnell Formation was originally designated by Fenton and Fenton (1931, 1937) for exposures in northwest GLAC. Fenton and Fenton (1937) describe the type locality as the mountain (now considered to be Crowfoot Mountain) between Red Gap and Ptarmigan Wall, GLAC (Figure 9; Table 1). Type locality exposures consist of fine-grained, red argillites that occur in thin to thick beds and contain ripple marks and abundant mud cracks (Fenton and Fenton 1937). The member is well-exposed in the Lewis Range north of Many Glacier and is recognizable for its thick beds of red argillite with flat mud-crack polygons (Fenton and Fenton 1937).

The Rising Bull Member of the Grinnell Formation was named by Fenton and Fenton (1931, 1937) for its type locality exposures in the upper cliffs of Mount Rockwell (Rising Bull of the Blackfeet), south of Upper Two Medicine Lake, GLAC (Figure 9; Table 1). Type locality exposures are approximately 183 m (600 ft) thick and consist of alternating white and pink quartzites, red argillites, and mud breccias (Fenton and Fenton 1937). Sedimentary features of the member include ripple marks, cross-bedding, mud cracks, and mud balls (Fenton and Fenton 1937).

The Mesoproterozoic Piegan Group of the Belt Supergroup was originally designated the “Siyeh or Wallace group” by Clapp (1932) and redesignated by Fenton and Fenton (1937) for its type locality at Piegan Mountain, GLAC (Figures 9 and 15; Table 1). Fenton and Fenton (1937) chose the type locality at Piegan Mountain for its excellent exposures of the Helena Formation. Other notable exposures for the Piegan Group occur at Mounts Gould, Wilbur, Cleveland, and Lineham of the Glacier–Waterton Lakes region (Fenton and Fenton 1937). The group is characterized as consisting of limestones, dolomites, and dominantly argillaceous clastics that stratigraphically occur between the Missoula and Ravalli groups (Fenton and Fenton 1937). The group is also known for displaying exceptionally preserved stromatolites.



**Figure 15.** Type locality exposures of the Piegan Group of the Belt Supergroup, Piegan Mountain, GLAC. Units of the Piegan Group occur below the base of Piegan Glacier (yellow dashed line). Diorite sill within the Helena Formation outlined by orange dashed lines (annotated USGS photo).

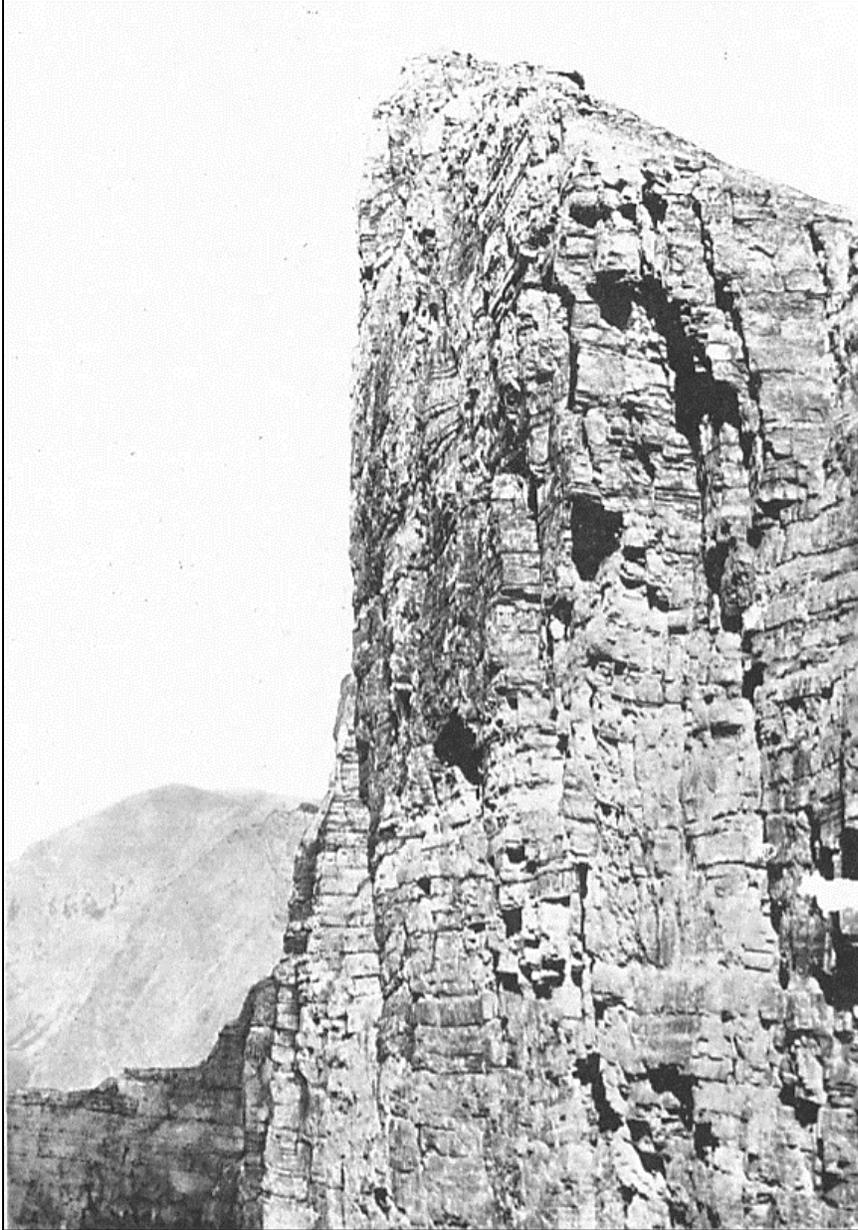
The Mesoproterozoic Helena Formation (formerly known as the Siyeh Formation) was named by Walcott (1899) for the occurrence of thick limestone exposures in the upper part of the city of Helena and on the hill slopes to the east, with an estimated thickness of 732 m (2,400 ft). The type locality assigned to the superseded Siyeh Formation by Willis (1902) at the head of Canyon Creek, GLAC is included in this inventory for the Helena Formation (Figure 9; Table 1). The Helena Formation is

characterized as dolomite and limestone that weathers gray or blue-gray, some siliceous limestone oolite, and interbedded gray siliceous shale beds (Figure 16A; Walcott 1899; Knopf 1950; Pratt 2017). Particularly notable features are abundant molar-tooth structures (Figure 16B) and 3 m (10 ft)-thick *Collenia* stromatolites that occur at intervals throughout the formation (Knopf 1950; Pratt 2017).



**Figure 16.** Rocks of the Helena Formation. (A) Laminated and thin-bedded dolomitic lime mudstone sharply overlain by oolite containing mudstone rafts and intraclasts; roadcut on Going-to-the-Sun Road between Lunch Creek and Logan Pass, GLAC. (B) Laminated dolomitic lime mudstone riddled with molar-tooth structures, block at side of Highway 6 north of entrance to Waterton Lakes National Park. Figure from Pratt (2017: Figure 8).

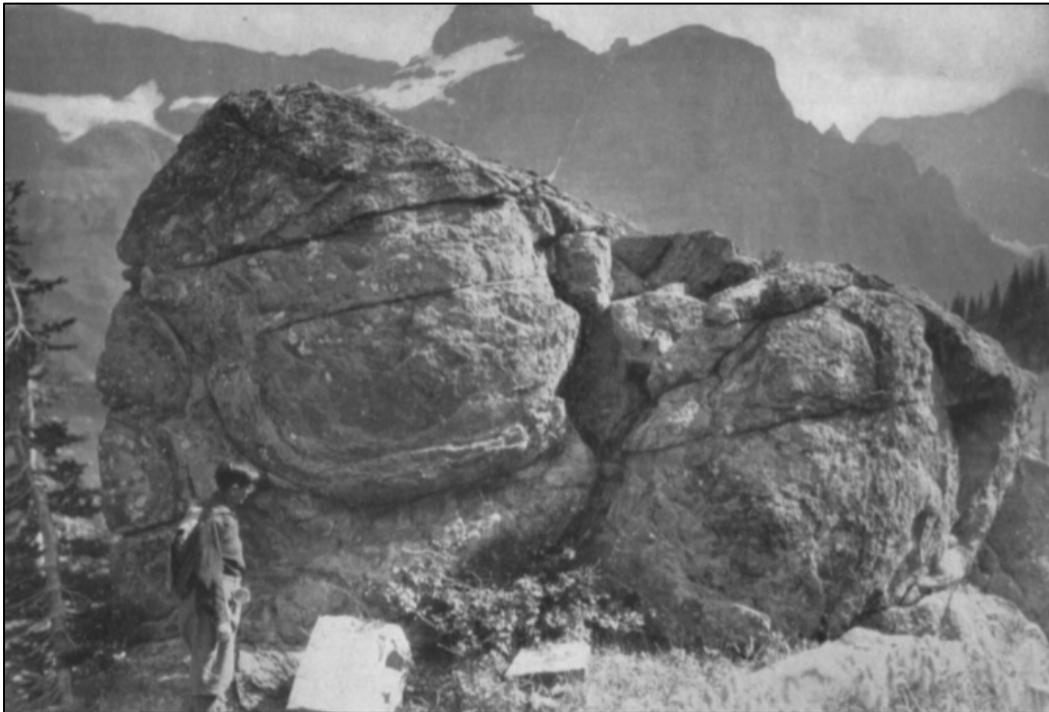
The Goathaunt Member of the Helena Formation was designated by Fenton and Fenton (1931, 1937) after its type locality in the south wall of the cirque between Mount Goat Haunt and Mount Cleveland, GLAC (Figures 9 and 17; Table 1). The Goathaunt Member is characterized as limestones, dolomites, oolites, dolomitic sandstones, and argillites that are generally thick-bedded and dark gray (Fenton and Fenton 1937). Common sedimentary structures of the unit include mud breccias, mud cracks, and ripple marks. Near Piegan and Swiftcurrent Passes, the member contains abundant molar-tooth structures (Fenton and Fenton 1937). Stromatolites are abundant throughout the upper half of the member, and exposures on Going-to-the-Sun and Cataract Mountains contain colonies of *Collenia willisii* that reach 0.9–1.5 m (3–5 ft) in diameter (Fenton and Fenton 1937).



**Figure 17.** Spur of Mount Cleveland, GLAC, consisting entirely of the Helena Formation and type locality exposures of the Goathaunt Member. Thickness of cliff exposure is approximately 366 m (1,200 ft). Figure from Willis (1902: Plate 49).

The Granite Park Member of the Helena Formation was named by Fenton and Fenton (1931, 1937) for its type locality in the cliffs of the Continental Divide southeast from Granite Park, GLAC, where the strata are crossed by a trail to the dike above Grinnell Glacier (Figure 9; Table 1). Type locality exposures of the member are approximately 87 m (285 ft) thick and consist of dolomites, argillites, and thin quartzites with thin strata of oolite, sandstone, and mud breccia (Fenton and Fenton 1937). Flattened stromatolite colonies of *Collenia willisii* are found in several intervals at the type locality and measure 0.3–1.2 m (1–4 ft) in diameter (Fenton and Fenton 1937). The Granite Park Member

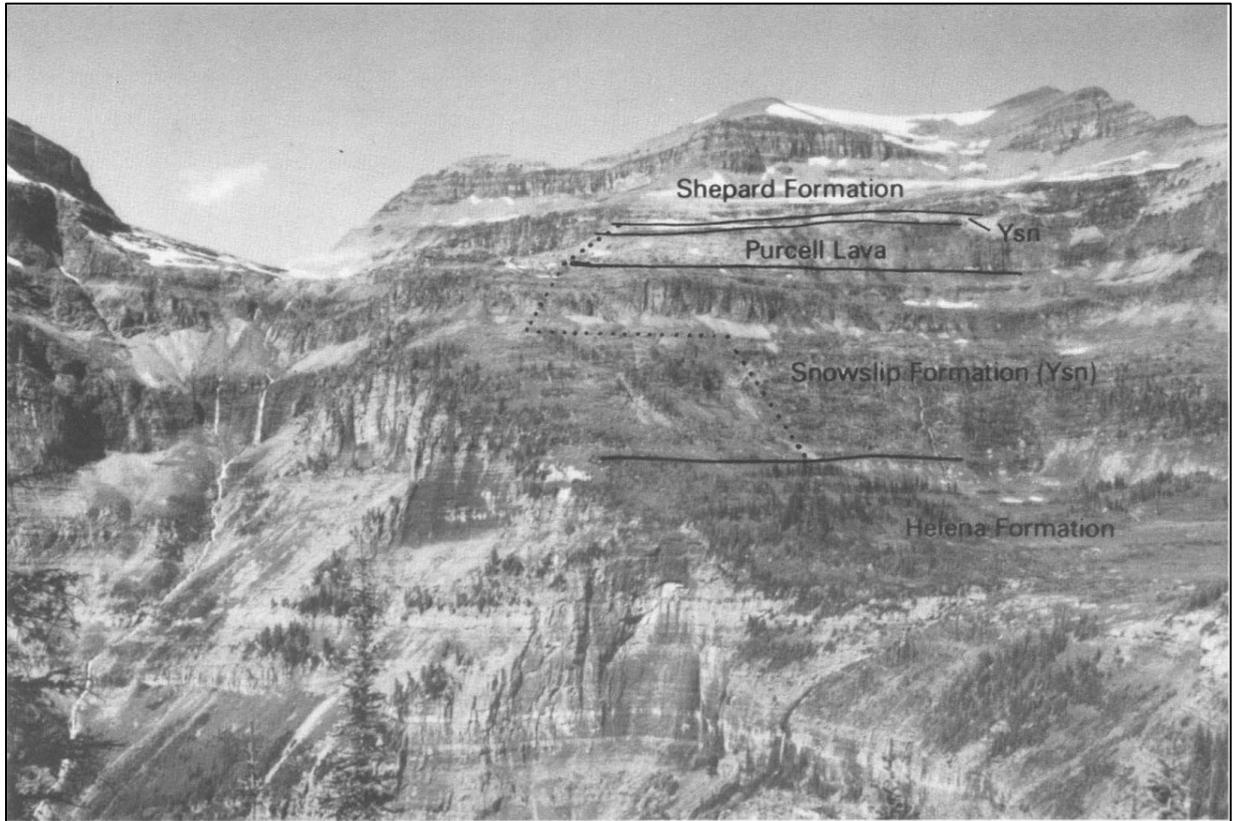
contains abundant stromatolites at other locations in GLAC that include exposures along Going-to-the-Sun Highway, Hole-in-the-Wall cirque, and Flattop Mountain (Figure 18; Fenton and Fenton 1937).



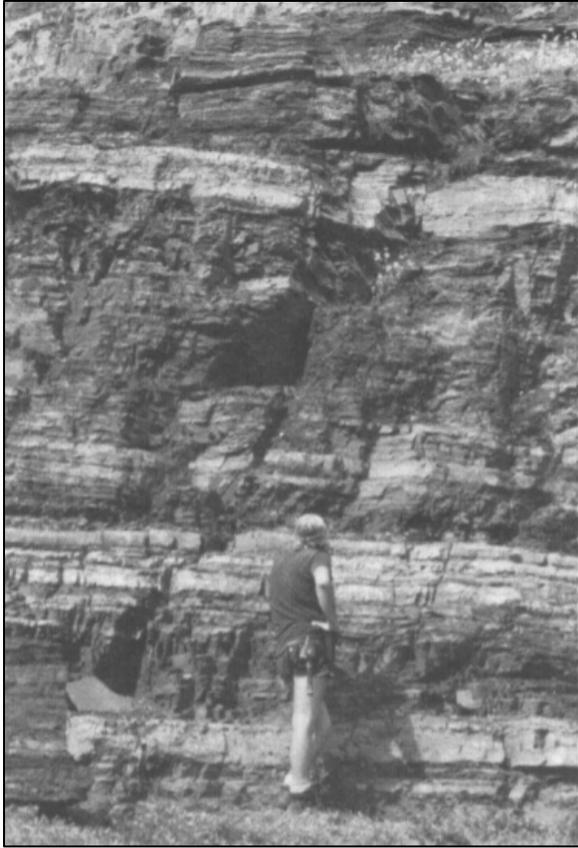
**Figure 18.** Upper surfaces of two large colonies of *Collenia* sp. from the Granite Park Member of the Helena Formation, Hole-in-the-Wall cirque, GLAC. Figure from Fenton and Fenton (1931: Plate X).

The Mesoproterozoic Snowslip Formation was designated by Childers (1963) after the type section occurrence on the ridge between Snowslip Mountain and Mount Shields, GLAC (Figure 9; Table 1). Measured on the north spur of Snowslip Mountain (latitude 48°16'30" N., longitude 113°31' W.), the type section exposure is approximately 490 m (1,600 ft) thick and consists predominantly of quartzites and argillites, with a distinct basal section of sandy argillite breccias (Childers 1963). Conspicuous type section features include ripple marks, mud cracks, cross-bedding, and the occurrence of a stromatolite zone in the lower part of the unit, which Rezak (1957) named the *Collenia undosa* Zone 2 (Childers 1963). Stratigraphically, the formation conformably overlies the Helena (formerly Siyeh) Formation and is conformably overlain by the Shepard Formation. Since the type section of the Snowslip Formation does not contain the Purcell Lava, Whipple and Johnson (1988) designated a reference section containing the lava that is accessible and well-exposed in the northern part of GLAC, just east of Boulder Pass, in the east-facing wall of the Hole-in-the-Wall cirque (Figures 9 and 19; Table 1). The reference section contains six informal members that are designated, from oldest to youngest, 1 through 6; the uppermost member, 6, encloses the Purcell Lava and a diabase sill (Figure 21; Whipple and Johnson 1988). Common sedimentary structures of the reference section include fining-upward sequences, desiccation cracks, cross-bedding, ripple marks, and mud chips (Figure 20; Whipple and Johnson 1988). Upper and lower contacts of the

formation are exposed, showing the Snowslip Formation to be conformable with adjacent stratigraphic units. The total thickness of the Snowslip, the Purcell Lava, and enclosed diabase sill is 358 m (1,173 ft).



**Figure 19.** Hole-in-the-Wall basin, looking west at location of the Snowslip Formation reference section, GLAC. Dotted line is measured reference section. Figure from Whipple and Johnson (1988: Figure 4).



**Figure 20.** Rhythmic, fining-upward sequences in member 5 of the Snowslip Formation reference section located at Hole-in-the-Wall basin, GLAC. Figure from Whipple and Johnson (1988: Figure 9).

The Mesoproterozoic Shepard Formation was originally named by Willis (1902) after exposures that form the crest of the Lewis Range in the vicinity of Mount Cleveland and Shepard Glacier between Belly River and Flattop Mountain, GLAC. The unit is described as containing gray or brown argillaceous and siliceous dolomites, magnesian limestones, and interbedded greenish-white magnesian quartzites (Willis 1902; Fenton and Fenton 1937). Characteristic sedimentary features include ripple marks, mud cracks, channel fillings, and edgewise mud breccias. Fenton and Fenton (1937) later designated the type locality as the cliffs of the Lewis Range near Shepard Glacier. Well-exposed sections occur on Mount Carthew, Bounder, and Swiftcurrent peaks, and mountains near Logan Pass, as well as in the valley of the Middle Fork of the Flathead River (Fenton and Fenton 1937).

The Mesoproterozoic Mount Shields Formation was named by Childers (1963) to describe exposures consisting of thin-bedded bright-red and maroon siltstones, sandstones, quartzites, and shales in the region of Mount Shields, GLAC. Childers (1963) designated the type section along the ridge between Mount Shields and Blacktail Mountain (Fig. 2; PL 1), latitude 48°17' N., longitude 113°29' W. Measured type section thickness is approximately 777.5 m (2,551 ft). Common sedimentary features that occur throughout most of the formation include black hematite staining, salt casts, oscillation ripple bedding, and mud cracks (Childers 1963). Stratigraphically, the Mount Shields Formation

appears to be conformable with the overlying Red Plume Quartzite and underlying Shepard Formation (Childers 1963).

In addition to the designated stratotypes located within GLAC boundaries, a list of stratotypes located within 48 km (30 mi) of park boundaries is included here for reference. These nearby stratotypes include the Proterozoic-age Roosville, Mount Rowe, and Kintla Members of the Miller Peak Formation (type localities), Jurassic Swift Formation (type locality), and Cretaceous Cut Bank Member of the Kootenai Formation (reference section).



## **Grant-Kohrs Ranch National Historic Site (GRKO)**

Grant-Kohrs Ranch National Historic Site (GRKO) is located in western Montana and was authorized as an NPS unit on August 25, 1972 (Figure 21). The historic site was first developed into a ranch by John Francis Grant in 1862. Grant sold the ranch to Conrad Kohrs in 1866, who expanded the ranch by taking advantage of the free range in western Montana (Thornberry-Ehrlich 2007). Today this 655-hectare (1,618 acre) site serves as a living museum, and commemorates the frontier cattle ranch lifestyle through preservation, interpretation, and operation of an intact ranch (Anderson 2017). GRKO contains 90 historic structures and maintains an active ranch with an unbroken 150-year history (Thornberry-Ehrlich 2007).

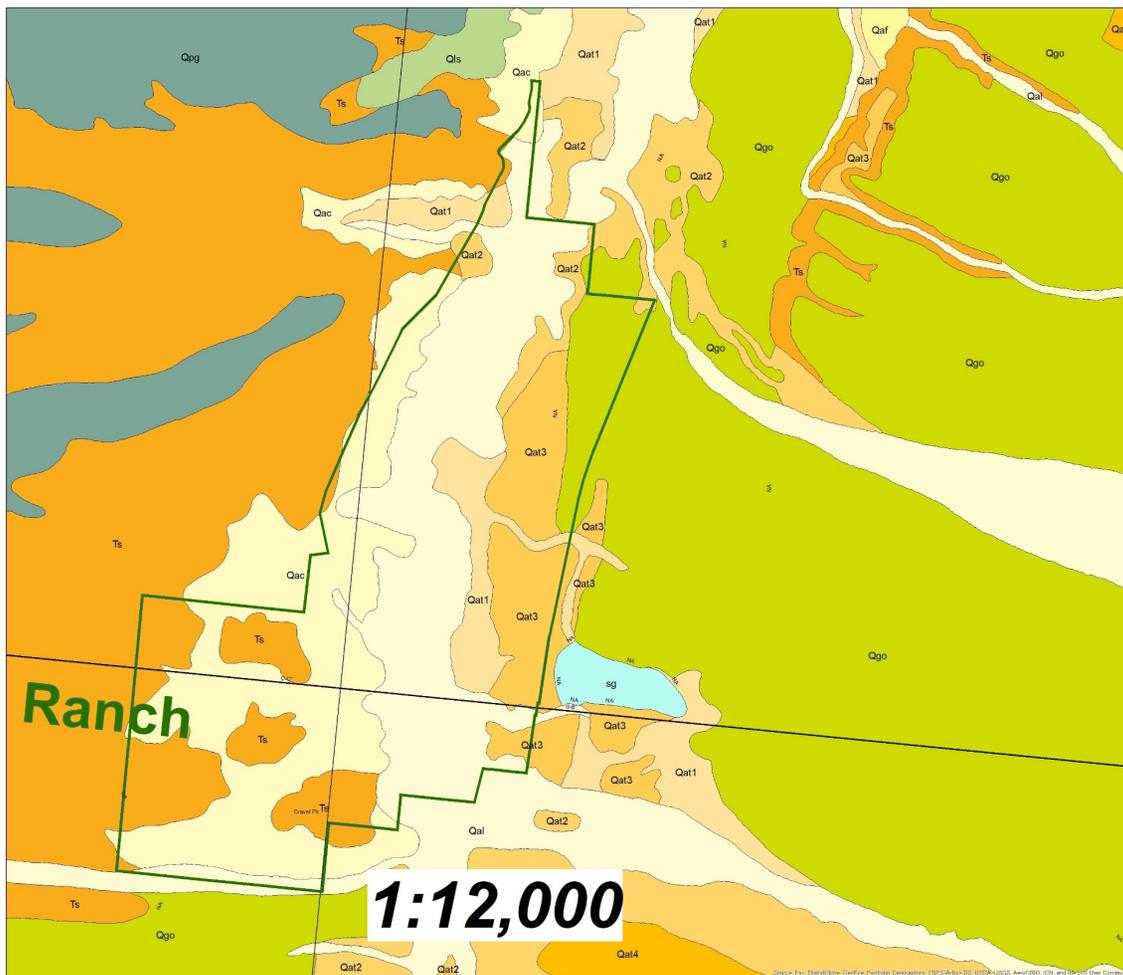
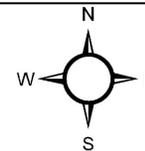
GRKO lies within the Northern Rocky Mountains Physiographic Province, which contains exposed geologic units ranging from Precambrian to Tertiary in age, as well as recent alluvial and glacial deposits (Figure 22; Thornberry-Ehrlich 2007). Pre-Tertiary rocks are complex and were folded and deformed multiple times due to immense tectonic forces associated with the Sevier and Laramide orogenic events. In the eastern mountains, igneous activity that formed the Cretaceous Boulder Batholith also concentrated vast mineral deposits. Sixteen different mining districts of the area are a result of this igneous activity (Madison et al. 1995). Along the western side of the valley, rocks consist of folded and faulted sedimentary units intruded by Cretaceous granitic to dioritic igneous dikes and stocks (Thornberry-Ehrlich 2007). Terraces and rolling hills along the valley consist of thick, unconsolidated alluvium deposits.

As of the writing of this paper, there are no designated type formations identified within the boundaries of GRKO. A list of stratotypes located within 48 km (30 mi) of park boundaries is included here for reference. These nearby stratotypes include the Cretaceous-age units of the Golden Spike Formation (type section) and Carter Creek Formation (type area).



Figure 21. Regional map of GRKO, Montana (NPS).

# Geology of Grant-Kohrs National Historic Site, Montana



## Legend

- NPS boundary
- known or certain
- concealed
- cross-section line
- sg - Sand and gravel (Holocene)
- Qal - Alluvium (Holocene)
- Qat1 - Alluvial terrace deposit, youngest (Holocene)
- Qat2 - Alluvial terrace deposit, second youngest (Holocene)
- Qat3 - Alluvial terrace deposit, third youngest (Holocene)
- Qac - Alluvium and colluvium (Holocene and Pleistocene)
- Qls - Landslide deposit (Holocene and Pleistocene)
- Qaf - Alluvial fan deposit (Holocene and Pleistocene)
- Qat4 - Alluvial terrace deposit, fourth youngest (Holocene and Pleistocene)
- Qgo - Glacial outwash deposit (Holocene and Pleistocene)
- Qpg - Pediment gravel deposit (Holocene and Pleistocene)
- Ts - Sedimentary rocks, undivided (Eocene to Pliocene)
- Tsa - Ash bed, known or certain (Eocene to Pliocene)
- gravel pit
- known or certain
- sg - Sand and gravel pit



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Figure 22. Geologic map of GRKO, Montana.



## Great Sand Dunes National Park and Preserve (GRSA)

Great Sand Dunes National Park and Preserve (GRSA) is located in the San Luis Valley of Colorado and is home to the tallest sand dunes in North America, with some dunes rising 230 m (750 ft) above the valley floor (Figure 23). GRSA was originally established as a national monument March 17, 1932 and was redesignated as a national park and national preserve November 22, 2000. The national park encompasses 43,423.5 hectares (107,302 acres) of land, includes an 33,994 hectare (84,000 acre) dune field, alpine lakes, tundra, mountain peaks exceeding 3,962 m (13,000 ft), ancient spruce and pine forests, large strands of aspen and cottonwood, grasslands, and wetlands (Anderson 2017; Graham 2006).

The geology of GRSA and the Sangre de Cristo Mountains consists of Precambrian igneous and metamorphic rocks, Paleozoic and Mesozoic sedimentary rocks, Tertiary igneous and sedimentary rocks, and unconsolidated Quaternary sediments (Figure 24; Graham 2006). Precambrian rocks span the Early Proterozoic (2.5 to 1.6 billion years ago) and consist of quartz monzonite, diorite, and gneiss. Paleozoic and Mesozoic (320 to 146 million years ago) exposures are primarily shale, sandstone and conglomerate of the Upper Jurassic Morrison Formation, Middle Jurassic Entrada Sandstone, Pennsylvanian Minturn Formation, and the Pennsylvanian–Permian Sangre de Cristo Formation. Mississippian, Devonian, and Ordovician strata (485 to 323 million years ago) include the Lower Mississippian Leadville Limestone, the Mississippian(?) to Devonian Chaffee Group, the Upper Ordovician Fremont Dolomite, the Middle Ordovician Harding Sandstone, and the Lower Ordovician Manitou Limestone (Graham 2006). Silurian age rocks are not present in the region, and only rare exposures of the Cambrian Sawatch Quartzite are present. Tertiary rocks in the Sangre de Cristo Mountains consist of Oligocene and Miocene igneous rocks and the sedimentary rocks of the Miocene–Pliocene Santa Fe Formation (Graham 2006). A variety of unconsolidated Quaternary-age glacial, aeolian, and alluvial deposits have been mapped in GRSA and the western flank of the Sangre de Cristo Mountains (Lindsey et al. 1986).

As of the writing of this paper, there are no designated type formations identified within the boundaries of GRSA. A list of stratotypes located within 48 km (30 mi) of park boundaries is included here for reference. These nearby stratotypes include the Pennsylvanian–Permian Sangre de Cristo Formation (type area), Crestone Conglomerate Member of the Sangre de Cristo Formation (reference section), and the Pliocene–Pleistocene Alamosa Formation (type area).

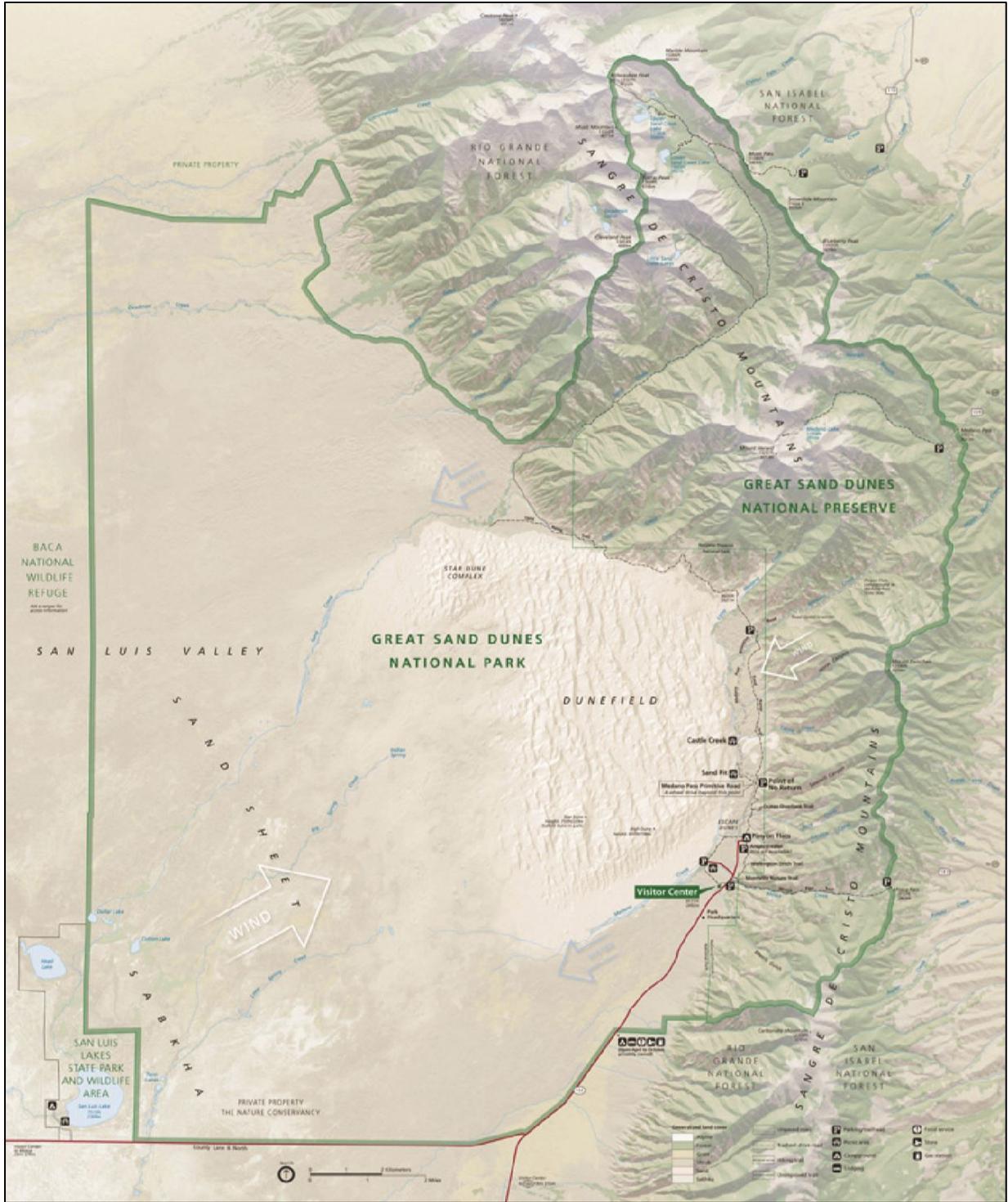


Figure 23. Park map of GRSA, Colorado (NPS).

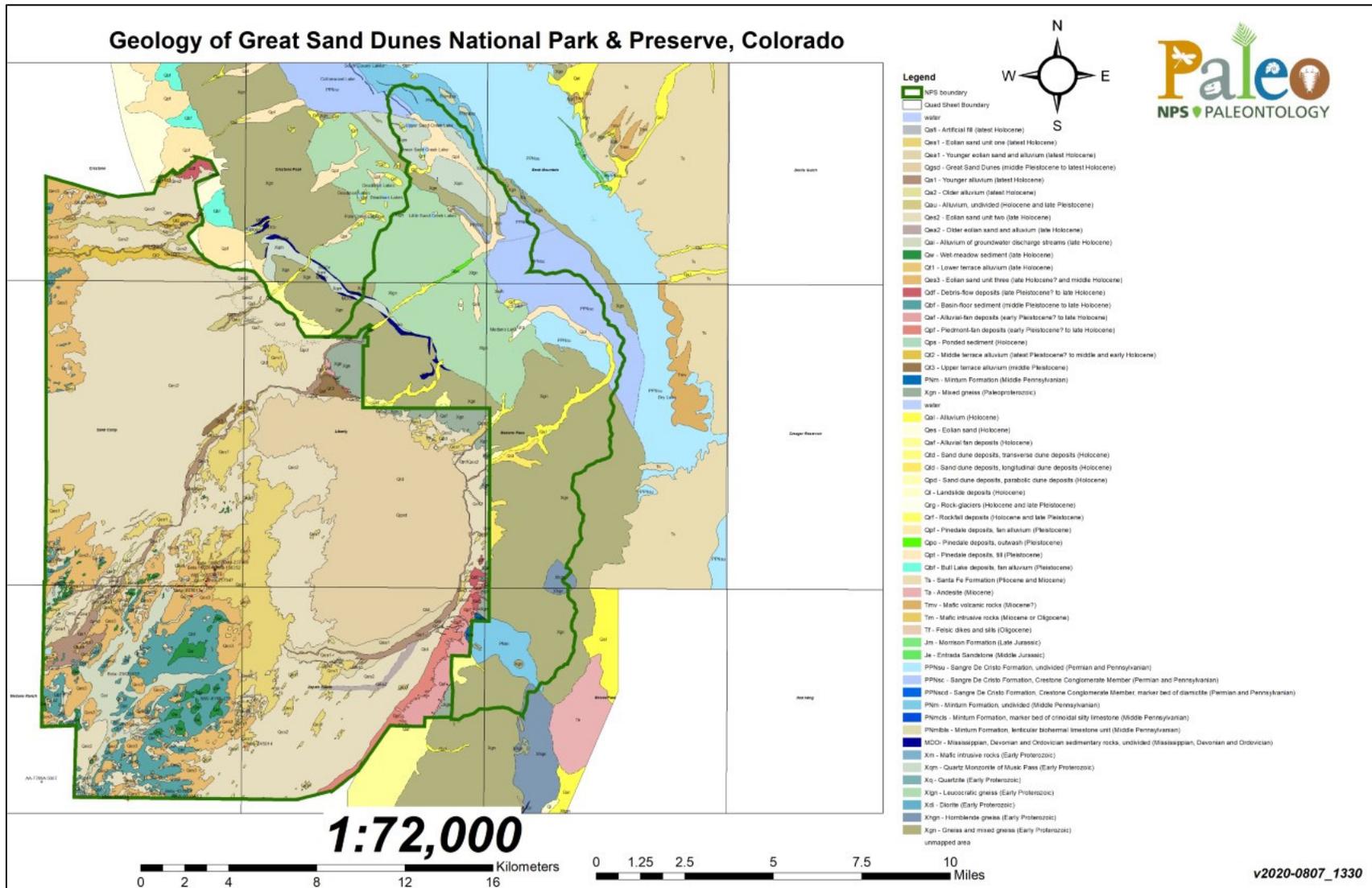
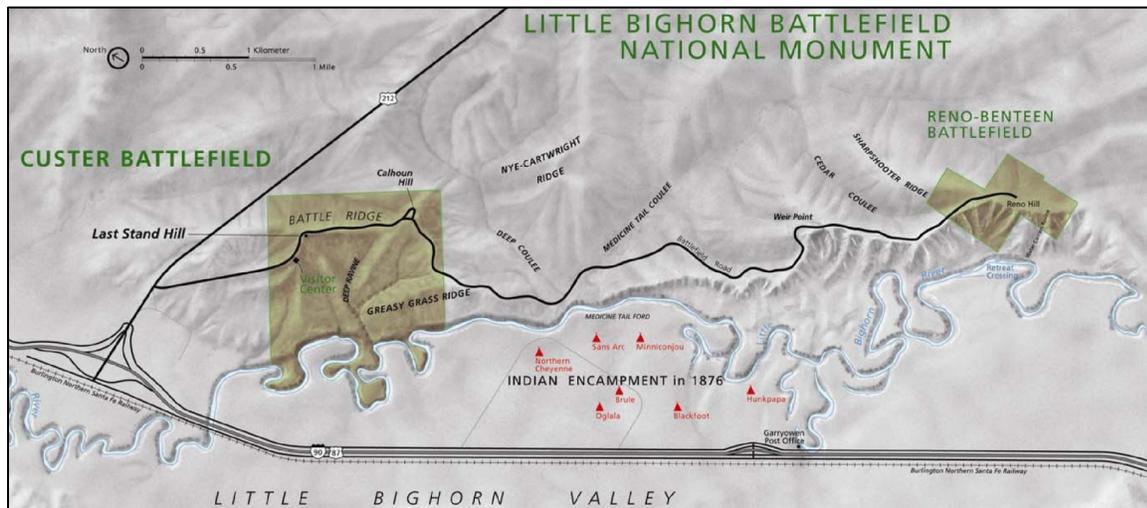


Figure 24. Geologic map of GRSA, Colorado.



## Little Bighorn Battlefield National Monument (LIBI)

Little Bighorn Battlefield National Monument (LIBI), located in southeastern Montana, was originally established as a national cemetery on Jan. 29, 1879, less than three years after the Battle of the Little Bighorn (Figure 25). The national monument memorializes one of the last major victories of the Northern Plains Native Americans to preserve their ancestral way of life, and protects the site where Lieutenant Colonel George A. Custer and all the men under his immediate command met their demise on what is now “Last Stand Hill” (KellerLynn 2011). LIBI was renamed as a national monument Dec. 10, 1991 and encompasses 765 acres of federal land (Anderson 2017). The primary purpose of LIBI is to preserve and protect the historic and natural resources related to the Battle of Little Bighorn, as well as educate visitors about the events surrounding the battle and its resulting effects (KellerLynn 2011).

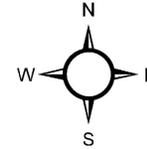


**Figure 25.** Park map of LIBI, Montana (NPS).

Various geologic landforms dot the landscape of LIBI, with the primary form consisting of ridges dissected by ravines and small stream beds (“coulees”). During the Battle of the Little Bighorn, these ridges provided views across the broad valley and offered defensible high ground for soldiers of the 7<sup>th</sup> Cavalry (KellerLynn 2011). Ravines and coulees, which cut into the ridges to form trenches, allowed for the shielded advance of the Native American tribes. The bedrock that underlies LIBI is primarily shale and sandstone from the Late Cretaceous Period, about 100 million to 66 million years ago (Figure 26). These geologic units represent sediments originally deposited in the Cretaceous Interior Seaway, a shallow sea that inundated west-central North America. Surficial units consist of Pleistocene (2.6 million to 11,700 years ago) terrace deposits, and Holocene (the past 11,700 years) river alluvium consisting of unconsolidated gravel, sand, silt, and clay. These rocks and unconsolidated deposits give rise to the landforms that ultimately influenced the events and outcomes of the Battle of the Little Bighorn (KellerLynn 2011).

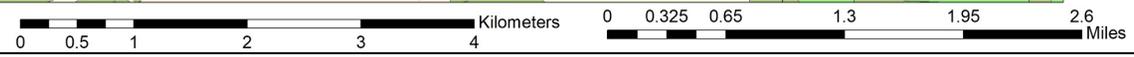
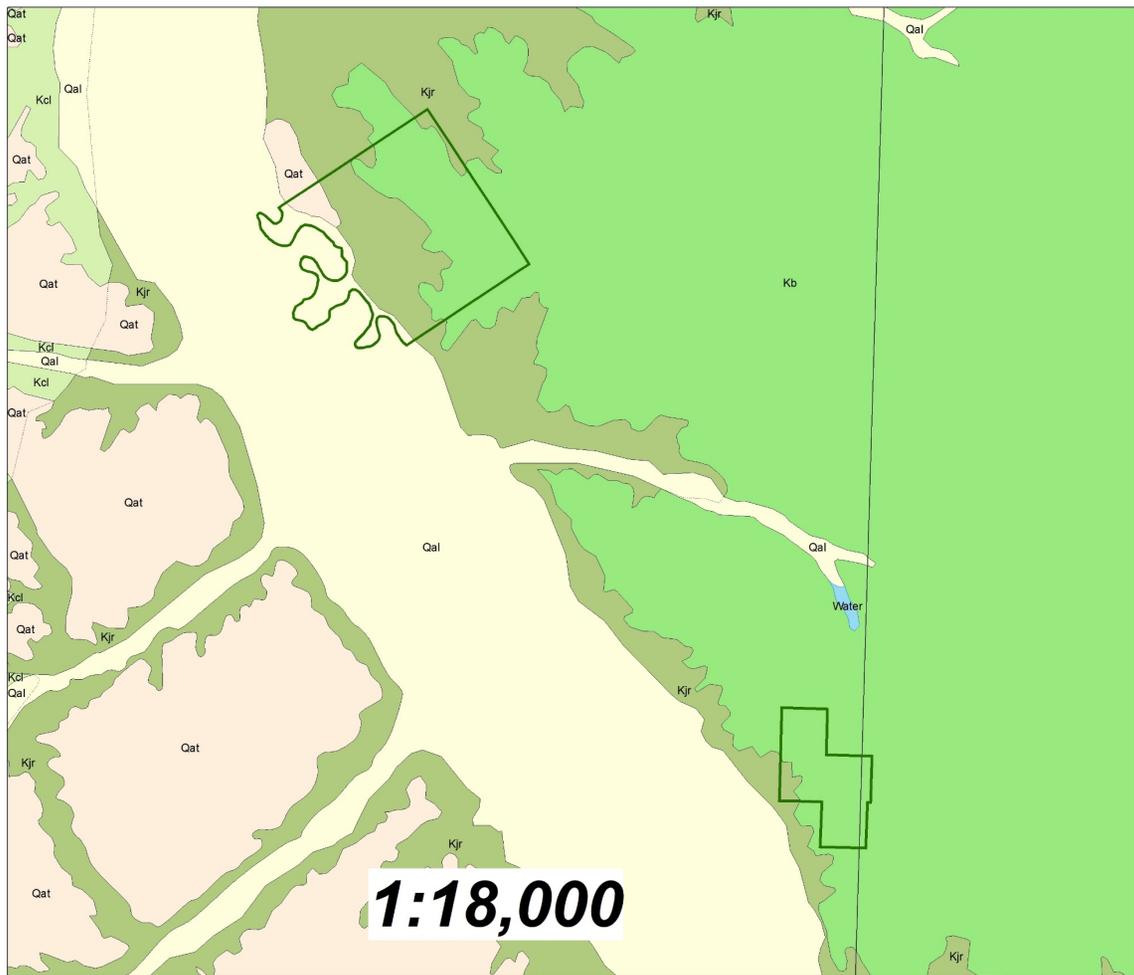
As of the writing of this paper, there are no designated type formations identified within the boundaries of LIBI. There are also no reported stratotypes within 48 km (30 mi) of the park.

# Geology of Little Bighorn Battlefield National Monument, Montana



## Legend

- NPS boundary
- known or certain
- concealed
- water or shoreline
- Qal - Alluvium
- Qat - Alluvial terrace deposit
- Kb - Bearpaw Formation
- Kjr - Judith River Formation
- Kcl - Claggett Formation
- Water



v2020-0806\_1635

Figure 26. Geologic map of LIBI, Montana.



## Rocky Mountain National Park (ROMO)

Rocky Mountain National Park (ROMO) was established on January 26, 1915 and is located in Boulder, Grand, and Larimer counties, northern Colorado (Figure 27). ROMO offers the rich scenery of the majestic Rocky Mountains and encompasses 107,563 hectares (265,795 acres) of mountain meadows, snow-fed streams, rolling alpine uplands, glacial moraines and valleys, volcanoes, lava, and ash (KellerLynn 2004; Anderson 2017). The park consists of towering mountain peaks ranging in elevation from 3,350 to 4,270 m (11,000 to 14,000 ft) above sea level that form the Continental Divide, Trail Ridge, the Mummy Range, and the Never Summer Mountains (KellerLynn 2004). Longs Peak, the tallest mountain in ROMO with an elevation of 4,345 m (14,256 ft) above sea level, rises 2,743 m (9,000 ft) over the nearby lowland plain. More than 480 km (300 mi) of hiking trails provide access from roadways and trailheads to remote alpine country areas of the park. ROMO was designated a Biosphere Reserve in 1976.

Rocks and deposits record the geologic history and evolution of ROMO, which spans nearly two billion years (Figure 28). The ancient age of the rocks that form the core of the mountains in ROMO is impressive. Although not the oldest rocks in the NPS, they are from the Precambrian, which contains the oldest rocks on Earth and harkens back to a time when Earth's early crust and continents were forming (KellerLynn 2004). Longs Peak consists of a mass of the Precambrian-age Silver Plume Granite dated at ~1.4 billion years old (Tweto 1987). Timing of the Rocky Mountain uplift (~70 million years ago) is related to a period of mountain building called the Laramide Orogeny. Isolated exposures of Mesozoic strata from the Western Interior Seaway exist in Laramide-age faults in the western area of the park (Braddock and Cole 1990). Tertiary volcanism formed much of the younger rocks (29 to 23 million years ago) found on the western slope of the park and which constitute much of the Never Summer Mountains (KellerLynn 2004).



Figure 27. Park map of ROMO, Colorado (NPS).

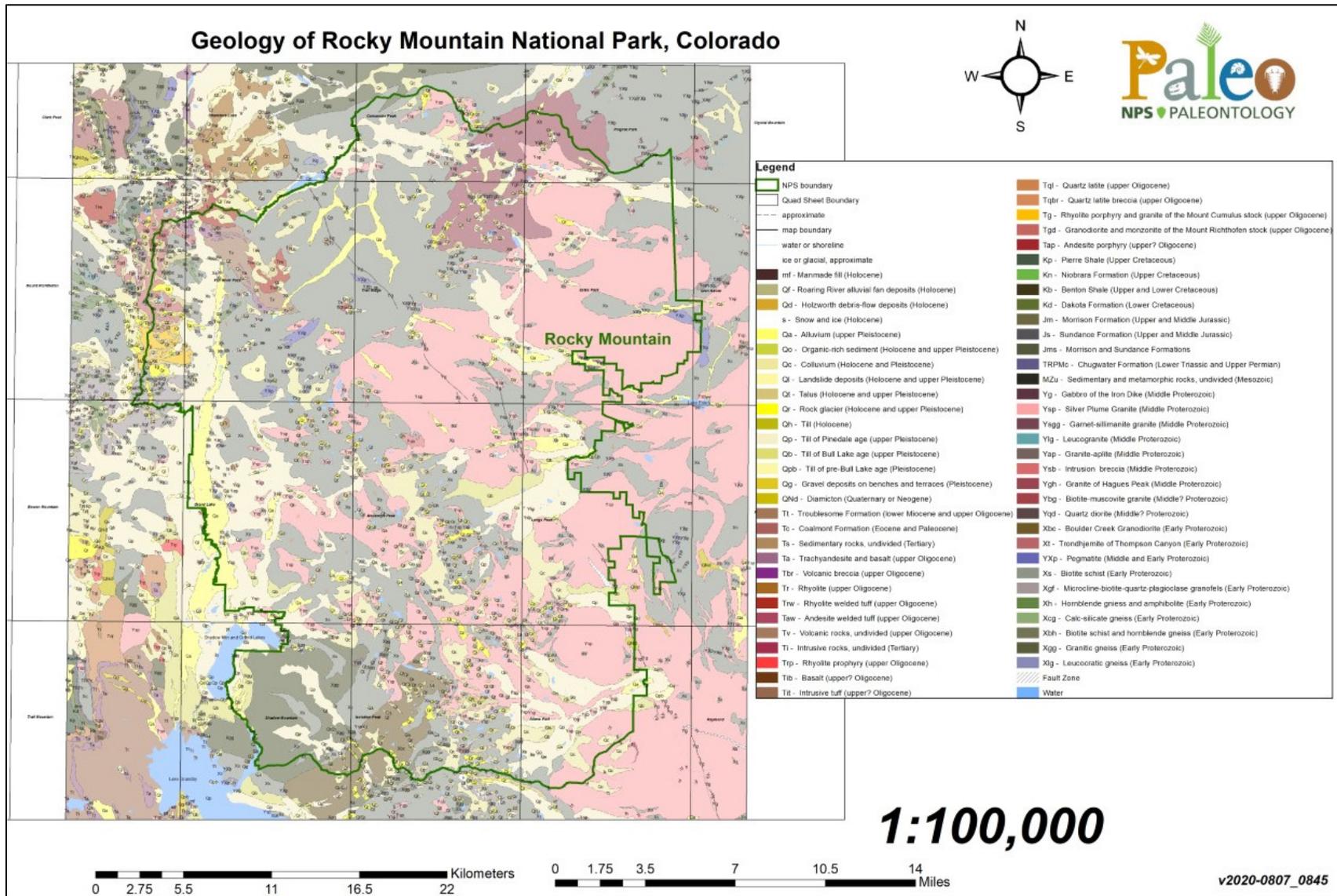


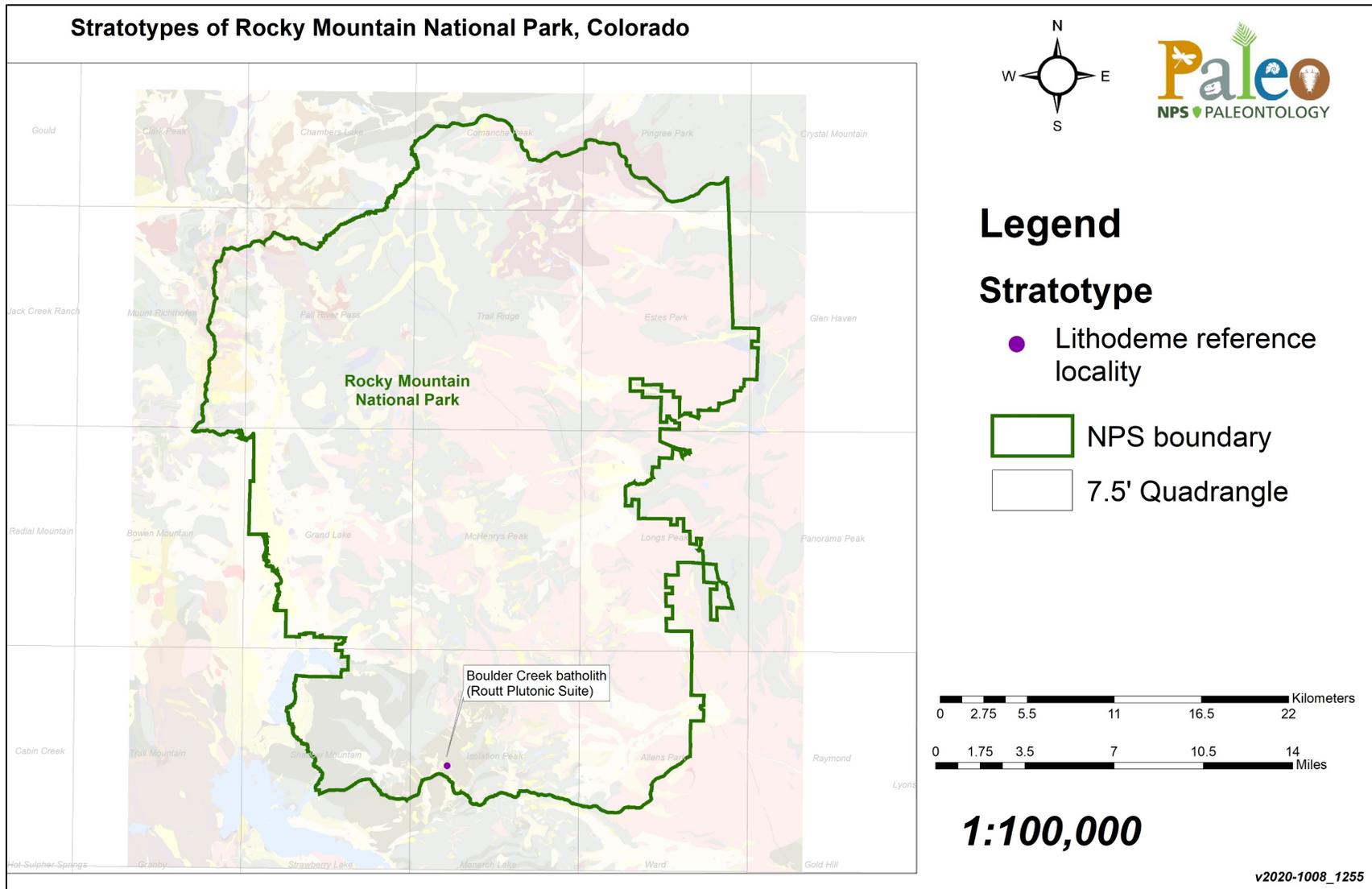
Figure 28. Geologic map of ROMO, Colorado.

ROMO contains a single stratotype occurrence that is assigned to the Proterozoic Boulder Creek batholith and associated Boulder Creek Granodiorite of the Routt Plutonic Suite (Figures 29 and 30; Table 2). The Boulder Creek batholith body constitutes an important lithodeme reference locality for the Routt Plutonic Suite (Tweto 1987). Dominantly consisting of the Boulder Creek Granodiorite, the batholith is located west and southwest of Boulder, Colorado and is widely exposed on Boulder Creek and on the east flank of the Front Range (Boos and Boos 1934; Lovering and Goddard 1950; Tweto 1977). The best-known masses of Boulder Creek Granodiorite occur in the Georgetown 15-minute quadrangle south of Idaho Springs and in the type batholith region west of Boulder extending north from Coal Creek to Lefthand Creek (Lovering and Goddard 1950). Originally described as the Boulder Creek Granite Gneiss (Boos and Boos 1934) and as the Boulder Creek Granite (Lovering and Goddard 1938, 1950; Lovering and Tweto 1953), it was described more accurately as the Boulder Creek Granodiorite (Wells 1967; Gable 1980). The Boulder Creek Granodiorite is coarse-grained and locally coarsely porphyritic; it contains prismatic potassium feldspar crystals 1–5 cm (0.4–2 in) long (Tweto 1987). Biotite is an abundant constituent that occurs as packets of flakes, and hornblende is found as a minor constituent that is locally abundant (Tweto 1987).

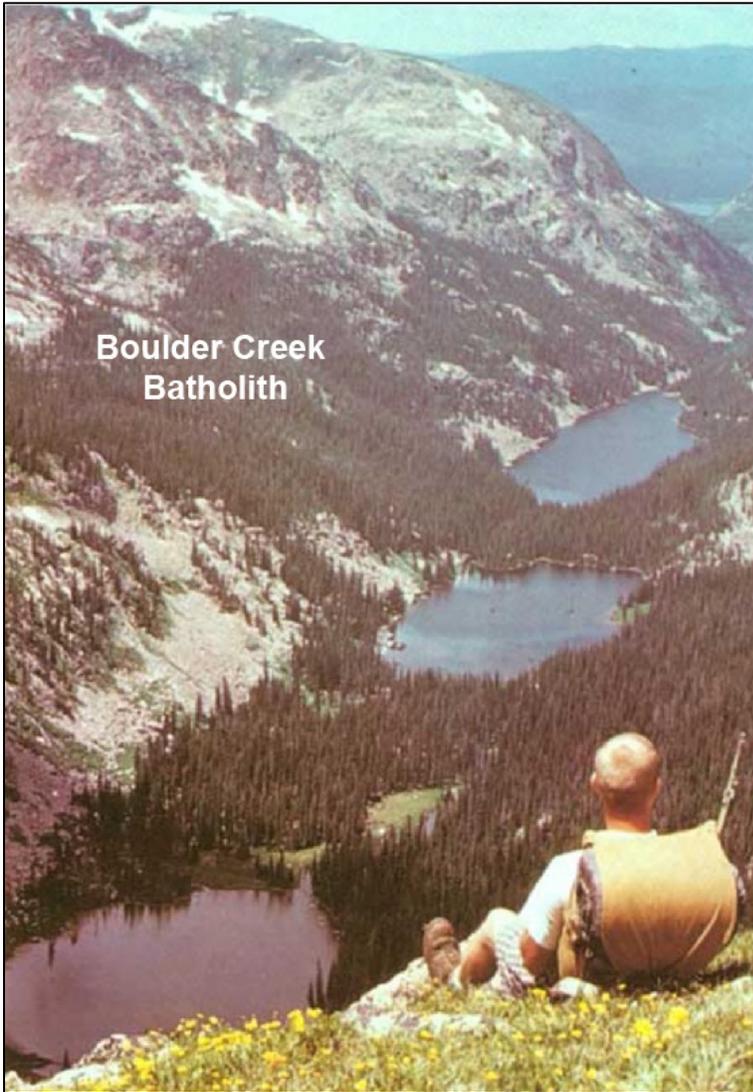
In addition to the designated stratotypes located within ROMO boundaries, a list of stratotypes located within 48 km (30 mi) of park boundaries is included here for reference. These nearby stratotypes include the Proterozoic Silver Plume batholith (lithodeme), Cretaceous Dakota Group (type section), and the Oligocene–Miocene Troublesome Formation (reference section).

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

Unit Name (map symbol)	Reference	Stratotype Location	Age
Boulder Creek batholith; Boulder Creek Granodiorite (Xbc)	Tweto 1987	Lithodeme reference locality: Boulder Creek batholith located west and southwest of Boulder, Colorado	Proterozoic



**Figure 29.** Modified geologic map of ROMO showing stratotype locations. The transparency of geologic units has been increased.



**Figure 30.** View west from Tanina Peak of Fourth, Spirit, and Verna Lakes, scoured by ice in bedrock of the upper canyon of East Inlet. Mountains to the left of the lakes consist of Boulder Creek Granodiorite of the Boulder Creek batholith. Figure modified from Richmond (1974: Figure 24).

## 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 ROMN Geologic Type Section Inventory report is finalized, the NPS Geologic Resources Division will schedule a briefing for the staff of the ROMN network and respective network parks.
- 3) To better safeguard the excellently preserved fossil specimens in FLFO, it is strongly recommended that the Florissant Formation and its members be assigned formal stratotypes (Emmett Evanoff, pers. comm., 2020).
- 4) Localized geologic units such as the Never Summer Range volcanics do not have a designated stratotype but are unique to the area and should not be overlooked by NPS staff. It is recommended that a separate inventory category be established that recognizes geographically distinct geologic units that may never need a type location.
- 5) 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.
- 6) 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.
- 7) 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.
- 8) 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.
- 9) The NPS Geologic Resources Division should ensure the park-specific Geologic Type Section Inventory Reports are widely distributed and available online.
- 10) 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.
- 11) 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.

- 12) 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.
- 13) 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 ROMN Parks

### FLFO

- GMAP 932: Evanoff, E., R. Brill, P. de Toledo, P. Murphy, and R. Cushman. 1992. Surficial geologic map of Florissant Fossil Beds National Monument, Colorado. University of Colorado, Boulder, Colorado. Unpublished map. Scale 1:10,000.
- GMAP 933: Root, R. 1981. Geologic map of Florissant Fossil Beds National Monument, Colorado. National Park Service. Unpublished map. Scale 1:7,000.

### GLAC

- GMAP 1171: Whipple, J. W. 1992. Geologic map of Glacier National Park, Montana. U.S. Geological Survey, Reston, Virginia. Miscellaneous Investigations Series Map 1508-F. Scale 1:100,000. Available at: [https://ngmdb.usgs.gov/Prodesc/proddesc\\_9273.htm](https://ngmdb.usgs.gov/Prodesc/proddesc_9273.htm) (accessed November 20, 2020).
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### GRKO

- GMAP 4950: Berg, R. B. 2004. Geologic map of the Deer Lodge and Conleys Lake 7.5' quadrangles, Powell County, southwestern Montana. Montana Bureau of Mines and Geology, Butte, Montana. Open File Report 509. Scale 1:24,000. Available at: [http://www.mbm.mtech.edu/mbmgcat/public/ListCitation.asp?pub\\_id=11380&](http://www.mbm.mtech.edu/mbmgcat/public/ListCitation.asp?pub_id=11380&) (accessed November 20, 2020).

### GRSA

- GMAP 78: Lindsey, D. A., B. R. Johnson, S. J. Soulliere, R. M. Bruce, and K. Hafner. 1986. Geologic map of the Beck Mountain, Crestone Peak and Crestone quadrangles, Custer, Huerfano and Saguache counties, Colorado. U.S. Geological Survey, Washington, D.C. Miscellaneous Field Studies Map 1878. Scale 1:24,000. Available at: [https://ngmdb.usgs.gov/Prodesc/proddesc\\_7435.htm](https://ngmdb.usgs.gov/Prodesc/proddesc_7435.htm) (accessed November 20, 2020).
- GMAP 80: Johnson, B. R., R. M. Bruce, and D. A. Lindsey. 1989. Reconnaissance geologic map of the Medano Pass Quadrangle and part of the Liberty Quadrangle, Alamosa, Huerfano and Saguache counties, Colorado. U.S. Geological Survey, Reston, Virginia. Miscellaneous Field Studies Map 2089. Scale 1:24,000. Available at: [https://ngmdb.usgs.gov/Prodesc/proddesc\\_5693.htm](https://ngmdb.usgs.gov/Prodesc/proddesc_5693.htm) (accessed November 20, 2020).

- GMAP 81: Lindsey, D. A, S. J. Soulliere, K. Hafner, and R. J. Flores. 1985. Geologic map of Rito Alto Peak and northeastern part of the Mirage quadrangles, Custer and Saguache counties, Colorado. U.S. Geological Survey, Washington, D.C. Miscellaneous Field Studies Map 1787. Scale 1:24,000. Available at: [https://ngmdb.usgs.gov/Prodesc/proddesc\\_7426.htm](https://ngmdb.usgs.gov/Prodesc/proddesc_7426.htm) (accessed November 20, 2020).
- GMAP 83: Johnson, B. R., and R. M. Bruce. 1991. Reconnaissance geologic map of parts of the Twin Peaks and Blanco Peak quadrangles, Alamosa, Costilla and Huerfano counties, Colorado. U.S. Geological Survey, Reston, Virginia. Miscellaneous Field Studies Map 2169. Scale 1:24,000. Available at: [https://ngmdb.usgs.gov/Prodesc/proddesc\\_5798.htm](https://ngmdb.usgs.gov/Prodesc/proddesc_5798.htm) (accessed November 20, 2020).
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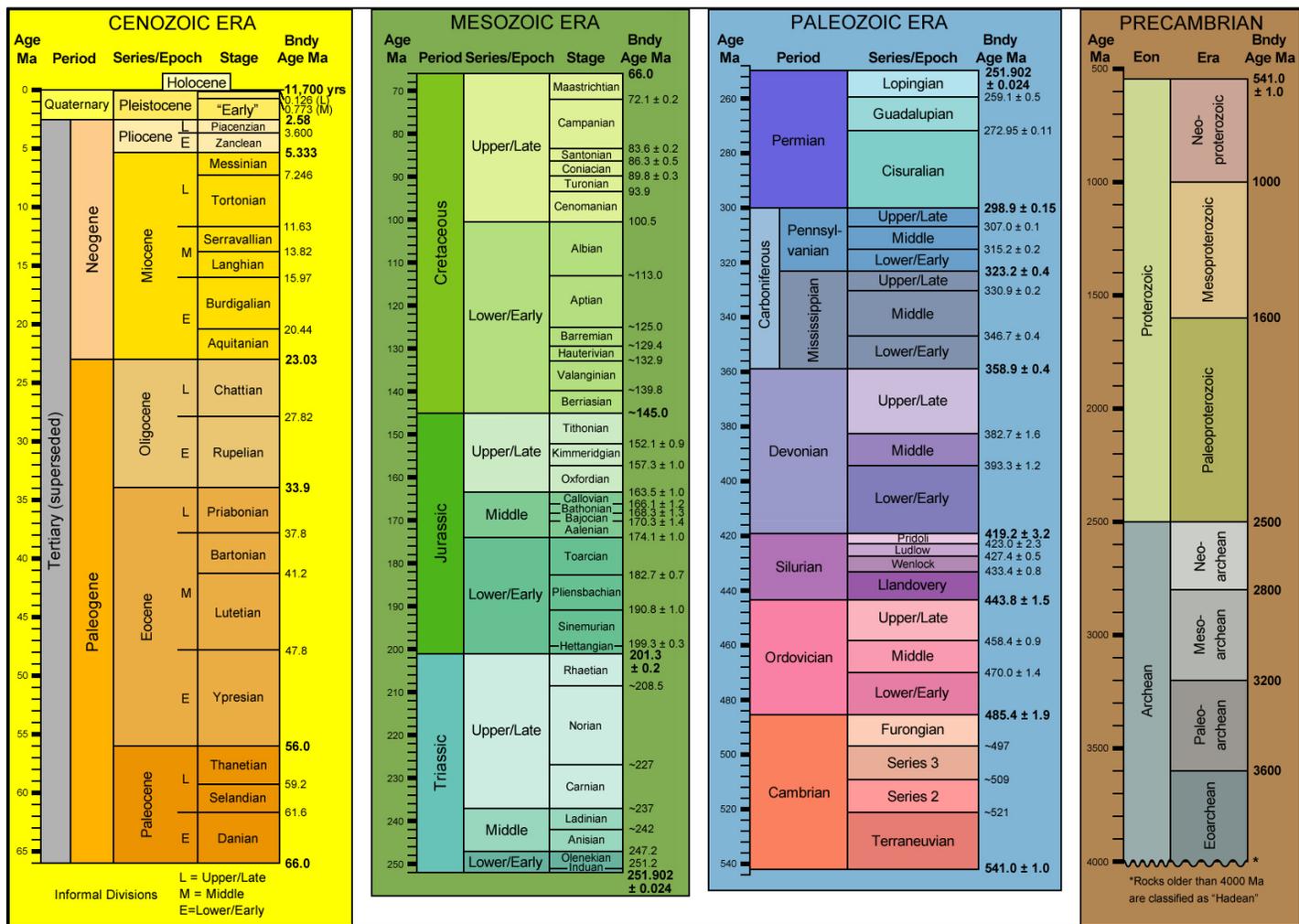
## **LIBI**

- GMAP 2732: Vuke, S. M., E. M. Wilde, D. A. Lopez, and R. N. Bergantino. 2000. Geologic map of the Lodge Grass 30' x 60' Quadrangle, Montana, Montana Bureau of Mines and Geology, Butte, Montana. Geologic Map 56. Scale 1:100,000. Available at: [http://www.mbmgs.mtech.edu/mbmgcat/public/ListCitation.asp?pub\\_id=10211&](http://www.mbmgs.mtech.edu/mbmgcat/public/ListCitation.asp?pub_id=10211&) (accessed November 20, 2020).
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## **ROMO**

- GMAP 141: Braddock, W. A., and J. C. Cole. 1990. Geologic map of Rocky Mountain National Park and vicinity, Colorado. U.S. Geological Survey, Reston, Virginia. Miscellaneous Investigations Series Map 1973. Scale 1:50,000. Available at: [https://ngmdb.usgs.gov/Prodesc/proddesc\\_10051.htm](https://ngmdb.usgs.gov/Prodesc/proddesc_10051.htm) (accessed November 20, 2020).

# 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.

NPS 960/174943, December 2020

**National Park Service**  
**U.S. Department of the Interior**



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