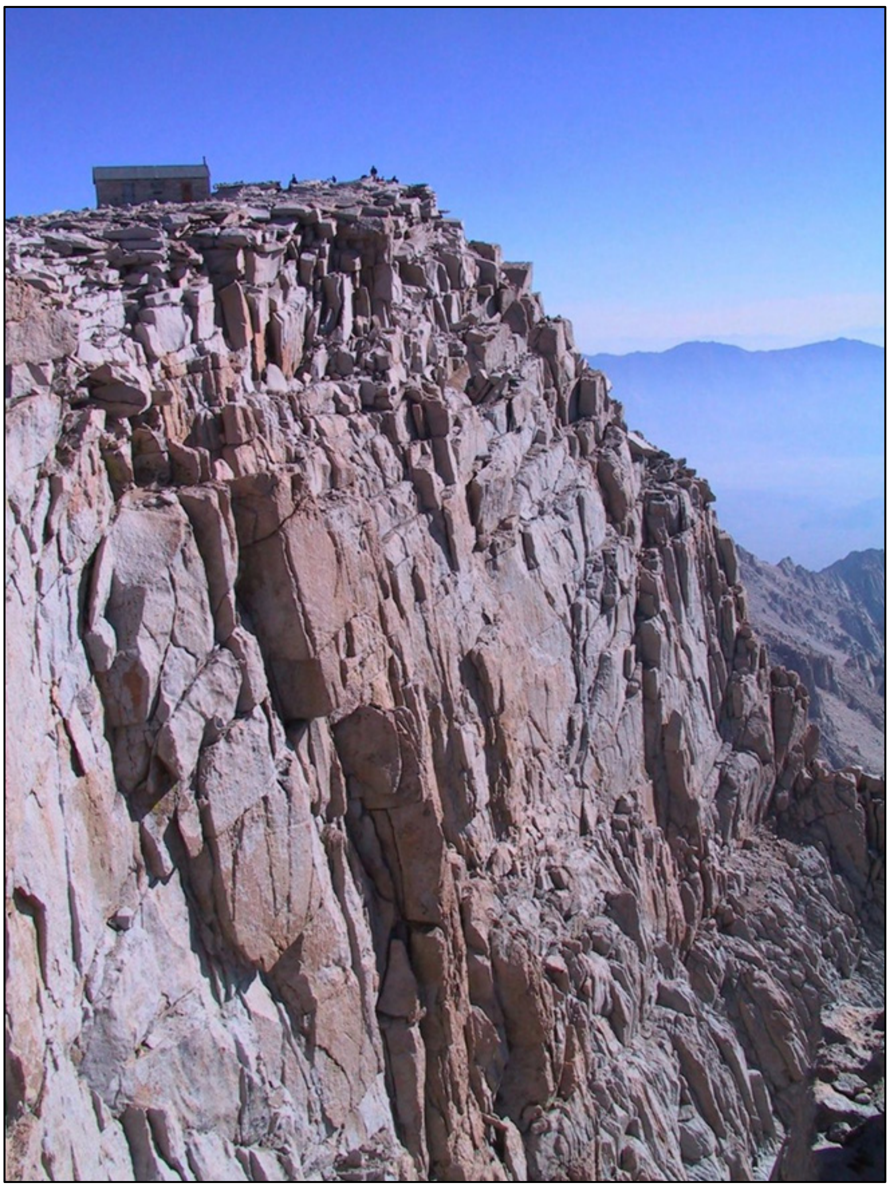
National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

National Park Service Geologic Type Section Inventory

Sierra Nevada Inventory & Monitoring Network

Natural Resource Report NPS/SIEN/NRR—2021/2219



ON THE COVER
Northeast view of the sheer cliffs and summit of Mount Whitney, SEKI, consisting of Late Cretaceous Whitney Granodiorite. NPS photo.

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

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

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

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

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

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Executive Summary

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

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

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

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

Methodologies and reporting adopted for the GRYN have been used in the development of this type section inventory for the Sierra Nevada 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 SIEN shows there are currently no designated stratotypes for Devils Postpile National Monument (DEPO); Sequoia & Kings Canyon National Parks (SEKI) have eight type localities and four type areas; and Yosemite National Park (YOSE) has one type locality and one type area.

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

Acknowledgments

Many individuals were consulted in the preparation of this report on the geologic type sections for the national parks of the Sierra Nevada 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 stratigraphic type section inventory and other important NPS projects. Randy, Nancy and David manage the National Geologic Map Database for the United States (NGMDB, https://ngmdb.usgs.gov/ngm-bin/ngm_compsearch.pl?glx=1) and the U.S. Geologic Names Lexicon ("GEOLEX", https://ngmdb.usgs.gov/Geolex/search), critical sources of geologic map information for science, industry and the American public. We also extend our appreciation to Allen Glazner (University of North Carolina at Chapel Hill) and Matt O'Neal (California Geological Survey) for their assistance with peer review of this inventory report.

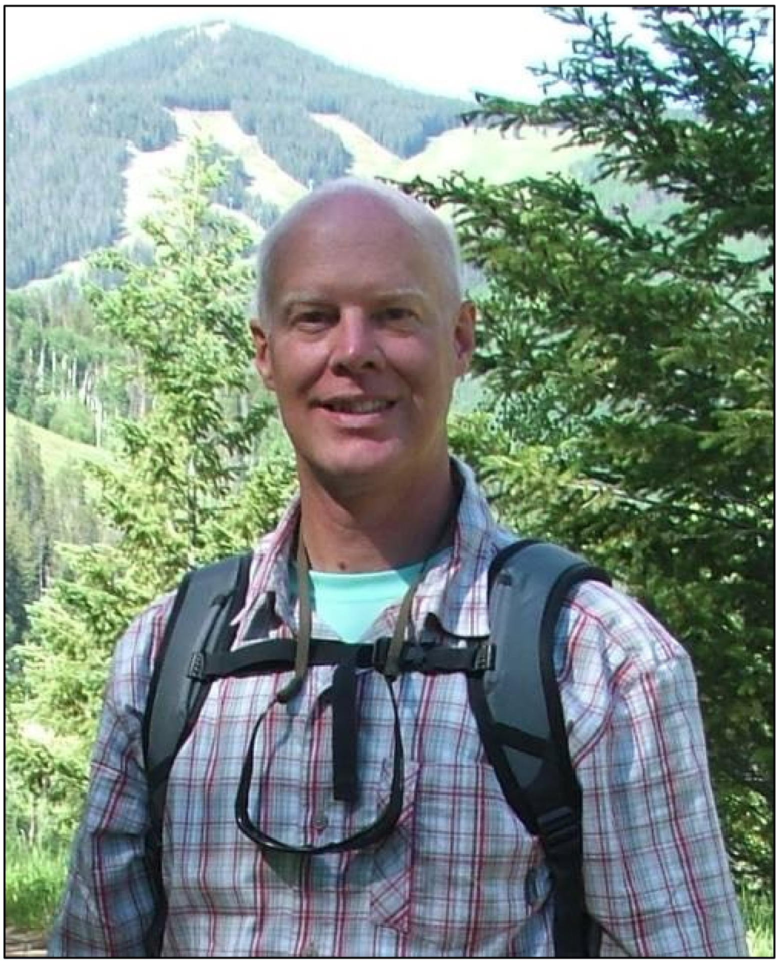
We thank our colleagues and partners in the Geological Society of America (GSA) and Stewards Individual Placement Program for their continued support to the NPS with the placement of geologic interns and other ventures. A special thanks to Jeanette Hammann (GSA Director of Publications) for the permission 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 Sierra Nevada Inventory and Monitoring Network and various network parks including: Sylvia Haultain, Alex Eddy, Jonathan Beals-Nesmith, Linda Mutch, Andi Heard, and Greg Stock. Additional thanks to Warren Nokleburg (USGS emeritus), Allen Glazner, Denise Louie, and Marsha Davis for continued support for this and other important geology projects in the "former" Pacific West Region (now Interior Regions 8, 9, 10, 12) of the NPS.

This project is possible through the support from staff in the National Park Service Geologic Resources Division and we extend our thanks to Guy Adema, Carol McCoy, Hal Pranger, Julia Brunner, Jason Kenworthy, Stephanie O'Meara, Jim Chappell, Katie KellerLynn, Chelsea Bitting, Rebecca Port, Ron Karpilo, Trista Thornberry-Ehrlich, James Winter and Jim Wood. We especially appreciate the dedicated assistance from Lima Soto, the Geoscientists-in-the-Parks Program (GIP) Coordinator, to ensure a highly qualified geology intern was hired for this project.

Dedication

We dedicate this SIEN inventory of geologic type sections to Hal Pranger, Chief of the Geologic Features and Systems Branch for the National Park Service Geologic Resources Division. For more than two decades Hal has helped advance geologic resource management and science in parks through his leadership, advocacy, and sincere interest. This inventory of NPS geologic type sections was made possible through Hal's support.



Hal Pranger

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 re-examined, 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 Sierra Nevada Inventory & Monitoring Network (SIEN) 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 helps to define characteristics used in classification;
- The documentation of geologic type sections in NPS areas has not been previously inventoried and there is a general absence of baseline information for this geologic resource category;
- NPS staff in parks may not be aware of the concept of geologic type sections and therefore may not understand the significance or occurrence of these natural landmarks in parks;
- Given the importance of geologic type sections as geologic landmarks and geologic heritage resources, these locations should be afforded some level of preservation or protection when they occur within NPS areas;
- If NPS staff are unaware of geologic type sections within parks, the NPS would not proactively monitor the stability, condition, or potential impacts to these locations during normal park operations or planning. The lack of baseline information pertaining to the geologic type sections in parks would limit the protection of these localities from activities which may involve ground disturbance or construction. Therefore, considerations need to be addressed about how the NPS may preserve geologic type sections and better inform NPS staff about their existence in the park.
- 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 Sierra Nevada I&M Network Parks

The Sierra Nevada Inventory & Monitoring Network (SIEN) consists of three parks: Devils Postpile National Monument (DEPO), Sequoia & Kings Canyon National Parks (SEKI), and Yosemite National Park (YOSE) (Figure 1). These parks are situated within the Sierra Nevada, a mountain range that extends north to south approximately 640 km (400 mi) along eastern California. To the east is the Basin and Range Province and to the west is the Great Valley Province of California. The Sierra Nevada is an asymmetrical range, with the peaks of highest elevation on the eastern flank. SEKI includes the tallest mountain in the continental United States (Mount Whitney), which rises to 4,421 m (14,505 ft) above sea level. YOSE contains two dozen peaks which reach more than 3,660 m (12,000 ft) in elevation, the highest of which is Mount Lyell at 3,997 m (13,114 ft) above sea level.

Geologically, the bedrock geology of the SIEN parks is dominated by granitic rocks formed during the Mesozoic. These rocks make up a batholith, an enormous igneous intrusion composed of numerous smaller bodies (plutons), in this case representing the backbone of the Sierra Nevada range (see Appendix B for a geologic time scale). The Mesozoic granitic magmas intruded older metamorphic rocks which are present as belts adjacent to, and also as engulfed fragments within the batholith. Overlying the granitic and metamorphic basement rocks in places are younger Cenozoic-age volcanic and sedimentary rocks. The Sierra Nevada is a massive uplifted and westward-tilted block of crust. This uplift occurred over the past several million years. The eastern edge of the uplifted mountains is an escarpment which has been heavily eroded by ice and water, forming a series of steep canyons. The western flank is a more gently dipping slope with alluvial fan development toward the Central Valley.

During the Pleistocene Epoch glaciers formed in the Sierra Nevada and sculpted the geologic landscape. The fluvial cut valleys were carved by glaciers into the famous U-shaped valleys and hanging valleys prominent in Yosemite Valley in YOSE. Large cirques, many glacial lakes and extensive accumulations of moraines are all evidence of past glacial activity in the parks of the SIEN. Glacial striations are seen in all the SIEN parks; the glacial polish and striations atop the columnar jointing are iconic features at DEPO.

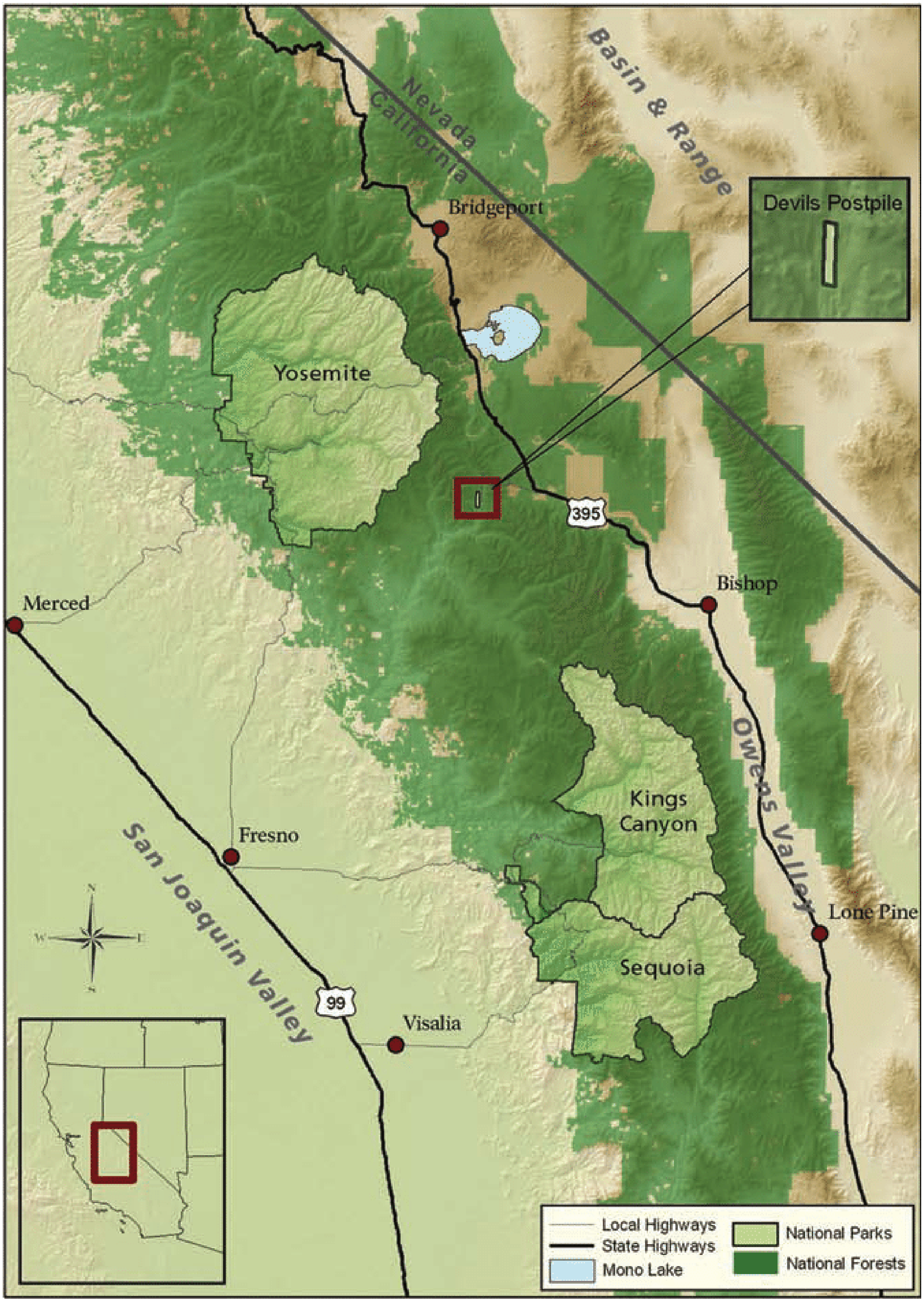


Figure 1. Map of Sierra Nevada Network parks: Devils Postpile National Monument (DEPO), Sequoia and Kings Canyon National Parks (SEKI), and Yosemite National Park (YOSE) (NPS/LINDA MUTCH).

Precambrian

There are no known Precambrian rocks exposed within the parks of the SIEN.

Paleozoic

The Paleozoic history of SEKI is not well studied or understood, although isolated Paleozoic strata occur east and north of the park. The Paleozoic units of interest in SEKI include the Cambrian Poleta and Campito formations, Pennsylvanian–Permian Keeler Canyon Formation, and Permian Lone Pine Formation. Moore and Foster (1980) provide an overview of Paleozoic metasedimentary rocks in the Sierra Nevada.

The oldest rocks in YOSE are Paleozoic metasedimentary and metavolcanic rocks preserved in roof pendants (localized remnants of the original intruded rock) on top of the batholith. Near the crest of the Sierra Nevada, on the eastern boundary of YOSE, is a contact between the Eastern Metamorphic Belt and the granitic batholith. These Paleozoic units include the Pennsylvanian–Permian Twin Peaks Sequence, Gull Lake roof pendant rocks, and Ritter Range roof pendant rocks. A similar Western Metamorphic Belt occurs just outside of the park's western boundary. The metasedimentary and metavolcanic rocks which flank the batholith on the west are referred to as the Calaveras Assemblage.

Mesozoic

The Mesozoic history of SEKI is represented by Triassic and Jurassic metasedimentary and metavolcanic rocks preserved as screens (remnants of the original intruded rock). The Mesozoic metamorphic rocks are well-exposed in the canyons of Kings River and Kaweah River, as well as in the Mineral King portion of the park. These rock units consist of marbles, schists, and cherts which are found in association with metavolcanic rocks. Many of the SEKI caves are formed within the Mesozoic marbles exposed in the park. During the Cretaceous, plutonic (intrusive igneous) activity was widespread in the Sierra Nevada. The Sierra Nevada batholith plutons were emplaced in a complex series of episodic events (Bateman 1992). The older granitic rocks have been dated from the western portion of the park and the younger granitic rocks were determined to be near the crest of the Sierra Nevada. The older intrusive rocks have a more mafic composition such as quartz diorite.

At YOSE, erosion has removed most of the Paleozoic and Jurassic rocks directly above the batholith. During the Early Cretaceous a series of widespread and complex igneous intrusion events occurred throughout the region. Within what is now Yosemite Valley, a series of magmas intruded the Paleozoic and Mesozoic sequences that belong to the Yosemite Valley Intrusive Suite and Fine Gold Intrusive Suite. The youngest of the Cretaceous intrusive events are represented by the Tuolumne Intrusive Suite. Together these suites consist of several units named after iconic geologic features of the park, including El Capitan Granite, Taft Granite, Granodiorite of Arch Rock, Sentinel Granodiorite, Half Dome Granodiorite, and Cathedral Peak Granodiorite. A total of eight separate intrusive suites are situated in YOSE and represent major events associated with the emplacement of the composite batholith (Figure 2).

At DEPO, an Upper Cretaceous intrusive unit known as the Cathedral Peak Granodiorite is mapped within the monument.

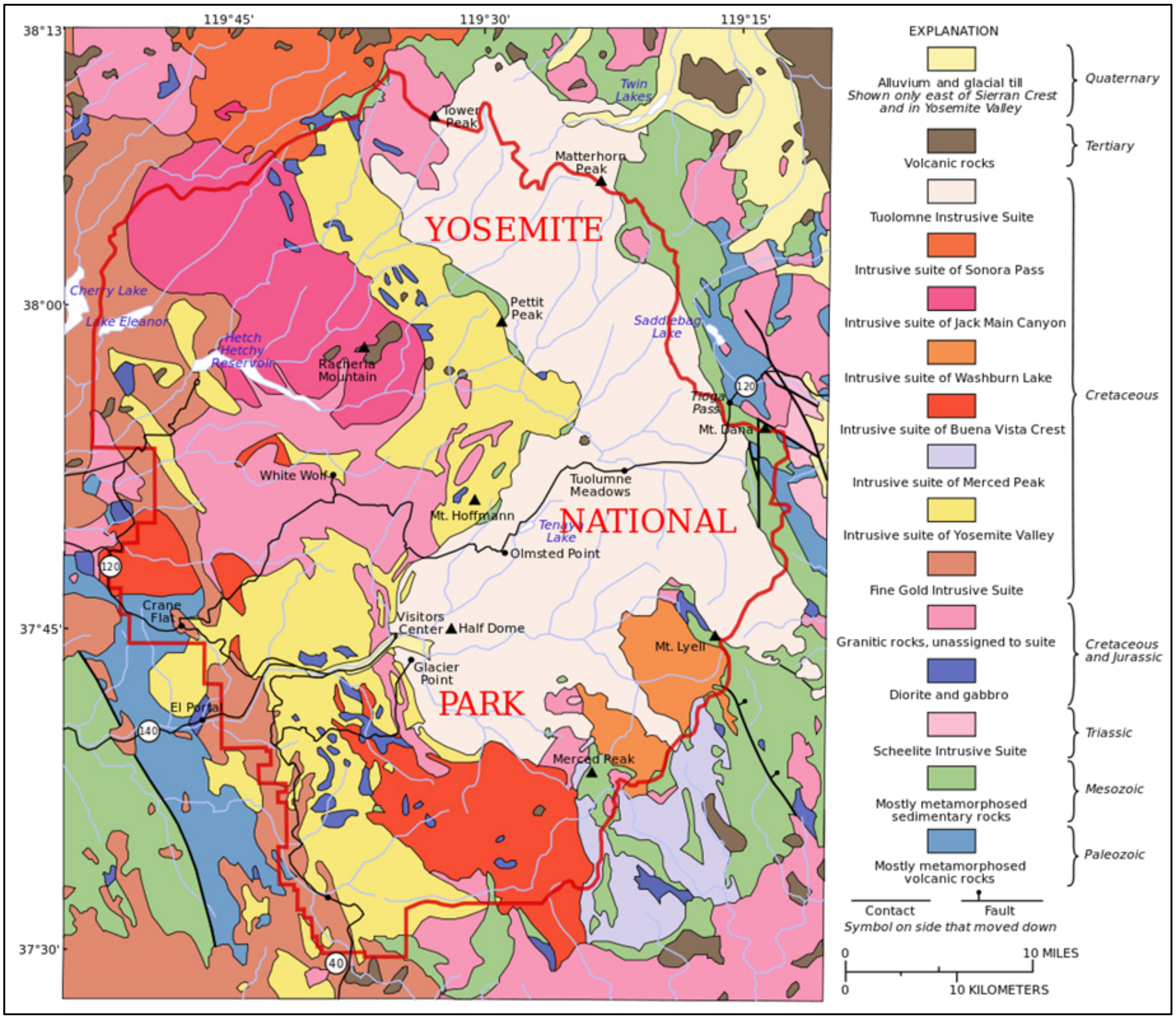


Figure 2. Generalized geologic map of the Sierra Nevada batholith in the region of YOSE showing various intrusive igneous suites (USGS).

Cenozoic

There are no exposed Cenozoic-age plutonic rocks in the Sierra Nevada batholith. Originally the batholith was formed at considerable depth and was covered by older Paleozoic and Mesozoic rock sequences. Today nearly all the Paleozoic and Mesozoic metamorphic rocks have been removed through erosion, leaving only some isolated screens and pendants. A sequence of Pliocene volcanics occur in SEKI, along with surficial Quaternary sediments and alluvium.

Glaciation at SEKI was not as extensive as at YOSE. However, the landscape has been influenced and shaped by the action of alpine glaciers. The development of glaciers in the southern Sierra began early, perhaps during the Late Pliocene. The river valleys on the western slope were transformed through glacier scouring to form typical U-shaped topography. The impacts of glaciation are more evident in Kings Canyon National Park than in Sequoia National Park. A period of renewed glacial development is documented at Kings Canyon National Park during the Little Ice Age (1450–1850

AD), when glaciers were re-established in Pleistocene cirques. Small valley glaciers also advanced near Mount Goddard and in the Palisades region along the northeast boundary of the park.

Regionally, there was volcanic activity during the Late Cenozoic. Most of the volcanic rocks of this period occur outside of the park boundaries except for some exposures north of the Grand Canyon of the Tuolumne River. These units are largely andesitic and include some lahar deposits (volcanic mudflows). As the Sierra Nevada was uplifted, a western and southwestern drainage pattern developed. The Merced River and other rivers incised into the western slopes of the mountains and eventually developed into broad river valleys. The drainage of tributaries to the Merced River proceeded at different rates and traversed rocks of varying hardness and resistance to erosion. As a result, waterfalls began to develop in the tributaries, such as Bridalveil Creek, which crossed more resistant rock.

By the Pleistocene, Yosemite Valley was a deep and V-shaped river valley with steep ridges dividing the tributary drainages. Pleistocene glacial activity dramatically altered its surface features and topography. Differential downcutting by tributary drainages resulted in the development of waterfalls emerging from the hanging valleys. Severe erosion occurred during advances within each of the four stages of glacial activity identified in YOSE (youngest to oldest): Sherwin, Tahoe, Tenaya, and Tioga. The earlier stages were longer and resulted in greater amounts of erosion. Most of the evidence of the Sherwin Glacial Stage was destroyed by younger stages. Tahoe Glacial Stage moraines indicate that glaciation extended a few kilometers west of El Portal near the park entrance. The Graveyard Glacial Stage advanced to the base of Bridalveil Falls. The Tioga Glacial Stage is the most recent of the glacial advances and is represented by the most extensive and undissected moraines.

Yosemite's Pleistocene glaciers were extremely thick and largely re-shaped Yosemite Valley. They rounded the V-shaped river valley to a classic U-shaped glacial valley floor. Glaciers further excavated and sculptured the area to form giant staircases and hanging valleys within the tributary valleys. Many of the famous waterfalls cascade over the staircases or dramatically drop, sometimes several hundred feet, from the locations where the hanging valleys open into Yosemite Valley. Glacial deposits and other evidence of the glacial activity can be found throughout the park. The last glacier retreated from Yosemite Valley approximately 15,000 years ago, depositing significant amounts of alluvial outwash, glacial debris and moraine material. Lake Yosemite temporarily developed behind the glacial deposits. The floor of Yosemite Valley is blanketed with approximately 610 m (2,000 ft) of alluvium. Glacial deposits and other evidence of the glacial activity can be found throughout the park. Today nearly 25 small glaciers occur within the park. During the last 3,000 to 4,000 years, groves of giant sequoia trees have been re-established in isolated areas along the western slopes of the Sierra Nevada, after being nearly extirpated by the widespread and successive Pleistocene glaciations. The giant sequoias have an affinity for sandy loam soils derived from granitic rock.

The Cenozoic geology of DEPO is dominated by a thick sequence of Quaternary volcanic flows, which includes the park's notable columnar basalts. Volcanism is associated with faulting in the eastern Sierra Nevada beginning approximately 3 million years ago. The oldest volcanic rocks in or near Devils Postpile are Quaternary basalt flows which date to about 82,000 years ago (Hildreth et al. 2014). The proposed source of the lava is near the Upper Soda Springs Campground, at the north end of Pumice Flat on the floor of the Middle Fork of the San Joaquin River. The lava flow appears to have been impounded by moraines and accumulated to a thickness of approximately 120 m (400 ft). Basalt flows at DEPO exhibit specialized fracturing (columnar joints) which occurred during the cooling and crystallization of the lava and divided it into tall polygonal columns or pillars. More recent Pleistocene glaciation eroded and removed large portions of the volcanic rocks, exposing the columnar basalts at DEPO and leaving a veneer of glacial polish.

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 SIEN parks:

- SEKI: September 23–24, 2002
- DEPO: September 25–26, 2002
- YOSE: September 25–26, 2002

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 SIEN except SEKI. 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 SIEN parks follows the selected source maps and includes components such as: faults, mine area features, mine point features, geologic contacts, geologic units (bedrock, surficial, glacial), geologic line features, structure contours, and so forth.

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

Geologic Maps

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

Source Maps

The GRI team does not conduct original geologic mapping. The team digitizes paper maps and compiles and converts digital data to conform to the GRI GIS data model. The GRI GIS dataset includes essential elements of the source maps such as map unit descriptions, a correlation chart of units, a map legend, map notes, cross sections, figures, and references. These items are typically included in a master geology document (PDF) for a specific park. The GRI team uses a unique "GMAP ID" value for each geologic source map, and all sources to produce the GRI GIS datasets for the SIEN 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 SEKI was compiled using data model version 2.1; versions 2.0+ are available at https://www.nps.gov/articles/gri-geodatabase-model.htm; the data for DEPO and YOSE 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 DEPO, SEKI, or YOSE from the unit list.

The following components are part of the dataset:

- 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 SIEN. 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 SIEN, 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 3).

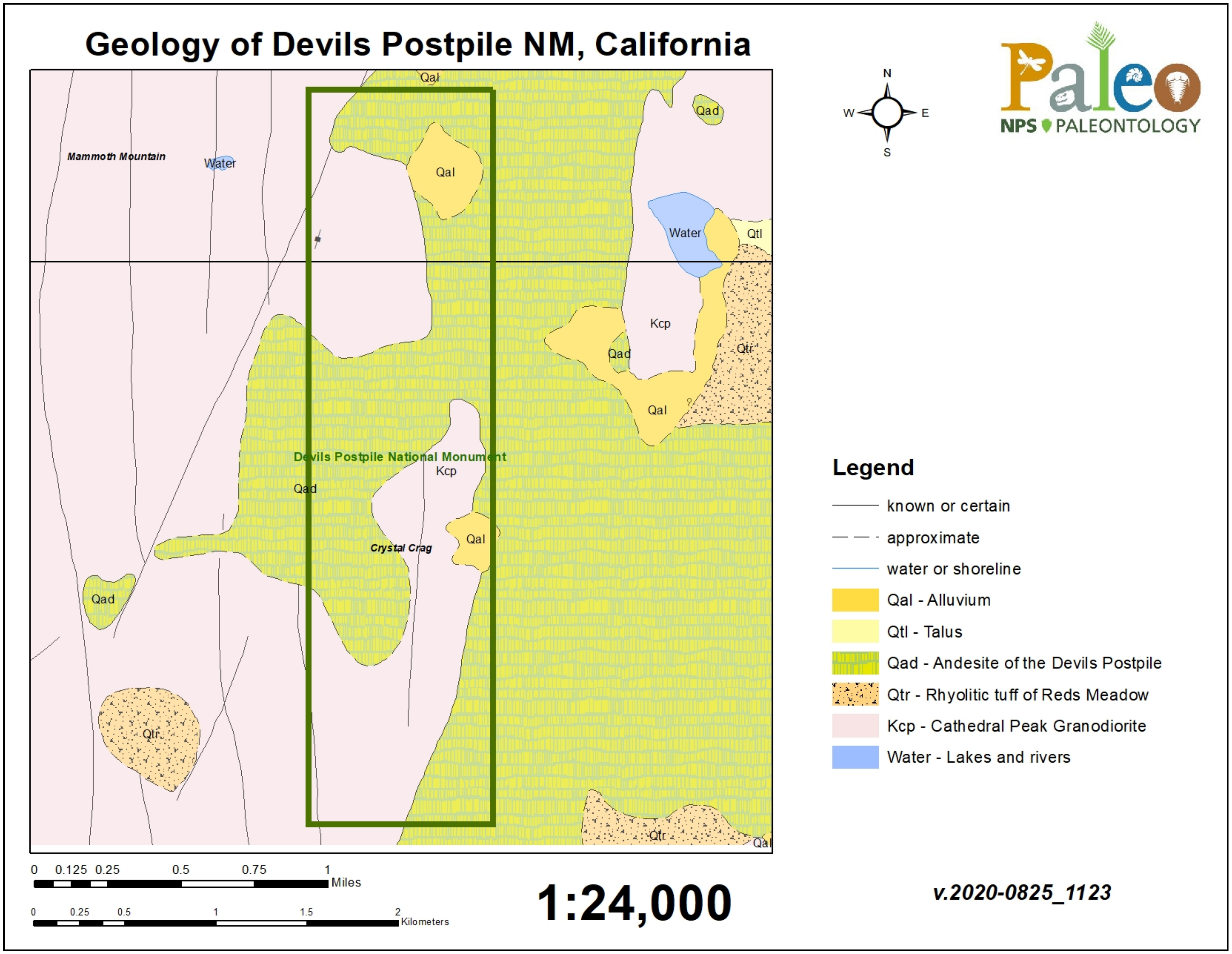


Figure 3. Screenshot of digital geologic map of DEPO showing mapped units.

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 4 below is taken from a search on the Mount Whitney Intrusive Suite.

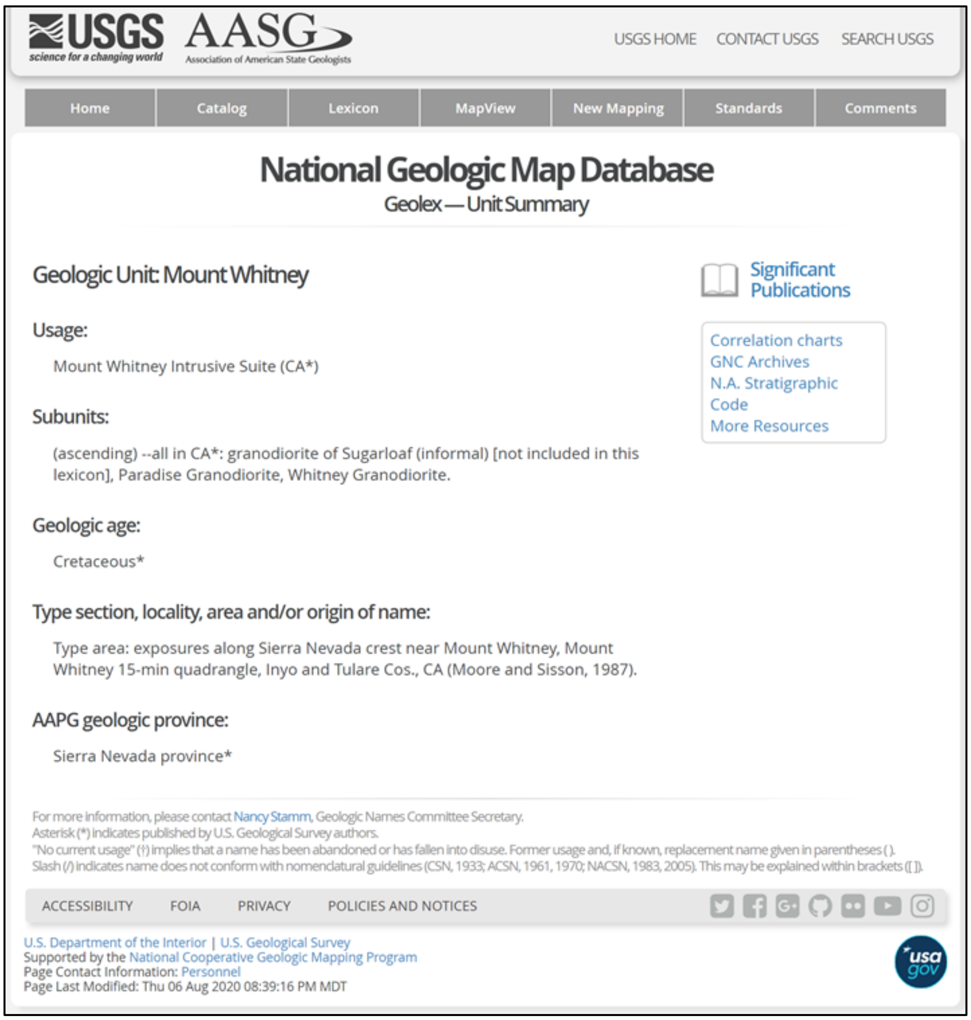
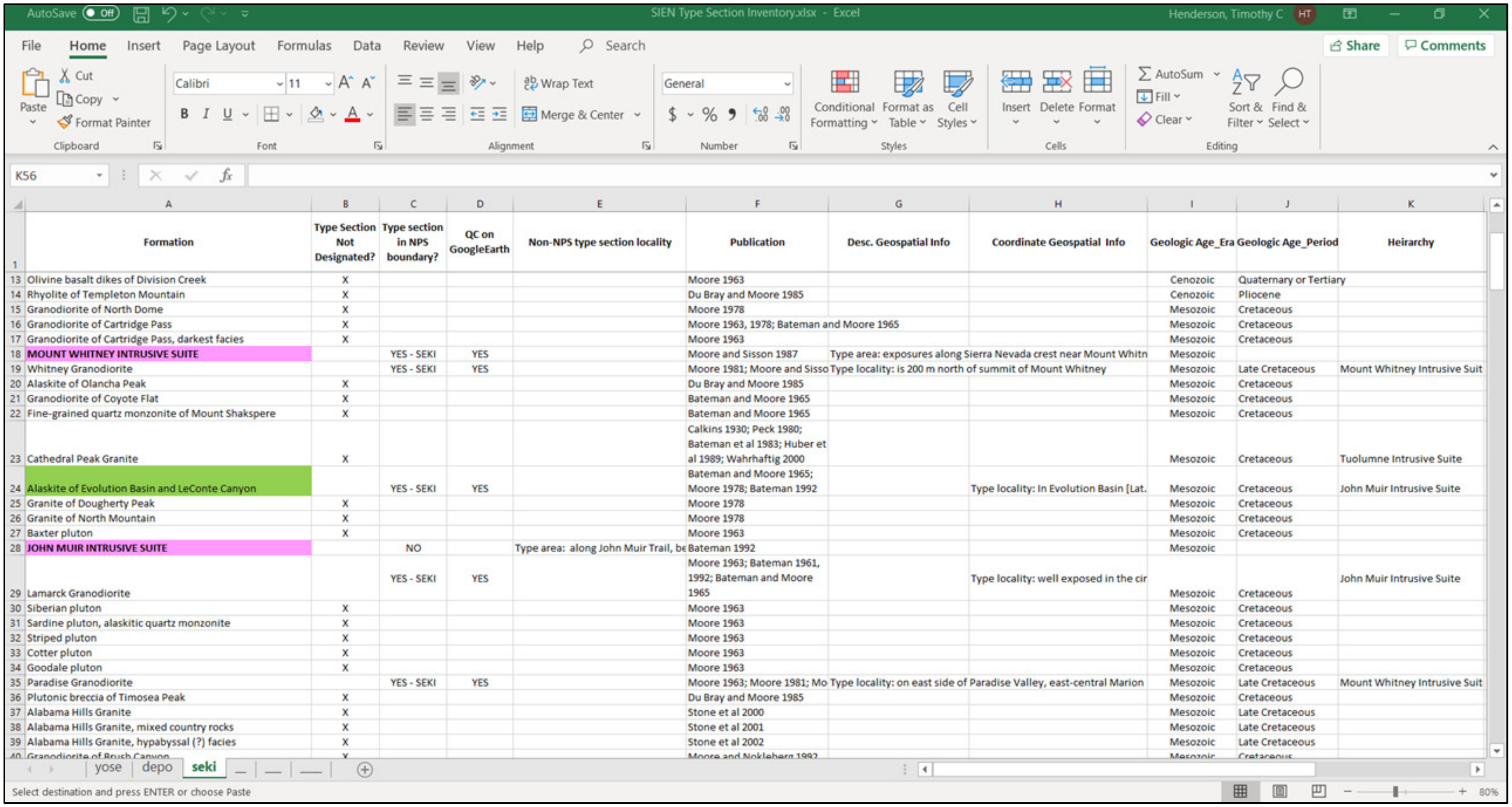


Figure 4. GEOLEX search result for the Mount Whitney Intrusive Suite unit.

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

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



	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	Olivine basalt dikes of Division Creek	X				Moore 1963			Cenozoic	Quaternary or Tertiary	
14	Rhyolite of Templeton Mountain	X				Du Bray and Moore 1985			Cenozoic	Pliocene	
15	Granodiorite of North Dome	X				Moore 1978			Mesozoic	Cretaceous	
16	Granodiorite of Cartridge Pass	X				Moore 1963, 1978; Bateman and Moore 1965			Mesozoic	Cretaceous	
17	Granodiorite of Cartridge Pass, darkest facies	X				Moore 1963			Mesozoic	Cretaceous	
18	**MOUNT WHITNEY INTRUSIVE SUITE**		YES - SEKI	YES		Moore and Sisson 1987	Type area: exposures along Sierra Nevada crest near Mount Whitn		Mesozoic		
19	Whitney Granodiorite		YES - SEKI	YES		Moore 1981; Moore and Sisso	Type locality: is 200 m north of summit of Mount Whitney		Mesozoic	Late Cretaceous	Mount Whitney Intrusive Suit
20	Alaskite of Olancha Peak	X				Du Bray and Moore 1985			Mesozoic	Cretaceous	
21	Granodiorite of Coyote Flat	X				Bateman and Moore 1965			Mesozoic	Cretaceous	
22	Fine-grained quartz monzonite of Mount Shakspere	X				Bateman and Moore 1965			Mesozoic	Cretaceous	
23	Cathedral Peak Granite	X				Calkins 1930; Peck 1980; Bateman et al 1983; Huber et al 1989; Wahrhaftig 2000			Mesozoic	Cretaceous	Tuolumne Intrusive Suite
24	Alaskite of Evolution Basin and LeConte Canyon		YES - SEKI	YES		Bateman and Moore 1965; Moore 1978; Bateman 1992		Type locality: In Evolution Basin [Lat.	Mesozoic	Cretaceous	John Muir Intrusive Suite
25	Granite of Dougherty Peak	X				Moore 1978			Mesozoic	Cretaceous	
26	Granite of North Mountain	X				Moore 1978			Mesozoic	Cretaceous	
27	Baxter pluton	X				Moore 1963			Mesozoic	Cretaceous	
28	**JOHN MUIR INTRUSIVE SUITE**		NO		Type area: along John Muir Trail, be	Bateman 1992			Mesozoic		
29	Lamarck Granodiorite		YES - SEKI	YES		Moore 1963; Bateman 1961, 1992; Bateman and Moore 1965		Type locality: well exposed in the cir	Mesozoic	Cretaceous	John Muir Intrusive Suite
30	Siberian pluton	X				Moore 1963			Mesozoic	Cretaceous	
31	Sardine pluton, alaskitic quartz monzonite	X				Moore 1963			Mesozoic	Cretaceous	
32	Striped pluton	X				Moore 1963			Mesozoic	Cretaceous	
33	Cotter pluton	X				Moore 1963			Mesozoic	Cretaceous	
34	Goodale pluton	X				Moore 1963			Mesozoic	Cretaceous	
35	Paradise Granodiorite		YES - SEKI	YES		Moore 1963; Moore 1981; Mo	Type locality: on east side of Paradise Valley, east-central Marion		Mesozoic	Late Cretaceous	Mount Whitney Intrusive Suit
36	Plutonic breccia of Timosea Peak	X				Du Bray and Moore 1985			Mesozoic	Cretaceous	
37	Alabama Hills Granite	X				Stone et al 2000			Mesozoic	Late Cretaceous	
38	Alabama Hills Granite, mixed country rocks	X				Stone et al 2001			Mesozoic	Late Cretaceous	
39	Alabama Hills Granite, hypabyssal (?) facies	X				Stone et al 2002			Mesozoic	Late Cretaceous	
40	Granodiorite of Brush Canyon	X				Moore and Nokleberg 1992			Mesozoic	Cretaceous	

Figure 5. Stratotype inventory spreadsheet of SIEN displaying attributes appropriate for geolocation assessment. Purple highlighted cells represent units that were added to the list of GRI geologic formations. Green highlighted cells represent units that have been formally renamed.

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 principal reference section may also be designated for units whose stratotypes have been destroyed, covered, or are otherwise inaccessible (North American Commission on Stratigraphic Nomenclature 2005). Multiple reference sections can be designated for a single unit to help illustrate heterogeneity or some critical feature not found in the stratotype. Reference sections can help supplement unit stratotypes in the case where the stratotype proves inadequate (North American Commission on Stratigraphic Nomenclature 2005).

(4) **Lithodeme**: the term "lithodeme" is defined as a mappable unit of plutonic, highly metamorphosed, or pervasively deformed rock and is a term equivalent in rank to "formation" among stratified rocks (North American Commission on Stratigraphic Nomenclature 2005). The formal name of a lithodeme consists of a geographic name followed by a descriptive term that denotes the average modal composition of the rock (example: Cathedral Peak Granodiorite). Lithodemes are commonly assigned type localities, type areas, and reference localities.

Devils Postpile National Monument (DEPO)

Devils Postpile National Monument (DEPO) was established on July 6, 1911 and is located 17 km (11 mi) southeast of YOSE in Madera County, California. The monument lies near the escarpment that defines the eastern edge of the Sierra Nevada fault block and encompasses approximately 324 hectares (800 acres; Figure 6). DEPO preserves and protects the glacially exposed columnar basalts of the Devils Postpile, the scenic Rainbow Falls, and the wilderness landscape of the upper Middle Fork San Joaquin River (Anderson 2017). The vertical columnar basalt at DEPO is world-renowned and a rare geological feature requiring homogeneous lava to solidify and crack under exceptionally uniform cooling conditions. These polygonal columns—the "posts" for which DEPO was named—stand 12 to 18 m (40 to 60 ft) high and are up to 1.1 m (3.5 ft) in diameter (Graham 2010). The columns are part of an informal geologic unit known as the Andesite of the Devils Postpile (Graham 2010). Traversing DEPO are both the John Muir Trail and Pacific Crest National Scenic Trail.

The geology of DEPO consists predominantly of Quaternary (2.6 million years ago to the present) extrusive volcanic rocks and Cretaceous (145 to 66 million years ago) intrusive igneous rocks. Rock units mapped in the vicinity of DEPO include Paleozoic- to Mesozoic-age metamorphosed sedimentary and volcanic rocks (Figure 7; Huber and Rinehart 1965). Approximately 82,000 years ago, a volcanic eruption filled the valley of the Middle Fork of the San Joaquin River with andesitic lava to a depth of 120 m (400 ft) (Hildreth et al. 2014). This remarkably deep lava flow would slowly cool to form the columnar features the monument takes its name after. After the lava solidified, Pleistocene glacial erosion removed approximately half of the flow, exposing the thick interior and sides of the columns (Graham 2010). Other volcanic features present in DEPO include the volcanic cliffs of The Buttresses and the 31 m (101 ft)-tall Rainbow Falls, both of which resulted from separate lava flows.

As of the writing of this paper, there are no designated stratotypes identified within the boundaries of DEPO. In addition to the designated stratotypes located within DEPO boundaries, a list of stratotypes located within 48 km (30 mi) of park boundaries is included here for reference. These nearby stratotypes include the Triassic Scheelite Intrusive Suite (type area), Wheeler Crest Granodiorite (type locality), Cretaceous John Muir Intrusive Suite (type area), Lake Edison Granodiorite (type locality), Round Valley Peak Granodiorite (type locality), Mount Givens Granodiorite (reference locality), and Pleistocene Bishop Tuff (type locality), Tenaya Till (type locality), Till of Sherwin Glaciation (type locality), and Recess Peak Till (type locality).

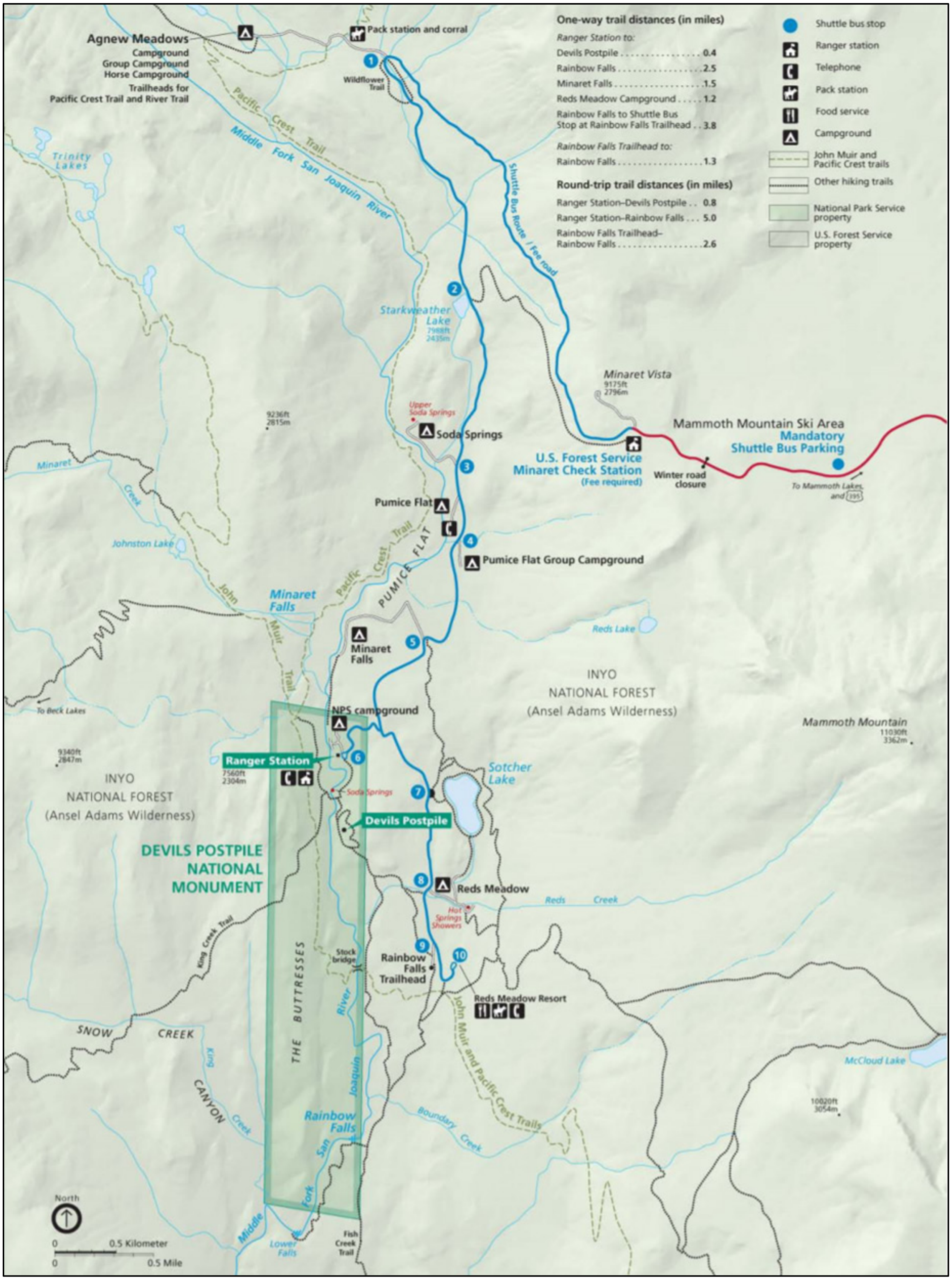


Figure 6. Park map of DEPO, California (NPS).

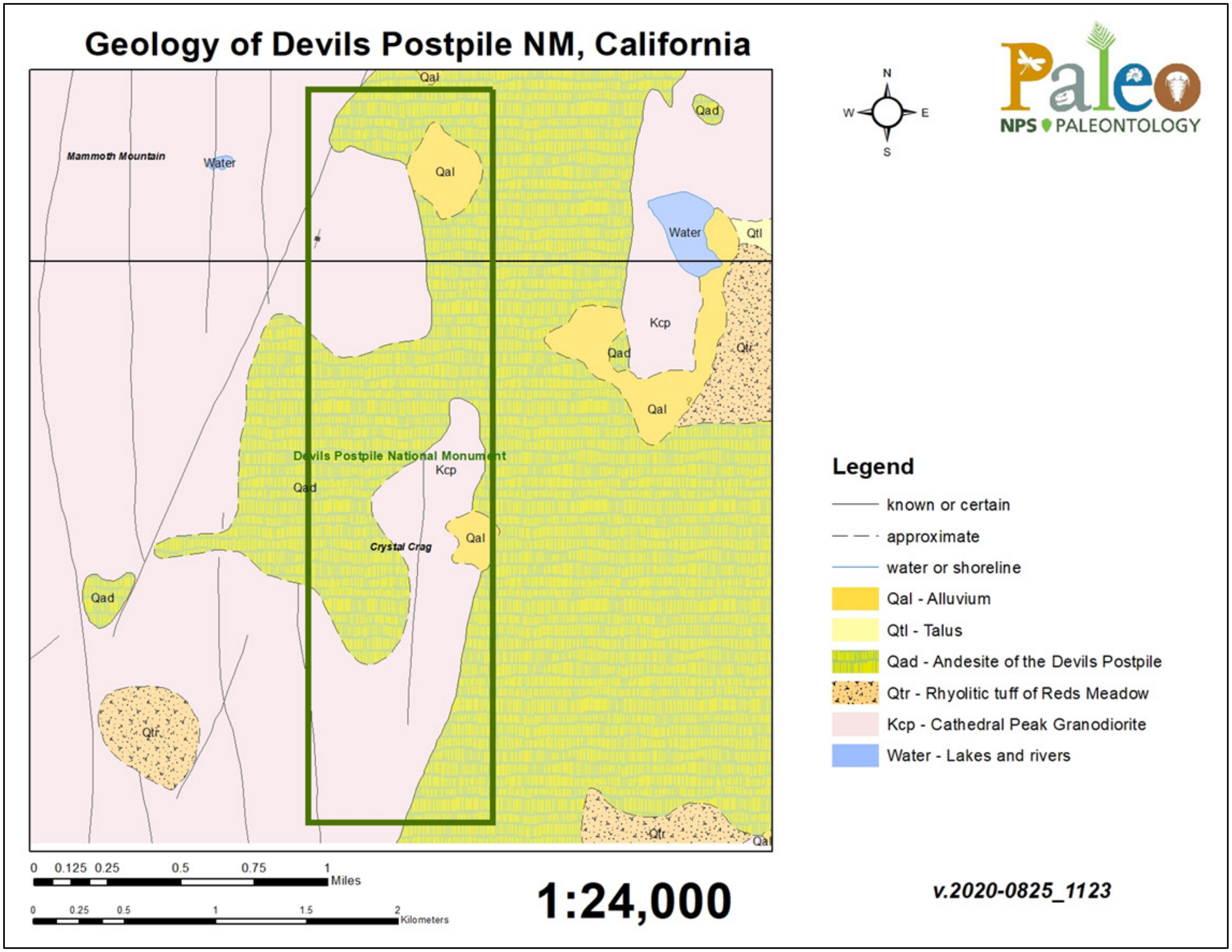


Figure 7. Geologic map of DEPO, California.

Sequoia and Kings Canyon National Parks (SEKI)

Sequoia and Kings Canyon National Parks (SEKI) are contiguous park units in the southern Sierra Nevada in Tulare and Fresno counties, California (Figure 8). Both parks were established in 1890. They encompass a combined area of 350,443 hectares (865,964 acres) with landscapes decorated with huge mountains, rugged foothills, deep canyons, vast caverns, and the world's largest trees (Anderson 2017). Weather varies greatly by season and elevation in SEKI, which ranges from 418 m (1,370 ft) in the foothills to 4,418 m (14,494 ft) at the summit of Mt. Whitney, the tallest mountain in the contiguous United States. Eleven additional peaks higher than 4,270 m (14,000 ft) are also found in SEKI, forming the crest of the Sierra Nevada along the eastern boundary of the parks. SEKI was designated a Biosphere Reserve in 1978.

The geology of SEKI dominantly consists of Mesozoic igneous rocks associated with the formation of the Sierra Nevada. Numerous geologic units situated within the parks record a complex, episodic emplacement of molten rock that represent the Mount Whitney, John Muir, Mitchell, Sequoia, Shaver, Fine Gold, Palisade Crest, and Scheelite Intrusive Suites (Figures 9 and 10). Isolated areas of SEKI contain older metamorphic rocks that are remnants of volcanic islands tectonically added to North America before the Sierra Nevada uplift. These metamorphic units include metavolcanic rocks, schist, quartzite, phyllite, and marble. Surprisingly, the marble rocks in the parks host more than 270 caves and include the longest cave in California (Lilburn Cave) with nearly 27 km (17 mi) of surveyed passageway. Paleozoic metasedimentary units that occur within SEKI consist of the Cambrian Campito and Poleta formations, as well as the Permian Keeler Canyon, Lone Pine, and Conglomerate Mesa formations. Younger Cenozoic deposits include rhyolites and olivine basalts, in addition to glacial till deposits from Pleistocene glaciers responsible for carving out deep, spectacular canyons that include Kings Canyon.

Figure 8. Park map of SEKI, California (NPS).

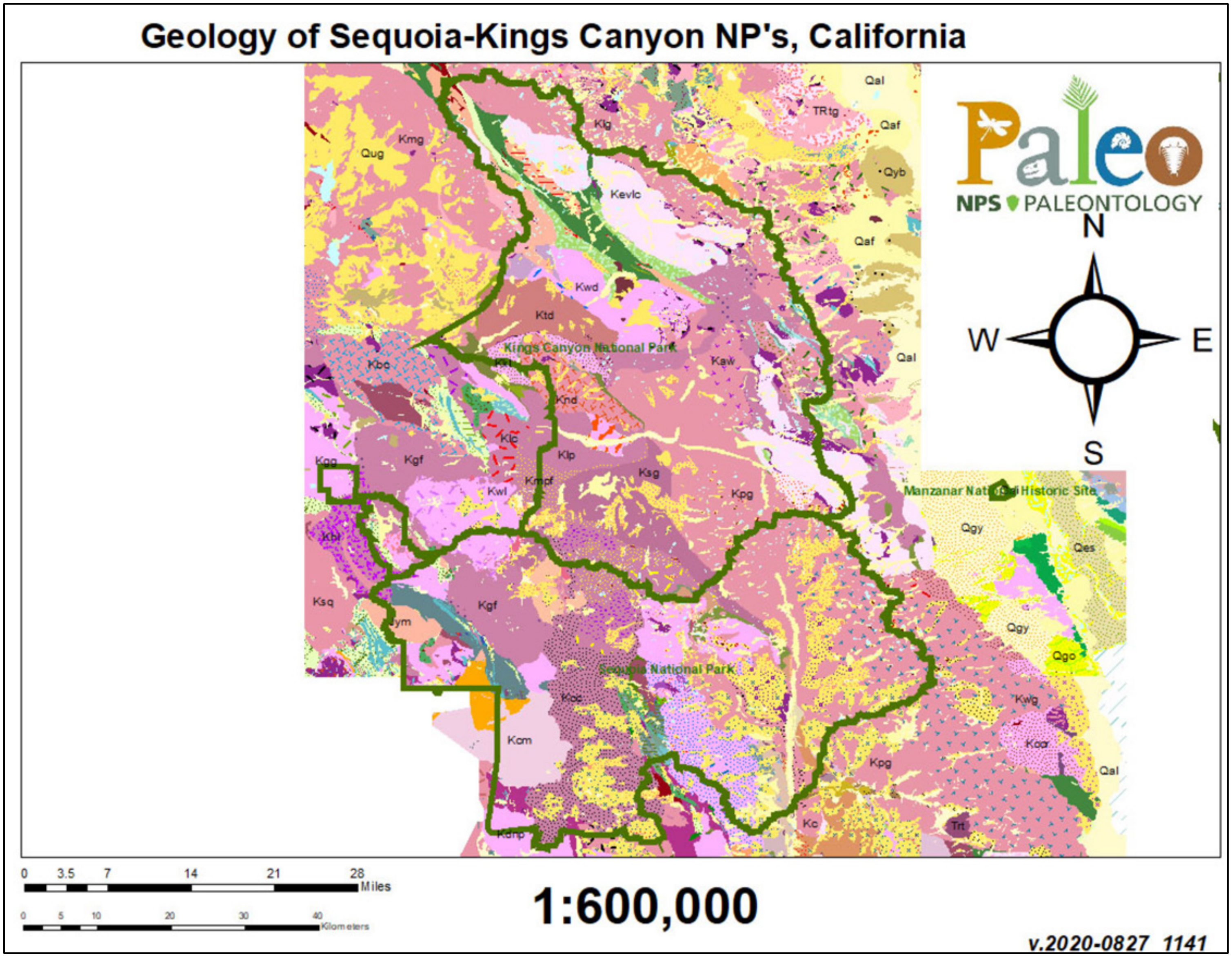


Figure 9. Geologic map of SEKI, California (legend is separate as Figures 10a and 10b).

Figure 10a. Geologic map legend of SEKI, California (part 1; continued on next page).

Figure 10b. Geologic map legend of SEKI, California (part 2).

The boundaries of SEKI contain 12 stratotypes that are associated with the formation of the Sierra Nevada batholith. These stratotypes are subdivided into eight type localities and four type areas (Table 1; Figure 11).

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

Unit Name (map symbol)	Reference	Stratotype Location	Age
Mount Whitney Intrusive Suite (Kp, Ks, Kw)	Moore and Sisson 1987	Type area: exposures along Sierra Nevada crest near Mount Whitney	Late Cretaceous
Whitney Granodiorite (Kw)	Moore 1981	Type locality: approximately 200 m (660 ft) north of summit of Mount Whitney	Late Cretaceous
Evolution Basin Alaskite (Kevb)	Bateman 1992	Type locality: exposures in Evolution Basin	Late Cretaceous
Lamarck Granodiorite (Klg)	Bateman 1961	Type locality: cirques east of Mt. Lamarck	Late Cretaceous
Paradise Granodiorite (Kpg)	Moore 1981	Type locality: on east side of Paradise Valley	Late Cretaceous
Mitchell Intrusive Suite (Kmf, Kmc, Klp, Kcc)	Moore and Sisson 1987	Type area: Tableland area, on divide between Kings and Kaweah Rivers	Cretaceous
Mitchell Peak Granodiorite (Kmf, Kmc)	Moore and Sisson 1987	Type locality: Mitchell Peak	Cretaceous
Sequoia Intrusive Suite (Kgf, Kcl, Kbm, Kwl)	Moore and Sisson 1987	Type area: exposures in Shell Mountain–Little Baldy area	Cretaceous
Giant Forest Granodiorite (Kgf)	Moore and Sisson 1987	Type locality: Moro Rock, just south of Giant Forest	Cretaceous
Inconsolable Quartz Monzodiorite (KJig)	Bateman 1961	Type locality: Inconsolable Range	Cretaceous
Palisade Crest Intrusive Suite (Jtn, Jmc)	Bateman 1992	Type area: exposures along Palisade Crest, from east escarpment of Sierra Nevada south of Big Pine Creek to Red Mountain Creek	Jurassic
Tinemaha Granodiorite (Jtn)	Bateman 1961	Type locality: in cirques at head of Tinemaha Creek	Jurassic

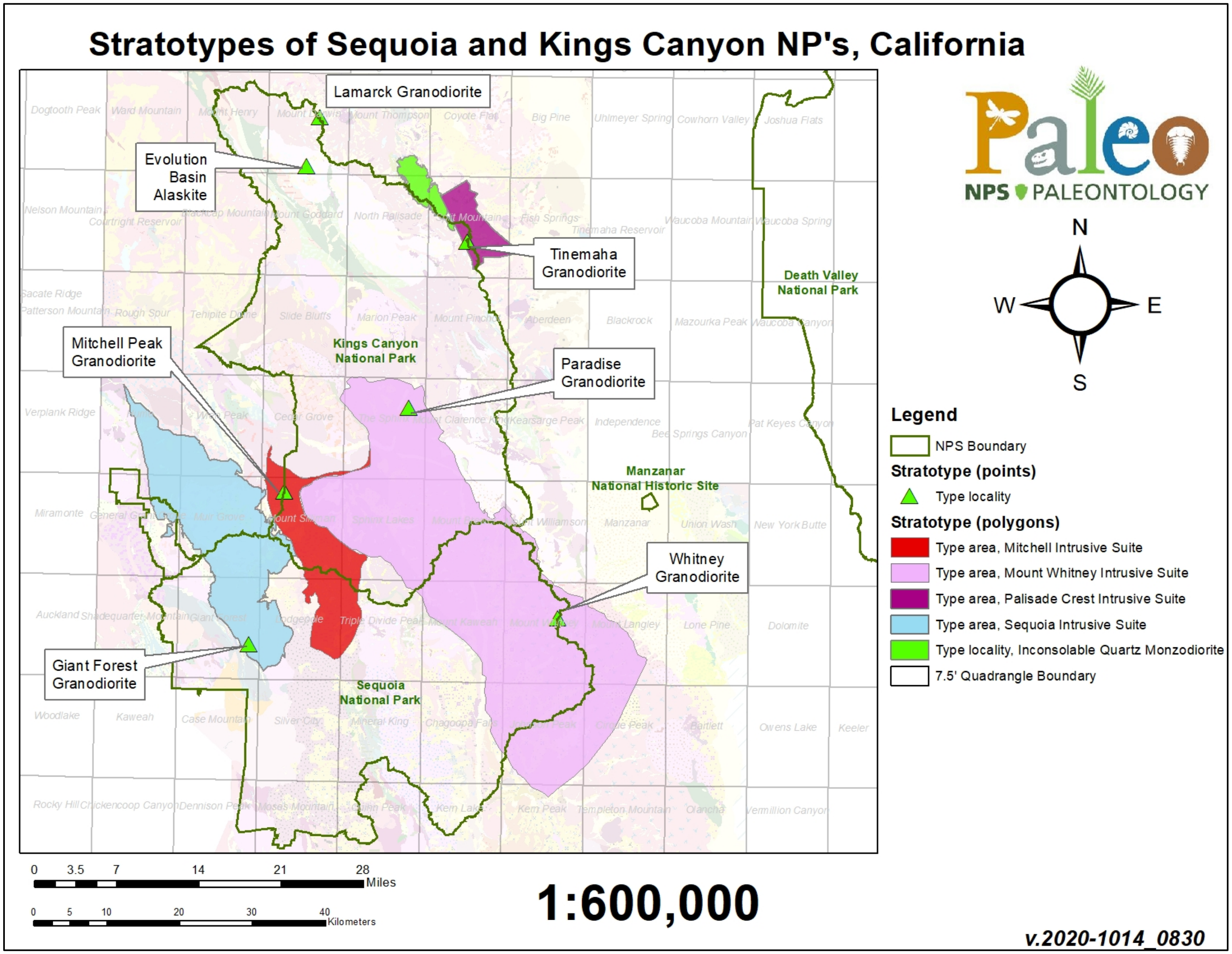


Figure 11. Modified geologic map of SEKI showing stratotype locations. The transparency of the geologic units layer has been increased.

The oldest designated stratotype in SEKI pertains to the Jurassic Tinemaha Granodiorite of the Palisade Crest Intrusive Suite. The granodiorite was named by Bateman (1961) after Mount Tinemaha, near the eastern border of Kings Canyon National Park. Type locality exposures are designated in the cirques at the head of Tinemaha Creek, in the cliffs of Mount Bolton Brown (Figure 11; Bateman 1961). Other notable exposures occur in the summits of Split Mountain, Mount Tinemaha, Birch Mountain, and The Thumb (Figure 12). The granodiorite is characterized as porphyritic with feldspar grains up to 1.5 cm (0.6 in) and containing numerous lenticular mafic inclusions rich in biotite and hornblende (Bateman 1961, 1992). The main outcrop area of the Tinemaha Granodiorite occurs as an 83 km^2 (32 mi^2) oval-shaped mass that is bisected by the granodiorite of McMurry Meadows (Bateman 1961, 1992). Exposures of the unit are nearly identical in appearance, with only minor differences in texture and color index.

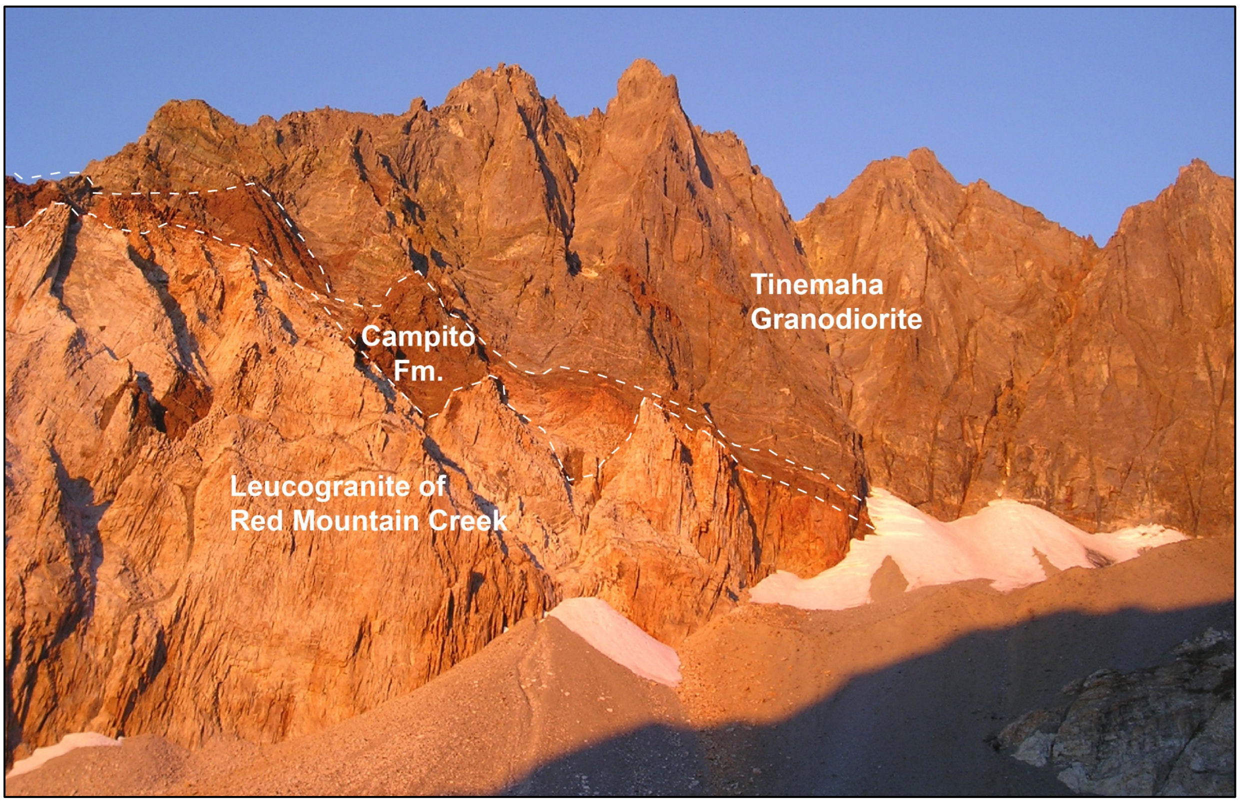


Figure 12. Western view of Split Mountain, SEKI. The upper, dark unit to the right consists of the Tinemaha Granodiorite. The lighter unit to the left is the leucogranite of Red Mountain Creek capped by dark brown Campito Formation quartzite (Bartley et al. 2012).

The Jurassic Palisade Crest Intrusive Suite was originally referred to as the Palisade Crest sequence by Bateman and Dodge (1970) and was formally named for exposures along and west of Palisade Crest, part of the Sierra Nevada divide west of Big Pine, California (Bateman 1992). Bateman (1992) states that the type area is located in the eastern escarpment of the Sierra Nevada from Big Pine Creek south to Red Mountain Creek (Figure 11). The suite consists of at least two intrusive units, the Tinemaha Granodiorite and the granodiorite of McMurry Meadows, but also probably includes the leucogranites of Red Mountain and Taboose Creeks (Bateman 1992). The younger granodiorite of McMurry Meadows is nested within the Tinemaha Granodiorite (Bateman 1961, 1992).

The Cretaceous Inconsolable Quartz Monzodiorite was originally named the Inconsolable Granodiorite by Bateman (1961) after its type locality in the Inconsolable Range (Figure 11). The main pluton mass of the unit forms an elongate body in a northwesterly direction and has an outcrop area of approximately 32.4 km^2 (12.5 $mi.^2$) (Bateman 1961, 1992). Exposures of the monzodiorite can be found along the northeastern boundary of Kings Canyon National Park in the region from the Middle Palisade to Mount Agassiz. Spectacular cirques found at the heads of the North and South forks of Big Pine Creek are carved into the Inconsolable Quartz Monzodiorite (Bateman 1961). The unit is characterized as a medium grained, medium-gray quartz monzodiorite with a high average mafic mineral content that includes biotite, hornblende, and augite (Bateman 1961, 1992).

The Cretaceous Giant Forest Granodiorite of the Sequoia Intrusive Suite was informally termed the Giant Forest pluton by Ross (1958) and formally named by Moore and Sisson (1987) after Giant Forest, located in both the Triple Divide Peak and Giant Forest quadrangles, California. Moore and Sisson (1987) state the type locality of the unit is at Moro Rock, just south of Giant Forest in the Giant Forest 15'-quadrangle (Figures 11, 13, and 14). Exposures of the Giant Forest Granodiorite occur over a broad area in both quadrangles, and the rock is characterized as a hornblende-rich granodiorite that contains abundant mafic inclusions. Uranium-lead dating by Chen and Moore (1982) indicate the unit is approximately 102–97 million years old.

The Cretaceous Sequoia Intrusive Suite was formally named by Moore and Sisson (1987) after Sequoia National Park. The type area of the Sequoia Intrusive Suite is in the Shell Mountain–Little Baldy area in the Giant Forest 15' quadrangle, California (Figure 11; Moore and Sisson 1987). Units that comprise the suite include the Giant Forest Granodiorite (oldest unit) and three younger, smaller plutons: the granite of Big Meadows, granodiorite of Clover Creek, and the granite of Weaver Lake (youngest unit). These four units show that the intrusive suite is compositionally zoned, with granodiorite at the margins and leucogranite located in the core (Bateman 1992). Most of the U-Pb ages from samples of the Sequoia Intrusive Suite reported in Chen and Moore (1982) are approximately 102.3 to 96.3 million years old.

The Cretaceous Mitchell Peak Granodiorite of the Mitchell Intrusive Suite was informally referred to as the granodiorite of Mitchell Peak by Moore (1978, 1981) and formally renamed by Moore and Sisson (1987). The unit is named after its type locality exposures that occur on the summit of Mitchell Peak in SEKI (Figure 11). The granodiorite is the most extensive unit of the Mitchell Intrusive Suite, covering an area approximately 32 km (19.9 mi) long and 13 km (8 mi) wide. Moore and Sisson (1987) describe two distinct facies that comprise the unit: 1) a younger, more dominant fine-grained, porphyritic facies with plagioclase feldspar phenocrysts (mineral crystals) 2–4 cm (0.8–1.6 in) length; and 2) an older, coarse-grained, porphyritic facies with alkali feldspar phenocrysts 3–4 cm (1.2–1.6 in) in length. The type locality, designated at the summit of Mitchell Peak, consists of the fine-grained facies (Moore and Sisson 1987).

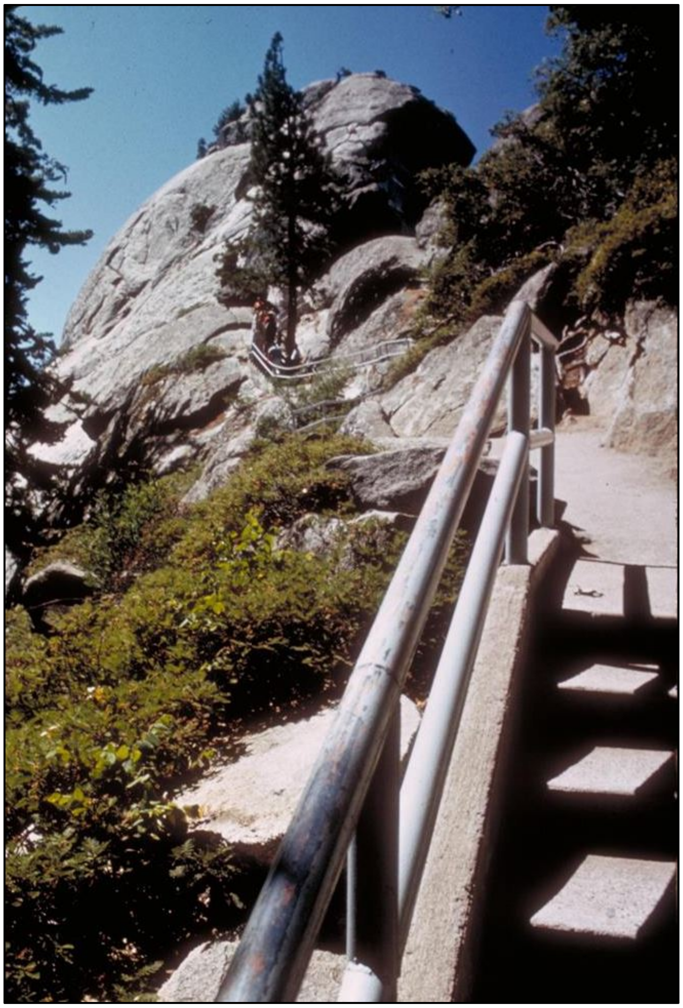


Figure 13. Trail to the top of Moro Rock, SEKI, type locality of the Giant Forest Granodiorite (NPS).

Figure 14. Visitor walkway at the top of Moro Rock, SEKI, type locality of the Giant Forest Granodiorite (NPS).

The Cretaceous Mitchell Intrusive Suite was originally named by Moore and Sisson (1987) after Mitchell Peak, SEKI and occupies much of the central part of the Triple Divide Peak quadrangle, California. Moore and Sisson (1987) state that the type area for the suite is the Tableland area on the divide between the Kings and Kaweah Rivers, SEKI (Figure 11). Members of the suite include the granodiorite of the Castle Creek (oldest unit), granodiorite of Lookout Peak, and the Mitchell Peak Granodiorite (youngest unit).

The Upper Cretaceous Paradise Granodiorite of the Mount Whitney Intrusive Suite was informally referred to as the Paradise pluton by Moore (1963, 1978) before being formally renamed by Moore (1981) after its type locality on the east side of Paradise Valley in the east-central Marion Peak quadrangle, California (Figure 11). The nested sequence of the Paradise Granodiorite and the Cretaceous Whitney Granodiorite represents one of the largest and youngest granitic sequences in the Sierra Nevada, covering an area 1,100 km^2 (425 mi^2). The Paradise Granodiorite is believed to have been emplaced as a single intrusion about 85 million years ago (Moore 1981). The unit is characterized as a porphyritic granodiorite with minor granite that contains potassium feldspar phenocrysts with abundant, zoned inclusions of biotite and hornblende (Moore 1978).

The Upper Cretaceous Lamarck Granodiorite of the John Muir Intrusive Suite was named by Bateman (1961) after Mount Lamarck in SEKI. Excellent exposures that occur east of Mount Lamarck constitute the type locality (Figure 11; Bateman 1961). The granodiorite is the oldest unit of the John Muir Intrusive Suite (approximately 90 million years old) and forms a lenticular-shaped pluton approximately 60 km (37 mi) long and 10 km (6 mi) wide (Bateman 1992). The unit is characterized as a medium-grained, porphyritic granodiorite that contains biotite and hornblende that occur as both clusters and discrete crystals (Bateman 1992).

The Upper Cretaceous Evolution Basin Alaskite of the John Muir Intrusive Suite was informally referred to as the Alaskite of Evolution Basin and LeConte Canyon by Bateman and Moore (1965) and the leucogranite of Evolution Basin by Stern et al. (1981) before being formally named by Bateman (1992). Bateman (1992) designated exposures in Evolution Basin, SEKI as the type locality (Figures 11 and 15). The Evolution Basin Alaskite is described as an extremely felsic, light-colored, medium- to fine-grained alaskite that forms a lenticular igneous body approximately 30 km (19 mi) long and 6 km (4 mi) wide.

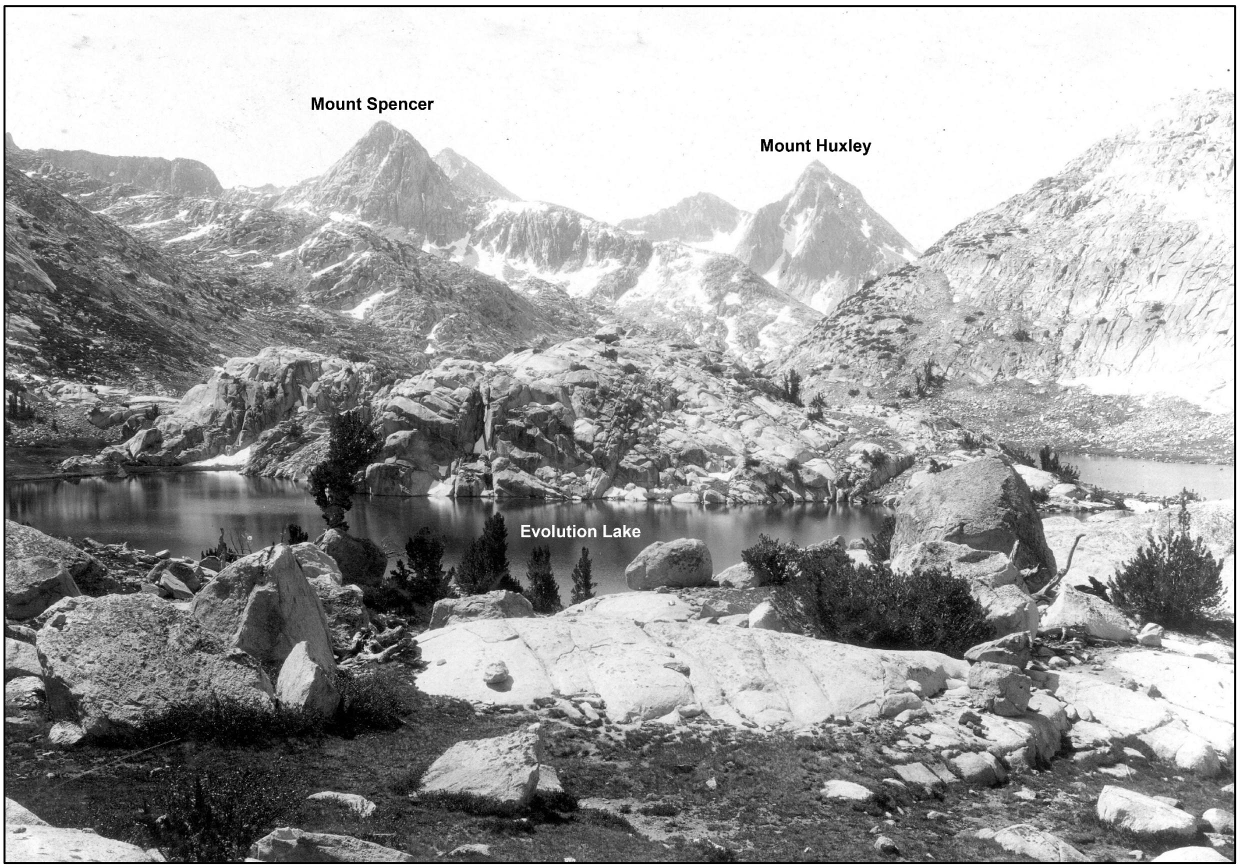


Figure 15. Southern view across Evolution Lake, located in the Evolution Basin, SEKI. Evolution Basin represents the type locality of the Evolution Basin Alaskite. At left of center is Mount Spencer; at right of center is the more distant Mount Huxley (USGS).

The Upper Cretaceous Whitney Granodiorite of the Mount Whitney Intrusive Suite was formally named by Moore (1981) after Mount Whitney, SEKI. Exposures that occur 200 m (660 ft) north of the summit of Mount Whitney are designated the type locality (Figures 11 and 16; Moore 1981). The unit is described as a porphyritic granodiorite and granite with a domical pluton profile that contains large phenocrysts of potassium feldspar 4–8 cm (1.6–3.0 in) in length and an average potassium-argon age of 83 million years old (Moore 1981).

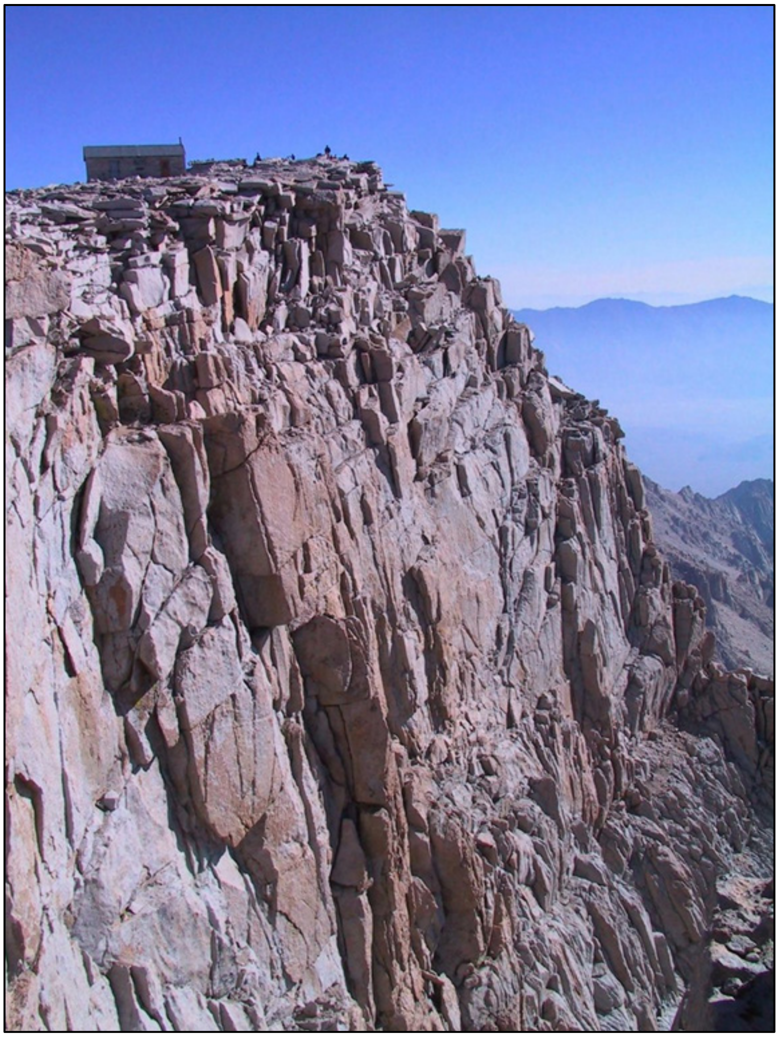


Figure 16. Northeast view of the sheer cliffs and summit of Mount Whitney, SEKI, consisting of Upper Cretaceous Whitney Granodiorite (NPS). The type locality of the Whitney Granodiorite is approximately 200 m (660 ft) north of the summit.

The Upper Cretaceous Mount Whitney Intrusive Suite was originally named for Mount Whitney by Moore and Sisson (1987). The type area of the suite is located along the Sierra Nevada crest near Mount Whitney (Figure 11; Moore and Sisson 1987). Members of the suite include the granodiorite of Sugarloaf (oldest unit), the Paradise Granodiorite, and the Whitney Granodiorite (youngest unit). The Mount Whitney Intrusive Suite represents one of the youngest granitic sequences of the Sierra Nevada, extending approximately 83 km (52 mi) southeastward from the central part of the Marion Peak 15' quadrangle on the northwest to the southeastern part of the Olancha 15'-quadrangle on the southeast (Moore and Sisson 1987).

In addition to the designated stratotypes located within SEKI boundaries, a list of stratotypes located within 48 km (30 mi) of park boundaries is included here for reference. These nearby stratotypes include the Cambrian Poleta Formation (type section), Andrew Mountains Member of the Campito Formation (reference section), Permian Lone Pine Formation (type locality), Reward Conglomerate

Member of the Lone Pine Formation (type section), Conglomerate Mesa Formation (type section), Pennsylvanian–Permian Keeler Canyon Formation (type locality), Triassic Scheelite Intrusive Suite (type area), Wheeler Crest Granodiorite (type locality), Union Wash Formation (type section and type locality), Tungsten Hills Granite (type locality), Cretaceous John Muir Intrusive Suite (type area), Lake Edison Granodiorite (type locality), Round Valley Peak Granodiorite (type locality), Mount Givens Granodiorite (reference locality), Shaver Intrusive Suite (type area), Dinkey Creek Granodiorite (type locality), and Pleistocene-age units of the Bishop Tuff (type locality), Tenaya Till (type locality), Sherwin Till (type locality), and Recess Peak Till (type locality).

Yosemite National Park (YOSE)

Yosemite National Park (YOSE) is located in the heart of the Sierra Nevada in Madera, Mariposa, and Tuolumne counties, California (Figure 17). Established as a national park on October 1, 1890, the park encompasses 308,106 hectares (761,347.5 acres) of land consisting of granitic peaks and domes that rise high above broad meadows (Anderson 2017). YOSE is home to groves of giant sequoias, mountains, lakes, U-shaped valleys, and some of the tallest waterfalls found in the United States. The scenic landscape of Yosemite Valley is decorated with world-renowned geologic features that include Half Dome, El Capitan, Sentinel Rock, and the cliffs of Yosemite Valley. The lofty mountain peaks of Mount Lyell, Mount Dana, and Kuna Peak are the highest in YOSE with elevations that exceed 3,960 m (13,000 ft) above sea level. YOSE was designated a World Heritage Site on October 31, 1984.

The geology of YOSE is dominated by igneous rocks that form many of the park's iconic features. These plutonic igneous rocks form much of the Sierra Nevada Batholith and represent multiple episodes of magma intrusion and solidification in the vicinity of YOSE (Figures 18 and 19; Graham 2012). A majority of the granitoid rocks in YOSE are between 105 and 85 million years old, and record a complex history of pluton emplacement associated with subduction-zone volcanism that took place during the Mesozoic Era from 220 to 85 million years ago (Bateman 1992; Graham 2012). The oldest sedimentary rocks in YOSE are Paleozoic in age. They have been metamorphosed and form linear, northwest-trending outcrop belts along the western and eastern borders of YOSE (Huber 1989; Huber et al. 1989; Bateman 1992). During the Cenozoic, the Sierra Nevada Batholith was uplifted and tilted to the southwest, allowing streams and ice age glaciers to carve the dense, hard plutonic rocks into the inspiring landscape seen today in YOSE. Glacial features of YOSE originated from multiple episodes of glaciation and include cirque basins, alpine lakes, towering waterfalls, U-shaped and hanging valleys, polished granitic domes, glacial erratics, and glacial moraines. Pleistocene glaciers first impacted the region about 1.5 million years ago, and the most recent major episode of glaciation (Tioga glaciation) began ~26,000 years ago (Graham 2012; Glazner and Stock 2010).

YOSE contains two stratotype occurrences: one type locality and one type area (Table 2; Figure 20). The oldest stratotype of the park pertains to the Early Cretaceous Fine Gold Intrusive Suite, the oldest formally named intrusive suite in the western Sierra Nevada, dated between 123–105 million years old (Bateman 1992). The Fine Gold Intrusive suite was named after exposures along Fine Gold Creek and consists of several igneous units including, from oldest to youngest: the Granodiorite of Hazel Green Ranch; Tonalite of Poopenaut Valley; Tonalite of Blue Canyon; Tonalite of Oakhurst; Bass Lake Tonalite; Granite of Hogan Mountain; Granodiorite of Sawmill Mountain; Granodiorite of Crane Flat; Granodiorite of Arch Rock; and an unnamed alaskite unit. Bateman (1988, 1992) states that the type area is the Ward Mountain–Bass Lake area (Figure 20). A portion of the intrusive suite type area is located along the western boundary of YOSE. The suite is characterized by granitoid bodies containing a low presence of alkali feldspar and $^{87}Sr/^{86}Sr$ (strontium isotope) ratios indicative of source magmas containing substantial amounts of crustal material (Bateman 1992).

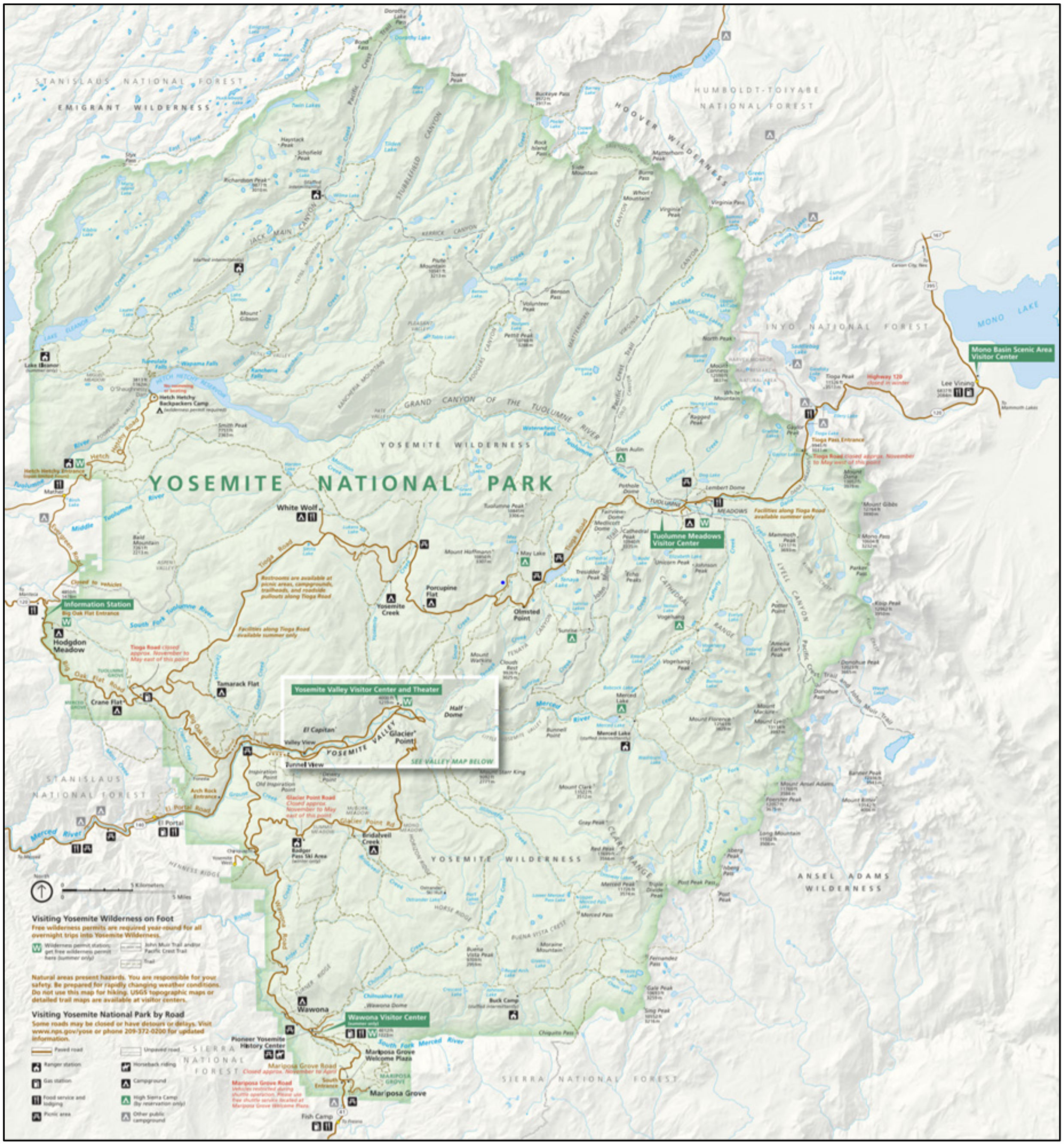


Figure 17. Park map of YOSE, California (NPS).

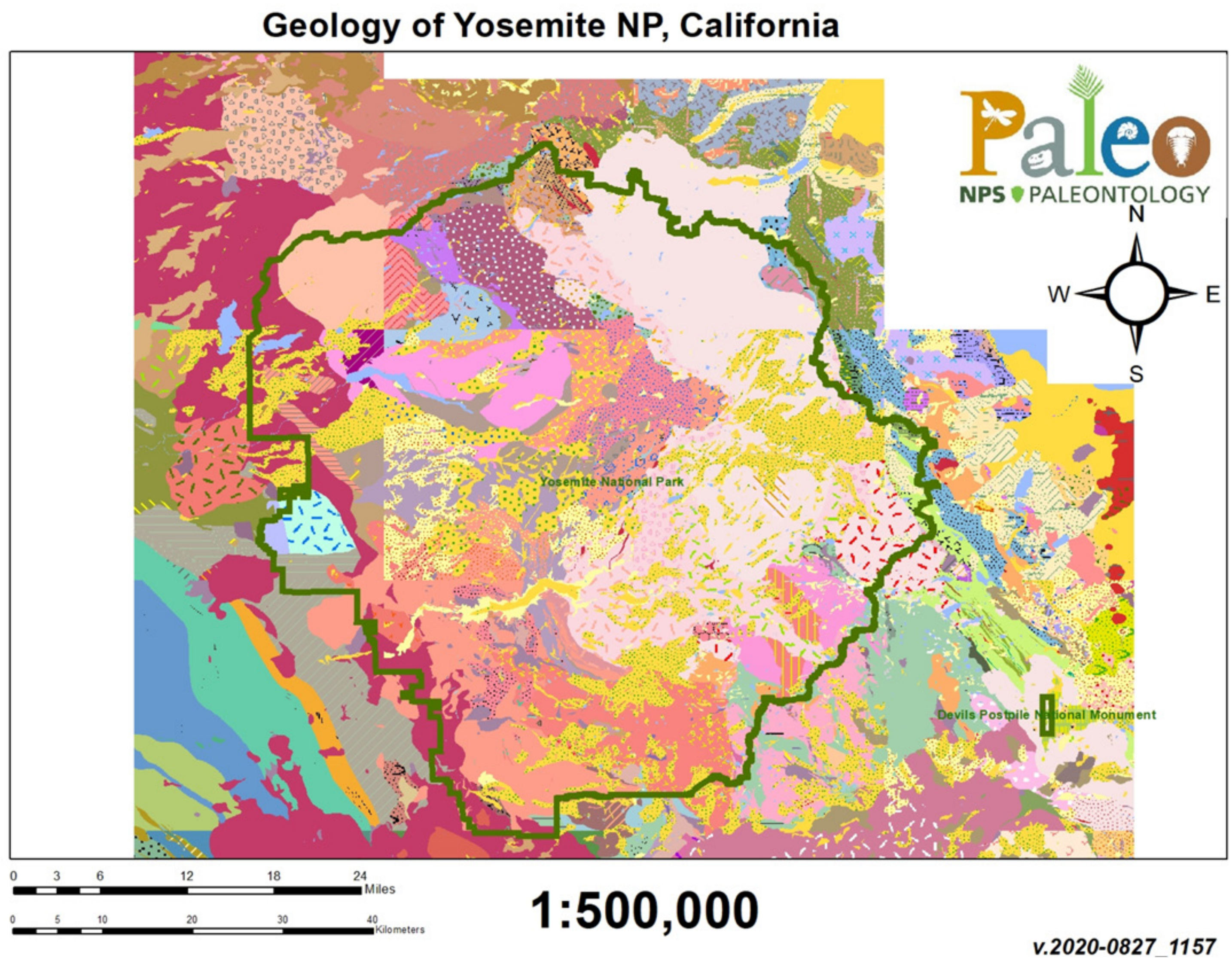


Figure 18. Geologic map of YOSE, California (legend is separate as Figures 19a and 19b).

Figure 19a. Geologic map legend of YOSE, California (part 1; continued on next page).

Figure 19b. Geologic map legend of YOSE, California (part 2).

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

Unit Name (map symbol)	Reference	Stratotype Location	Age
Sentinel Granodiorite (Kse)	Bateman and Chappell 1979; Bateman 1992	Type locality: Sentinel Rock	Late Cretaceous
Fine Gold Intrusive Suite (Kro, Kbl, Kar, Kwt, Kkn, Kga)	Bateman 1988, 1992	Type area: Ward Mountain–Bass Lake area, central Sierra Nevada	Early Cretaceous

The Upper Cretaceous Sentinel Granodiorite was originally named by Calkins (1930) after the world-renowned monolith Sentinel Rock in YOSE. Bateman and Chappell (1979) would later designate Sentinel Rock the type locality (Figures 20 and 21). The unit occurs as a narrow ~2 km (1.25 mi)-wide, north–south trending band south of Yosemite Valley, but its distribution widens north of the valley into the region near Bald Mountain. The granodiorite is characterized as being equigranular, containing well-formed crystals of hornblende and biotite and abundant wedge-shaped crystals of sphene (Figure 22; Bateman 1992).

In addition to the designated stratotypes located within YOSE boundaries, a list of stratotypes located within 48 km (30 mi) of park boundaries is included here for reference. These nearby stratotypes include the Jurassic Mariposa Formation (type area), Cretaceous-age Bass Lake Tonalite (type locality), Ward Mountain Trondhjemite (type locality), Shaver Intrusive Suite (type area), Miocene-age Eureka Valley Tuff (type locality), Table Mountain Latite (type locality), and the Miocene–Pliocene Disaster Peak Formation (type locality).

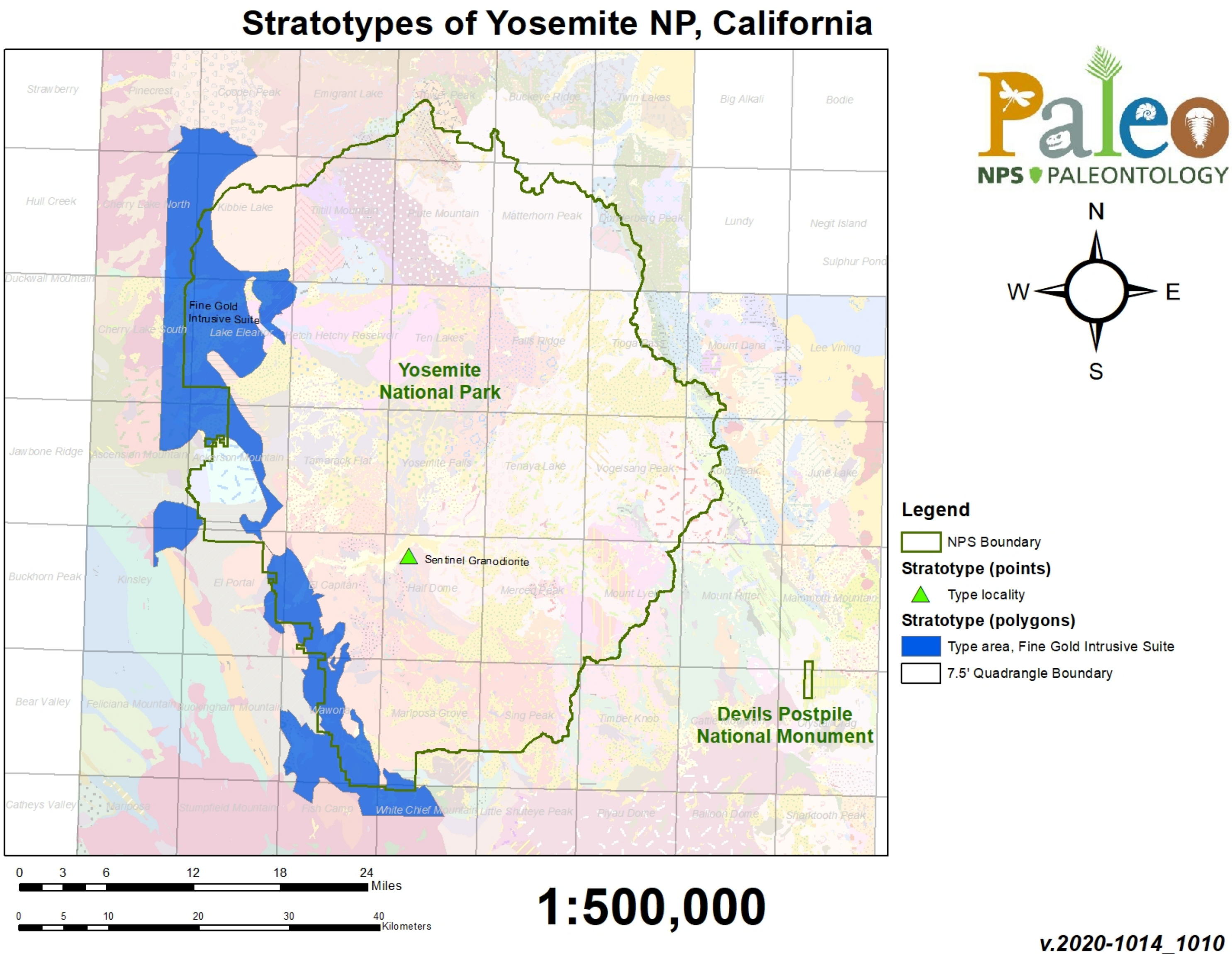


Figure 20. Modified geologic map of YOSE showing stratotype locations. The transparency of the geologic units layer has been increased.

Figure 21. Sentinel Rock, type locality of the Sentinel Granodiorite, YOSE (NPS/GREG STOCK).

Figure 22. View from the top of Sentinel Dome, YOSE, showing weathering pans in the Sentinel Granodiorite. Inset image shows close-up textural detail of the granodiorite near the precipice of Yosemite Falls; penny for scale is 1.9 cm (0.75 in). Photos courtesy of Allen Glazner (UNC) and Greg Stock (NPS).

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 SIEN Geologic Type Section Inventory report is finalized, the NPS Geologic Resources Division should schedule a briefing for the staff of the SIEN network and respective network parks.
3. Many geologic units of the Sierra Nevada are formally named after the iconic landmarks of YOSE but currently lack formal stratotype designations. These units include: the Johnson Granite Porphyry; Cathedral Peak Granodiorite; Half Dome Granodiorite; Bridalveil Granodiorite; Leaning Tower Granite; Taft Granite; and El Capitan Granite. It is recommended that stratotype designations of these units be made in order to: A) provide a standard reference for scientific research; B) educate park staff and visitors about the geoheritage significance of these units; and C) help safeguard these exposures.
4. The NPS Geologic Resources Division should work with park and network staff to ensure they are aware of the locations of stratotypes in park areas. This information would be important to ensure that proposed park activities or development would not adversely impact the stability and condition of these geologic exposures.
5. The NPS Geologic Resources Division should work with park and network staff, the U.S. Geological Survey, state geological surveys, academic geologists, and other partners to formally assess potential new stratotypes as to their significance (international, national, or state-wide), based on lithology, stratigraphy, fossils or notable features using procedural code outlined by the North American Commission on Stratigraphic Nomenclature.
6. From the assessment in (4), NPS staff should focus on registering new stratotypes at State and Local government levels where current legislation allows, followed by a focus on registering at Federal and State levels where current legislation allows.
7. The NPS Geologic Resources Division should work with park and network staff to compile and update a central inventory of all designated stratotypes and potential future nominations.
8. The NPS Geologic Resources Division should ensure the park-specific Geologic Type Section Inventory Reports are widely distributed and available online.
9. The NPS Geologic Resources Division should work with park and network staff to regularly monitor geologic type sections to identify any threats or impacts to these geologic heritage features in parks.
10. The NPS Geologic Resources Division should work with park and network staff to obtain good photographs of each geologic type section within the parks. In some cases, where there may be active geologic processes (rock falls, landslides, coastal erosion, etc.), the use of photogrammetry may be considered for monitoring of geologic type sections. GPS locations should also be recorded and kept in a database when the photographs are taken.

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

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Appendix A: Source Information for GRI Maps of SIEN Parks

DEPO

- GMAP 1370: Huber, N. K., and C. D. Rinehart. 1965. Geologic map of the Devils Postpile Quadrangle, Sierra Nevada, California. U.S. Geological Survey, Washington, D.C. Geologic Quadrangle Map 437. Scale 1:62,500. Available at: http://ngmdb.usgs.gov/Prodesc/proddesc_319.htm (accessed December 7, 2020).

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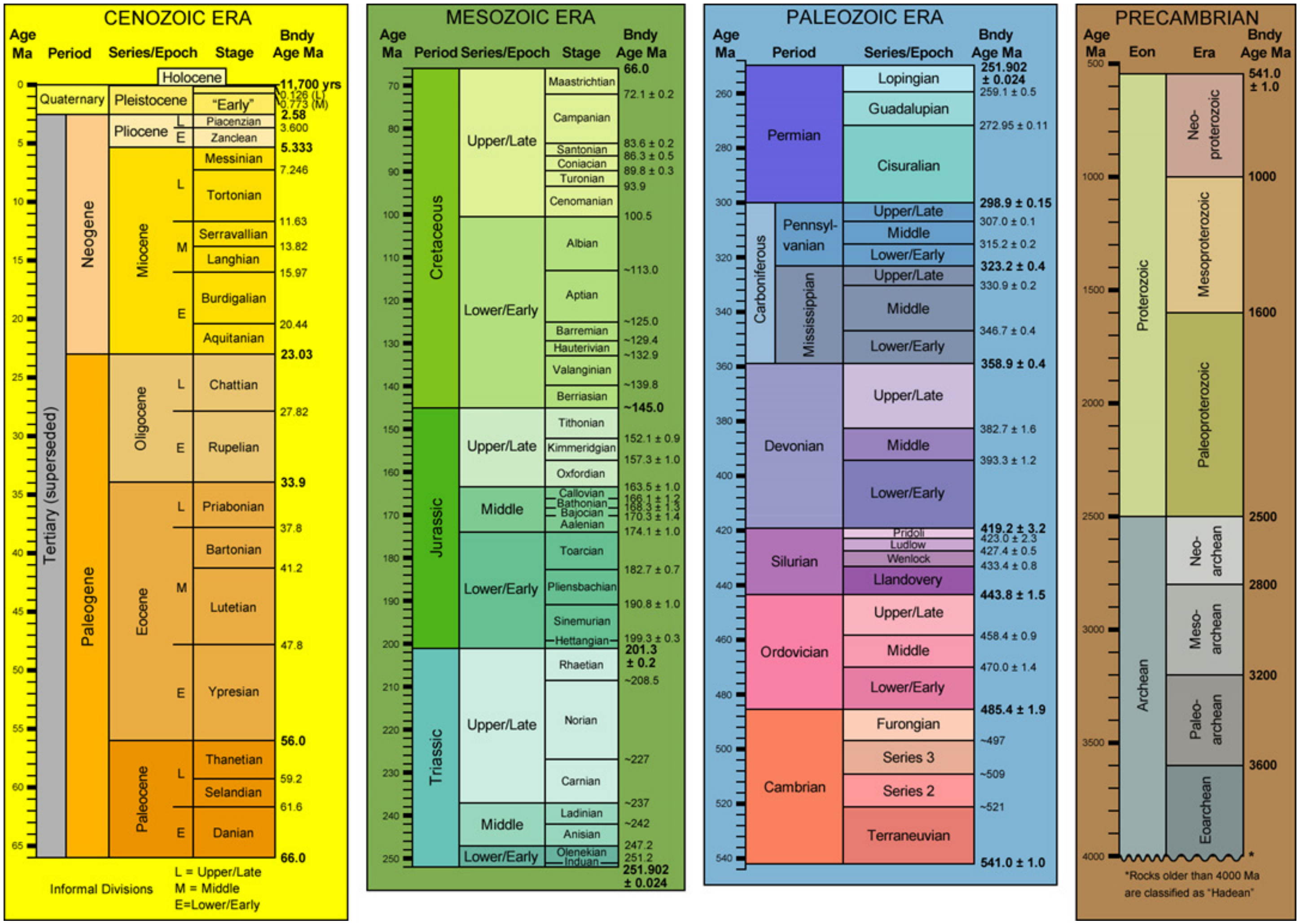
Appendix B: Geologic Time Scale



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

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