National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

National Park Service Geologic Type Section Inventory

San Francisco Bay Area Inventory & Monitoring Network

Natural Resource Report NPS/SFAN/NRR—2022/2388

ON THE COVER

View from the High Peaks Trail of spire-like rock formations of the Oligocene-Miocene Pinnacles Volcanics. The type section of the Pinnacles Volcanics is along the High Peaks Trail west of Chalone Creek in Pinnacles National Park. Photo courtesy of Arman Sabouri (@armansabouriphoto).

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Executive Summary

A fundamental responsibility of the National Park Service (NPS) is to ensure that the resources of the National Park System 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 that may threaten or influence their stability and preservation.

There are several different categories of geologic or stratigraphic units (supergroup, group, formation, member, bed) that form a hierarchical system of classification. The mapping of stratigraphic units involves the evaluation of lithologies (rock types), bedding properties, thickness, geographic distribution, and other factors. Mappable geologic units may be described and named through a rigorously defined process that is standardized and codified by the professional geologic community (North American Commission on Stratigraphic Nomenclature 2021). In most instances when a new geologic unit such as a formation is described and named in the scientific literature, a specific and well-exposed section or exposure area of the unit is designated as the stratotype (see “Definitions” below). The type section is an important reference exposure for a named geologic unit that presents a relatively complete and representative example for this unit. Geologic stratotypes are important both historically and scientifically, and should be available for other researchers to evaluate in the future.

The inventory of all geologic stratotypes throughout the 423 units of the NPS is an important effort in documenting these locations in order that NPS staff recognize and protect these areas for future studies. The focus adopted for completing the baseline inventories throughout the NPS is 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 planning team from the NPS Geologic Resources Division who proposed and designed this inventory selected the Greater Yellowstone Inventory & Monitoring Network (GRYN) as the pilot network for initiating this project (Henderson et al. 2020). Through the research undertaken to identify the geologic stratotypes within the parks of the GRYN methodologies for data mining and reporting on these resources were established. Methodologies and reporting adopted for the GRYN have been used in the development of this report for the San Francisco Bay Area Inventory & Monitoring Network (SFAN).

The goal of this project is to consolidate information pertaining to geologic type sections that occur within NPS-administered areas, in order that this information is available throughout the NPS to inform park managers and to promote the preservation and protection of these important geologic landmarks and geologic heritage resources. The review of stratotype occurrences for the SFAN shows there are currently no designated stratotypes for Fort Point National Historic Site (FOPO) and Muir Woods National Monument (MUWO). Golden Gate National Recreation Area (GOGA) has one type section and four type localities; John Muir National Historic Site (JOMU) has one type locality; Pinnacles National Park (PINN) has one type section; and Point Reyes National Seashore (PORE) has two type sections, one type locality, and two type areas (Table 1).

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.

Table 1. List of SFAN stratotype units sorted by park unit and geologic age, with associated reference publications and locations.

Park	Unit Name (GRI map symbol)	Reference	Stratotype Location	Age
GOGA	Olema Creek Formation (Qoc)	Galloway 1977	**Type section**: outcrop in Olema Creek between Boyd Stewart Ranch and Vedanta Retreat, Marin County, CA.	Pleistocene
GOGA	Millerton Formation (Qml)	Dickerson 1922	**Type locality**: in the headland near Millerton Station, northwest of Inverness on Tomales Bay, Marin County, CA.	Pleistocene
GOGA	Merced Formation (QTm)	Lawson 1893; Arnold 1906; Glen 1959	**Type locality**: sea-cliffs south of Lake Merced that extend to Mussel Rock about 13 km (8 mi) south of Point Lobos, San Mateo County, CA.	Pliocene–Pleistocene
GOGA	Calera Limestone, Franciscan Complex	Schlocker 1974	**Type locality**: stated to be along Pacific Ocean shoreline, 15 km (9.5 mi) south of San Francisco North Quadrangle, in Calera Valley adjacent to Rockaway quarry [Montara Mountain 7.5′ Quadrangle], San Mateo County, CA.	Cretaceous
GOGA	Franciscan Complex (KJf*)	Schlocker et al. 1954	**Type locality**: narrow band of exposures in cliffs along the southern shore of inlet to San Francisco Bay, San Francisco County, CA.	Jurassic–Eocene
JOMU	Martinez Formation (Tmz, Tmzu, Tmzl)	Merriam 1897; Arnold 1906	**Type locality**: designated as exposures south of town of Martinez, Contra Costa County, CA.	Paleocene
PINN	Pinnacles Volcanics (Tpv, Tpbr, Tpbb, Tpbt, Tppr, Tpd, Tpa, Tpag, Tppl, Tprm, Tprf, Tprv, Tprp, Tdi)	Matthews 1973a; Sims 1993	**Type section**: exposures along High Peaks Trail west of Chalone Creek Campground in Pinnacles National Monument, from SW/4 SE/4 sec. 35 to SW/4 SE/4 sec. 34, T. 16 S., R. 7 E., North Chalone Peak 7.5′ Quadrangle, San Benito County, CA. The campground no longer exists but was located at latitude 36°29′35″ N., longitude 121°10′27″ W., about 200 m (650 ft) south of the Old Pinnacles Trailhead parking area.	Oligocene–Miocene
PORE	Drakes Bay Formation	Galloway 1977	**Type section**: Drakes Bay sea cliff extending from Drakes Estero [southwest about 6 km] to granitic outcrop at east end of Point Reyes ridge, Marin County, CA. **Type locality**: the syncline lying between the granitic ridges of Inverness Ridge and Point Reyes, CA.	Miocene–Pliocene
PORE	Laird Sandstone (Tls)	Weaver 1949; Galloway 1977	**Type area**: exposures west of Laird's Landing on Tomales Bay, Marin County, CA.	Miocene
PORE	Point Reyes Conglomerate (Tpr)	Galloway 1977	**Type section**: the westernmost fault block at the Point Reyes lighthouse on west end of Point Reyes Peninsula, Marin County, CA. **Type area**: Point Reyes, CA.	Eocene

Acknowledgments

Many individuals were consulted in the preparation of this report on the geologic type sections for the national parks of the San Francisco Bay Area Inventory & Monitoring Network (SFAN). We first want to extend our sincere appreciation to Randy Orndorff, David Soller, and Nancy Stamm (United States Geological Survey, USGS) for their assistance with this geologic type section inventory and other important NPS projects. Randy, Dave, and Nancy manage the National Geologic Map Database (https://ngmdb.usgs.gov/ngm-bin/ngm_compsearch.pl?glx=1) and GEOLEX (https://ngmdb.usgs.gov/Geolex/search, the U.S. Geologic Names Lexicon, a national compilation of names and descriptions of geologic units), critical sources of geologic information for science, industry, and the American public.

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 Susan Jordan (California Coastal Protection Network), Amy Loseth (California Geological Survey), and Arman Sabouri for their 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 SFAN and various network parks including: Jena Hickey, Elizabeth Edson, and Jessica Weinberg McClosky (SFAN), Will Elder (GOGA), and Paul Johnson (PINN). Additional thanks to Denise Louie, Ben Becker, and Jalyn Cummings for continued support for this and other important geology projects in the former Pacific West Region (now DOI Regions 8, 9, 10, and 12) of the NPS. Jalyn served as peer review coordinator for this report. We also extend our thanks to Will Elder (GOGA), Paul Johnson (PINN), and Phil Stoffer (retired USGS) for their reviews of this report.

This project is possible through the support from research associates and staff in the National Park Service Geologic Resources Division and we extend our thanks to Stephanie Gaswirth, Hal Pranger, Julia Brunner, Jason Kenworthy, and Jim Wood.

Dedication

We are pleased to dedicate this San Francisco Bay Area Inventory & Monitoring Network Geologic Type Section Inventory to NPS Geologist Rebecca Port. Rebecca joined the NPS Geologic Resources Division in 2010 and shortly after was hired to support the Geologic Resource Inventory team in 2012. Rebecca coordinates the Geologic Resources Inventory Reports, which are important publications that synthesize the geologic histories, resources, and processes of the national parks. The contributions put forth by Rebecca benefit park staff, geologists, teachers, and a wide audience, including our geologic type section inventory team working on these stratotype reports. Thank you, Rebecca, and we are proud of your work for the NPS!

NPS Geologist Rebecca Port hiking in Pinnacles National Park shown in front of one of the talus caves.

Introduction

The NPS Geologic Type Section Inventory Project ("Stratotype Inventory Project") is a continuation of and complements the work performed by the Geologic Resources Inventory (GRI). The GRI is funded by the NPS Inventory & Monitoring Program and administered by the Geologic Resources Division (GRD). The GRI is designed to compile and present baseline geologic resource information available to park managers, and advance science-informed management of natural resources in the national parks. The goals of the GRI 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. Additional GRI information and products can be accessed on IRMA or the GRI publication page (https://www.nps.gov/subjects/geology/geologic-resources-inventory-products.htm).

Documentation of stratotypes (i.e., type sections/type localities/type areas; see "Definitions" below) 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 2021). The importance of stratotypes lies in the fact that they represent important comparative sites where past investigations can be built upon or re-examined, and can serve as teaching sites for the next generation of students (Brocx et al. 2019). The geoheritage significance of stratotypes is analogous to libraries and museums in that they are natural repositories of Earth history and record the physical and biological evolution of our planet.

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; those within 48 km (30 mi) of park boundaries are mentioned briefly in this report because of their proximity to parks.

This geologic type section inventory for the parks of the San Francisco Bay Area Inventory & Monitoring Network (SFAN) follows standard practices, methodologies, and organization of information introduced in the Greater Yellowstone I&M Network stratotype 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 has taken responsibility for this important inventory for the NPS.

This inventory fills a void in basic geologic information compiled by the NPS at most parks. Instances where geologic stratotypes occur within NPS areas were determined through research of published geologic literature and maps. Sometimes the lack of specific locality or other data limited determination of whether a particular stratotype was located within NPS administered boundaries. Below are the primary justifications that warrant this inventory of NPS geologic stratotypes.

- Geologic stratotypes 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 stratotypes are important geologic landmarks and reference locations that define important scientific information associated with geologic strata. Geologic formations are frequently named after topographic or geologic features and landmarks that are recognizable to park staff;
- Geologic stratotypes are both historically and scientifically important components of earth science investigations and mapping;
- Understanding and interpreting the geologic record depends on the stratigraphic occurrences of mappable lithologic units (formations, members, etc.). 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 stratotypes are similar in nature to type specimens in biology and paleontology, serving as the primary reference for defining distinctive characteristics and establishing accurate comparisons;
- Geologic stratotypes within NPS areas have not been previously inventoried and there is a general absence of baseline information for this geologic resource category;
- NPS staff may not be aware of the concept of geologic stratotypes and therefore would not understand the significance or occurrence of these natural references in the parks;
- Given the importance of geologic stratotypes as geologic references 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 stratotypes within parks, the NPS cannot proactively monitor the stability, condition, or potential impacts to these locations during normal park operations or planning. This lack of information also hinders the protection of these localities from activities that may involve ground disturbance or construction.
- This inventory can inform important conversations on whether geologic stratotypes rise to the level of national register documentation. The NPS should consider if any other legal authorities (e.g., National Historic Preservation Act), policy, or other safeguards currently in place can help protect geologic stratotypes that are established on NPS administered lands. Through this inventory, the associated report, and close communication with park and I&M Network staff, we hope there will be an increased awareness about these important geologic landmarks in parks. In turn, the awareness of these resources and their significance may be recognized in park planning and operations, to ensure that geologic stratotypes are preserved and available for future study.

Geology and Stratigraphy of the SFAN I&M Network Parks

The San Francisco Bay Area Inventory & Monitoring Network (SFAN) consists of six national park units along or near the west coast of central California (Figure 1). These parks include Fort Point National Historic Site (FOPO), Golden Gate National Recreation Area (GOGA), John Muir National Historic Site (JOMU), Muir Woods National Monument (MUWO), Pinnacles National Park (PINN), and Point Reyes National Seashore (PORE). Although Eugene O'Neill National Historic Site, Port Chicago Naval Magazine National Memorial, and Rosie the Riveter World War II Home Front National Historical Park are sometimes included in SFAN, they are not "natural resource" parks and will not be mentioned in this report. The parks that comprise the San Francisco Bay Area Network protect a combined 73,124 hectares (180,694 acres) of wilderness and vary in size from 12 hectares (29 acres) in FOPO to approximately 33,195 hectares (82,027 acres) in GOGA.

The park units of the SFAN are situated in one of the most geologically active areas in the country. The western coast of North America represents an active continental margin that marks the boundary between tectonic plates. Along the California coast, the oceanic Pacific Plate is moving northwest relative to the continental North American Plate along a transform boundary better known as the San Andreas fault system (Stoffer 2005, 2006). The rate of tectonic movement along the San Andreas fault system has varied over time, but modern geodetic data shows about 3.9 cm (1.5 in) of displacement occurs along the fault system in central California annually (Sims 1993; Argus and Gordon 2001). Although these movements are small and comparable to the rate at which fingernails grow, they accumulate to hundreds of kilometers or miles of lateral displacement over millions of years. The rocks underlying many of the SFAN park units originally formed in completely different geologic settings before they were transported north and juxtaposed against strata of very different ages and lithologies (Matthews 1973b; Sims 1993; Stoffer 2002).

The modern-day transform boundary did not always exist in California. Prior to the Oligocene Epoch, about 50 Ma (mega-annum, or millions of years ago; see Appendix B for a geologic time scale), the west coast was characterized by a convergent tectonic boundary where an ancient oceanic plate was thrust beneath the lighter continental North American plate to form an extensive subduction zone. Rocks of the Franciscan Complex, in addition to several Cretaceous-age intrusive bodies mapped in GOGA, PINN, and PORE, formed in association with this ancient collisional tectonic setting. The initiation of the modern transform boundary began in southern California about 28 Ma and extended through the Bay Area approximately 10 Ma, making the San Andreas Fault a relatively young geologic feature (Atwater 1989; Page and Wahrhaftig 1989; Elder 2013).

The geologic setting of the San Francisco Bay area is complex and well-studied. Widely mapped across the park units of the SFAN are basement rocks associated with the Jurassic–Eocene Franciscan Complex. The Franciscan Complex consists of an assemblage of rock types that were deposited in an accretionary wedge and subsequently metamorphosed, sheared, and added to the North American continent (Elder 2013). As tectonism in the San Francisco Bay area evolved from a convergent to a transform regime, geologic processes such as tension, compression, and localized faulting associated with the development of the San Andreas fault system broke the pre-Cenozoic bedrock into blocks which created basins and uplifts (Stoffer 2002; Port 2016). With the exception of the Pinnacles Volcanics in PINN, Cenozoic-age strata that underlie the park units of the SFAN are primarily sedimentary rocks deposited in a range of settings, from marine, to coastal, to nonmarine.

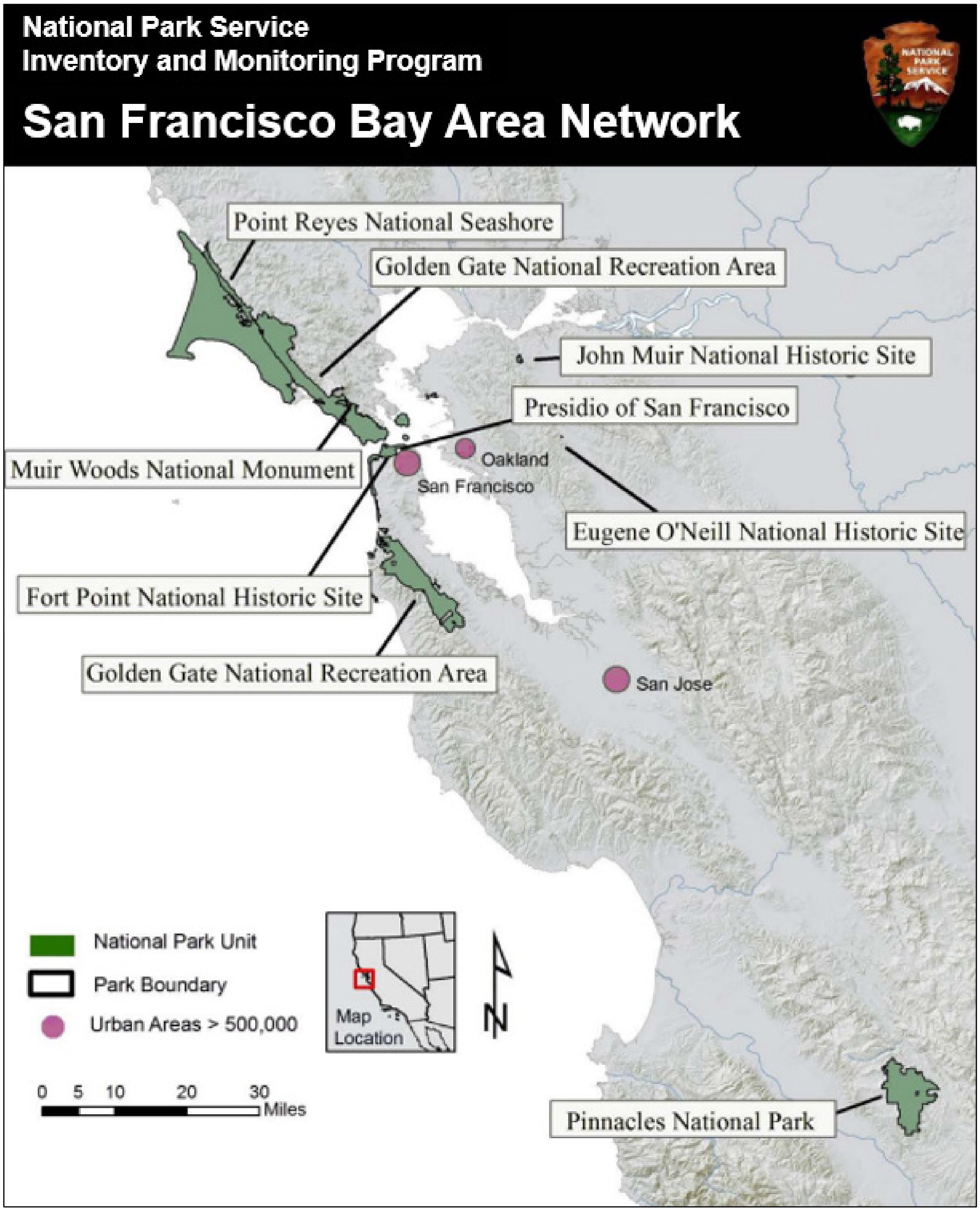


Figure 1. Map of San Francisco Bay Area I&M Network parks, including: Fort Point National Historic Site (FOPO), Golden Gate National Recreation Area (GOGA), John Muir National Historic Site (JOMU), Muir Woods National Monument (MUWO), Pinnacles National Park (PINN), and Point Reyes National Seashore (PORE) (NPS). The locations of Eugene O'Neill National Historic Site and Presidio of San Francisco are also shown, but these units are not mentioned in this report.

Precambrian

Precambrian rocks are not exposed in any of the parks of the SFAN.

Paleozoic

Paleozoic rocks are not exposed in any of the parks of the SFAN, with the exception of Paleozoic–Mesozoic-age metamorphic rocks that compose portions of Inverness Ridge in PORE.

Mesozoic

Mesozoic rocks are mapped in all six of the park units of the SFAN, with some of the oldest rocks consisting of Paleozoic–Mesozoic metamorphic rocks that occur as patches and small roof pendants on Inverness Ridge in PORE. Jurassic-age siliceous volcanic rocks and gabbro underlie portions of southern GOGA. Jurassic–Cretaceous-age rocks of the Franciscan Complex are located in FOPO, GOGA, MUWO, and PORE and represent a wide range of lithologies including sandstone, shale, limestone, greenstone, serpentinite, chert, meta-chert, and mélange. The Cretaceous Period is represented by interbedded sandstone, siltstone, and shale of the Great Valley Sequence in JOMU, in addition to intrusive rocks in GOGA, PINN, and PORE.

Cenozoic

Rocks of the Cenozoic Era are found in all six park units of the SFAN. The Paleocene Martinez Formation underlies southern JOMU and consists of fossiliferous sandstone, shale, and glauconitic sand (Merriam 1897; Arnold 1906; Dickerson 1914). The Eocene Period is represented by the Point Reyes Conglomerate in PORE and the Whiskey Hill Formation in GOGA. The Oligocene–Miocene Pinnacles Volcanics derives its name from exposures throughout PINN that consist of rhyolite, andesite, dacite, and pyroclastic deposits (Matthews 1973b; Sims 1993). The Miocene Monterey Formation is mapped in both PINN and PORE; other Miocene-age units include the Laird Sandstone, Santa Cruz Mudstone, and Santa Margarita Formation in PORE. Mudstone and sandstone of the Miocene–Pliocene Purisima Formation underlie GOGA and PORE. Pliocene-age strata include fossiliferous marine sandstones, shales, and conglomerates of the Pancho Rico Formation in PINN. The Pliocene–Pleistocene Merced Formation is mapped in both GOGA and PORE; other units of similar age include the Santa Clara Formation in GOGA and the Paso Robles Formation in PINN. The youngest formally named units in the SFAN are represented by the Pleistocene Colma Formation, Olema Creek Formation, and Millerton Formation in GOGA. Young surficial deposits mapped throughout the park units of the SFAN include Quaternary alluvium (GOGA, JOMU, MUWO, PINN, PORE), landslide deposits (FOPO, GOGA, PINN, PORE), slope and ravine deposits (FOPO, GOGA), beach and dune sand (GOGA, PORE), marine terrace deposits (GOGA, PORE), and unconsolidated surficial deposits (FOPO).

National Park Service Geologic Resources 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 four 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; (3) create posters to display the GRI GIS data; and (4) 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 SFAN parks: JOMU on September 24, 2007; PINN on September 25, 2007; and FOPO, GOGA, MUWO, and PORE on September 26–28, 2007.

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 2022, GRI reports have been completed for FOPO, GOGA, JOMU, MUWO, and PORE. Currently the GRI report for PINN is slated for 2022–2023 release. The GRI team conducts no new field work in association with their products.

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

Geologic Map Data

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

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

Geologic Maps

A geologic map is the fundamental tool for depicting the geology of an area. Geologic maps are two-dimensional representations of the three-dimensional geometry of rock and sediment at, or beneath the land surface (Evans 2016). Color and sometimes symbols on geologic maps are used to distinguish geologic map units. The unit labels consist of an uppercase letter (or symbol for some ages) 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) and work by Bernknopf et al. (1993) provide more information about geologic maps and their uses.

Geologic maps are typically one of three types: surficial, bedrock, or a combination of both. 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, geologic processes, and/or depositional environment. The GRI team has produced various maps for the SFAN 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 an ancillary map information 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 SFAN 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 FOPO, GOGA, MUWO, PINN, and PORE was compiled using data model version 2.1, which is available at https://www.nps.gov/articles/gri-geodatabase-model.htm; the JOMU data are based on older data models and need to be upgraded to the most recent version. The 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 FOPO, GOGA, JOMU, MUWO, PINN, or PORE 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. 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 on the information provided. Please contact GRI with any questions.

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

Methods

Described here are the methods employed and definitions adopted during this inventory of geologic stratotypes located within the administrative boundaries of the parks in the SFAN. This report is part of an inventory of geologic stratotypes throughout the National Park System. Therefore, the methods, definitions, and challenges identified here pertain not only to the parks of the SFAN, but also to other inventory and monitoring networks and parks.

There are several considerations for 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 new field work and is dependent on the existing information related to individual park geology and stratigraphy. Additionally, this inventory does not attempt to resolve any unresolved or controversial stratigraphic interpretations, which is beyond the scope of the project.

Stratigraphic nomenclature may change over time with refined stratigraphic field assessments and discovery of information through the expansion of stratigraphic mapping and measured sections. One important observation regarding stratigraphic nomenclature relates to differences in use of geologic names for units that transcend state boundaries. Geologic formations and other units that cross state boundaries may be referenced with different names in each of the states the units are mapped. An example is the Triassic Chugwater Formation in Wyoming, which is equivalent to the Spearfish Formation in the Black Hills of South Dakota.

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

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

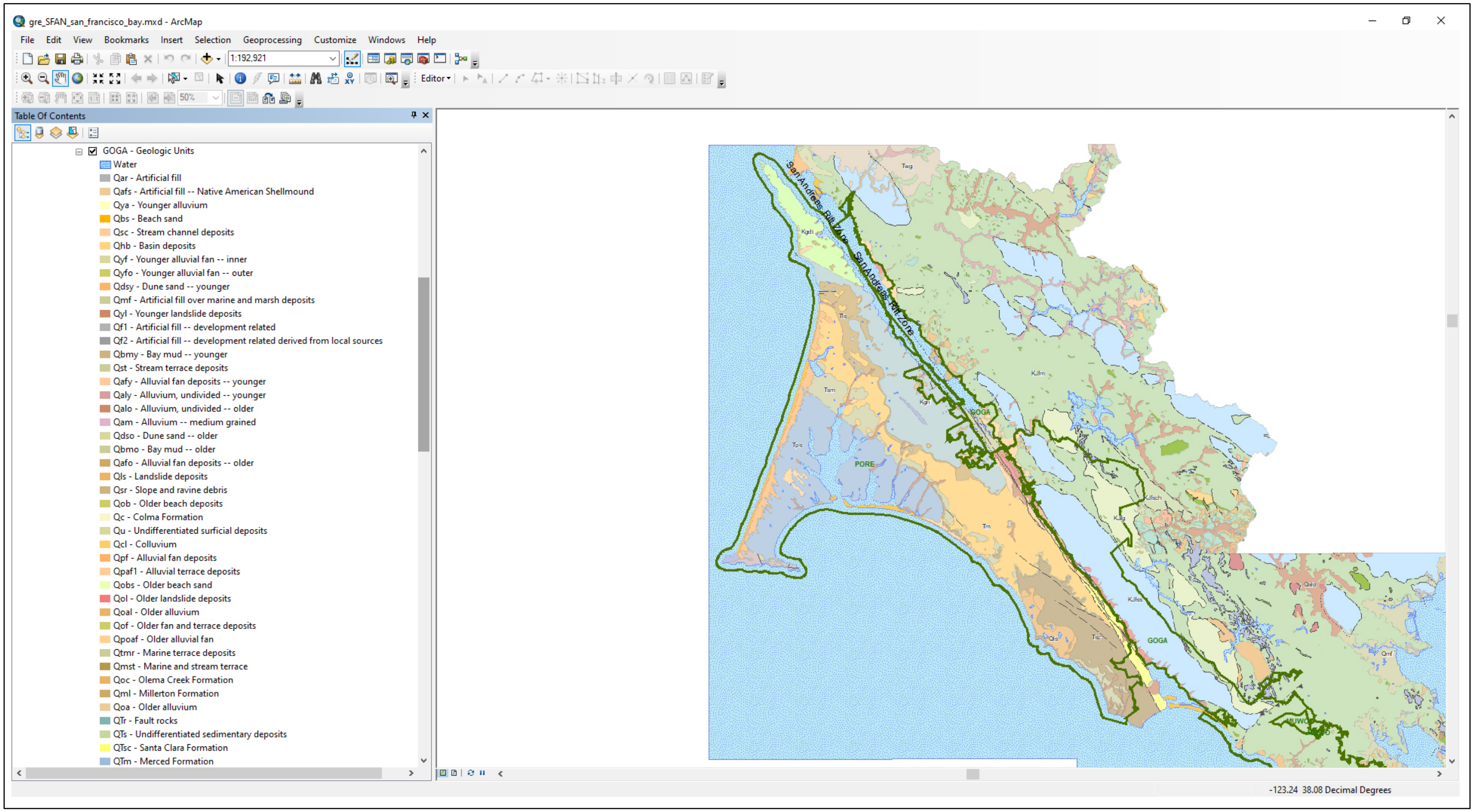


Figure 2. Screenshot of digital geologic map of Point Reyes National Seashore showing mapped units. Data modified from PORE GRI digital geologic map data at https://irma.nps.gov/DataStore/Reference/Profile/1048293.

Each map unit name is then queried in the USGS Geologic Names Lexicon online database ("GEOLEX", a national compilation of names and descriptions of geologic units) at https://ngmdb.usgs.gov/Geolex/search. Information provided by GEOLEX includes unit name, stratigraphic nomenclature usage, geologic age, and 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). The "Significant Publications" link provides published references and additional information about nomenclature revisions for certain geologic units. Figure 3 below is taken from a search on the Pinnacles Volcanics.

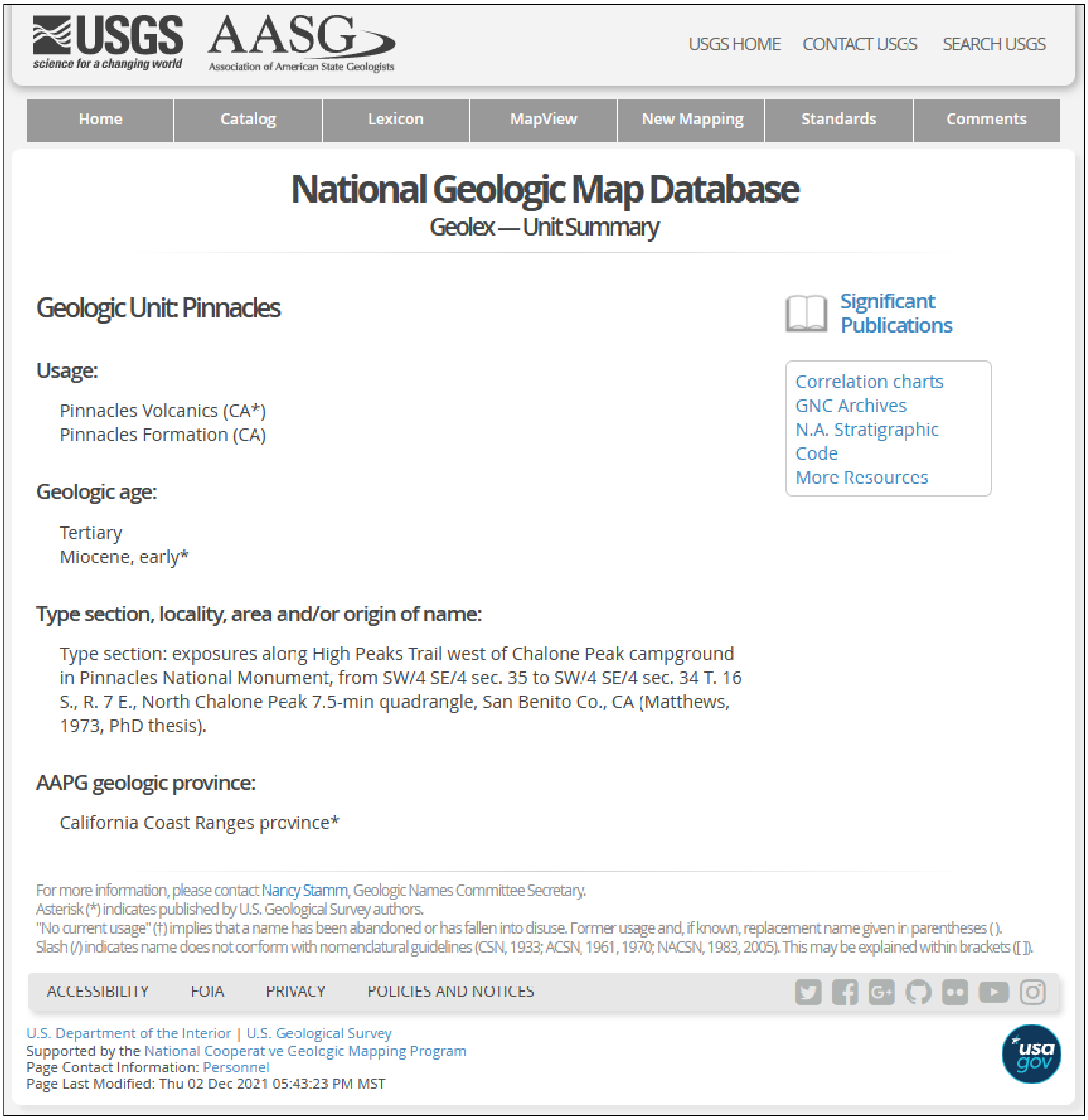
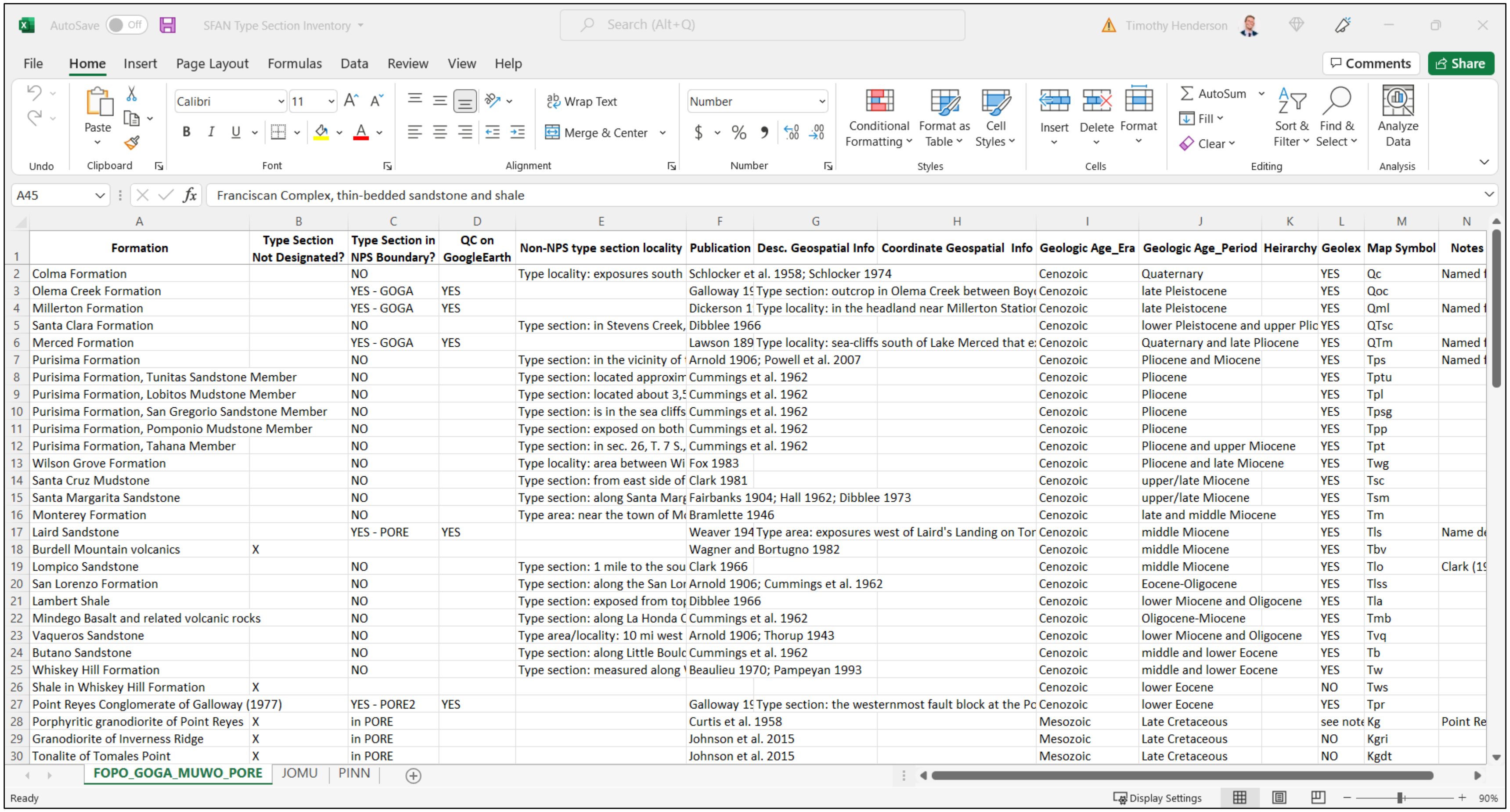


Figure 3. GEOLEX search result for Pinnacles Volcanics unit.

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). Coordinates are typically presented in an abbreviated format such as "sec. [#], T. [#] [N. or S.], R. [#] [E. or W.]". 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 area is draped over it. This step serves two functions: to improve accuracy in locating the stratotype, and validating the geologic polygon for agreement with GEOLEX nomenclature. Geolocations in Google Earth are then converted into an ArcGIS format using a "KML to Layer" conversion tool in ArcMap.

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



	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	Formation	Type Section Not Designated?	Type Section in NPS Boundary?	QC on GoogleEarth	Non-NPS type section locality	Publication	Desc. Geospatial Info	Coordinate Geospatial Info	Geologic Age_Era	Geologic Age_Period	Heirarchy	Geolex	Map Symbol	Notes
2	Colma Formation		NO		Type locality: exposures south	Schlocker et al. 1958; Schlocker 1974			Cenozoic	Quaternary		YES	Qc	Named f
3	Olema Creek Formation		YES - GOGA	YES		Galloway 19	Type section: outcrop in Olema Creek between Boy		Cenozoic	late Pleistocene		YES	Qoc	
4	Millerton Formation		YES - GOGA	YES		Dickerson 1	Type locality: in the headland near Millerton Statio		Cenozoic	late Pleistocene		YES	Qml	Named f
5	Santa Clara Formation		NO		Type section: in Stevens Creek,	Dibblee 1966			Cenozoic	lower Pleistocene and upper Plic		YES	QTsc	
6	Merced Formation		YES - GOGA	YES		Lawson 189	Type locality: sea-cliffs south of Lake Merced that e		Cenozoic	Quaternary and late Pliocene		YES	QTm	Named f
7	Purisima Formation		NO		Type section: in the vicinity of	Arnold 1906; Powell et al. 2007			Cenozoic	Pliocene and Miocene		YES	Tps	Named f
8	Purisima Formation, Tunitas Sandstone Member		NO		Type section: located approxim	Cummings et al. 1962			Cenozoic	Pliocene		YES	Tptu	
9	Purisima Formation, Lobitos Mudstone Member		NO		Type section: located about 3,5	Cummings et al. 1962			Cenozoic	Pliocene		YES	Tpl	
10	Purisima Formation, San Gregorio Sandstone Member		NO		Type section: is in the sea cliffs	Cummings et al. 1962			Cenozoic	Pliocene		YES	Tpsg	
11	Purisima Formation, Pomponio Mudstone Member		NO		Type section: exposed on both	Cummings et al. 1962			Cenozoic	Pliocene		YES	Tpp	
12	Purisima Formation, Tahana Member		NO		Type section: in sec. 26, T. 7 S.,	Cummings et al. 1962			Cenozoic	Pliocene and upper Miocene		YES	Tpt	
13	Wilson Grove Formation		NO		Type locality: area between Wi	Fox 1983			Cenozoic	Pliocene and late Miocene		YES	Twg	
14	Santa Cruz Mudstone		NO		Type section: from east side of	Clark 1981			Cenozoic	upper/late Miocene		YES	Tsc	
15	Santa Margarita Sandstone		NO		Type section: along Santa Marg	Fairbanks 1904; Hall 1962; Dibblee 1973			Cenozoic	upper/late Miocene		YES	Tsm	
16	Monterey Formation		NO		Type area: near the town of M	Bramlette 1946			Cenozoic	late and middle Miocene		YES	Tm	
17	Laird Sandstone		YES - PORE	YES		Weaver 194	Type area: exposures west of Laird's Landing on Tor		Cenozoic	middle Miocene		YES	Tls	Name de
18	Burdell Mountain volcanics	X				Wagner and Bortugno 1982			Cenozoic	middle Miocene		YES	Tbv	
19	Lompico Sandstone		NO		Type section: 1 mile to the sou	Clark 1966			Cenozoic	middle Miocene		YES	Tlo	Clark (19
20	San Lorenzo Formation		NO		Type section: along the San Lo	Arnold 1906; Cummings et al. 1962			Cenozoic	Eocene-Oligocene		YES	Tlss	
21	Lambert Shale		NO		Type section: exposed from to	Dibblee 1966			Cenozoic	lower Miocene and Oligocene		YES	Tla	
22	Mindego Basalt and related volcanic rocks		NO		Type section: along La Honda C	Cummings et al. 1962			Cenozoic	Oligocene-Miocene		YES	Tmb	
23	Vaqueros Sandstone		NO		Type area/locality: 10 mi west	Arnold 1906; Thorup 1943			Cenozoic	lower Miocene and Oligocene		YES	Tvq	
24	Butano Sandstone		NO		Type section: along Little Boulc	Cummings et al. 1962			Cenozoic	middle and lower Eocene		YES	Tb	
25	Whiskey Hill Formation		NO		Type section: measured along	Beaulieu 1970; Pampeyan 1993			Cenozoic	middle and lower Eocene		YES	Tw	
26	Shale in Whiskey Hill Formation	X							Cenozoic	lower Eocene		NO	Tws	
27	Point Reyes Conglomerate of Galloway (1977)		YES - PORE2	YES		Galloway 19	Type section: the westernmost fault block at the Pc		Cenozoic	lower Eocene		YES	Tpr	
28	Porphyritic granodiorite of Point Reyes	X	in PORE			Curtis et al. 1958			Mesozoic	Late Cretaceous		see note	Kg	Point Re
29	Granodiorite of Inverness Ridge	X	in PORE			Johnson et al. 2015			Mesozoic	Late Cretaceous		NO	Kgri	
30	Tonalite of Tomales Point	X	in PORE			Johnson et al. 2015			Mesozoic	Late Cretaceous		NO	Kgdt	

Figure 4. Stratotype inventory spreadsheet of the SFAN displaying attributes appropriate for geolocation assessment.

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 exposure (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 2021). There are several variations of stratotype referred to in the literature and this report, and they are defined as follows:

1. **Unit stratotype**: the **type section** for a stratified deposit or the **type area** for a non-stratified body that serves as the standard for recognition and definition of a geologic unit (North American Commission on Stratigraphic Nomenclature 2021). Once a unit stratotype is assigned, it is never changed. The term "unit stratotype" is commonly referred to as "type section" and "type area" in this report.
2. **Type locality**: the specific geographic locality encompassing the unit stratotype of a formally recognized and defined unit. On a broader scale, a type area is the geographic territory encompassing the type locality. Before development of the stratotype concept, only type localities and type areas were designated for many geologic units that are now long- and well-established (North American Commission on Stratigraphic Nomenclature 2021).
3. **Reference sections**: for well-established geologic units for which a type section was never assigned, a reference section may serve as an invaluable standard in definitions or revisions. A principal reference section may also be designated for units whose stratotypes have been destroyed, covered, or are otherwise inaccessible (North American Commission on Stratigraphic Nomenclature 2021). Multiple reference sections can be designated for a single unit to help illustrate heterogeneity or some critical feature not found in the stratotype. Reference sections can help supplement unit stratotypes in the case where the stratotype proves inadequate (North American Commission on Stratigraphic Nomenclature 2021).
4. **Lithodeme**: the term "lithodeme" is defined as a mappable unit of plutonic (igneous rock that solidified at great depth) or highly metamorphosed and pervasively deformed rock and is a term equivalent in rank to "formation" among stratified rocks (North American Commission on Stratigraphic Nomenclature 2021). The formal name of a lithodeme consists of a geographic name followed by a descriptive term that denotes the average modal composition of the rock (example: Cathedral Peak Granodiorite). Lithodemes are commonly assigned type localities, type areas, and reference localities.

Fort Point National Historic Site (FOPO)

Fort Point National Historic Site (FOPO) is located at the southern entrance to San Francisco Bay in the shadow of the Golden Gate Bridge in San Francisco County, California (Figure 5). Established on October 16, 1970, FOPO preserves approximately 11 hectares (29 acres) that include Fort Point, one of the finest examples of Civil War-era forts in the United States and one of the first major U.S. Army installations in the Bay Area (National Park Service 2016, 2017). Constructed between 1853 and 1861, Fort Point is situated at the narrows of the "Golden Gate", a strategic coastal location that has held economic, political, social, and environmental influence on the region and world from 18th-century Spanish settlement through the present day. The fort played a role in the harbor defenses of San Francisco during both the Civil War and World War II. Construction of the Golden Gate Bridge in the early 1930s almost demolished Fort Point, but the bridge's chief engineer Joseph Strauss decided to save the fort because of its exquisite masonry work (Port 2016). The presence of Fort Point influenced the design of the Golden Gate Bridge, with the southern anchorage of the bridge engineered to gracefully arch over the fort. Today, Fort Point National Historic Site is managed as a distinct park unit within the larger Golden Gate National Recreation Area.

The history and construction of Fort Point is heavily influenced by its strategic location and surrounding geology, with a history of military installations extending back to the Spanish army in the late 18th century (Castillo de San Joaquin). Bedrock underlying Fort Point National Historic Site primarily consists of serpentinite, sandstone, and shale of the Jurassic–Cretaceous Franciscan Complex (Figure 6). The Cantil Blanco ("White Cliff") bluff in FOPO overlooks the Golden Gate and consists of resistant serpentinite. During the 1850s the U.S. Army began construction on Fort Point, building the new military post atop the abandoned Castillo de San Joaquin. Before the US Army began building Fort Point, the cliffs of Cantil Blanco were leveled to strategically install gun mounts as close to the water as possible. Engineers began to level the serpentinite bluff from its original position approximately 30 m (100 ft) above sea level down to only about 5 m (15 ft) above sea level, a project that would take an entire year to complete (Port 2016). Younger surficial units mapped within FOPO include Quaternary-age slope and ravine deposits, landslide deposits, unconsolidated surficial deposits, and artificial fill.

There are no designated stratotypes identified within the boundaries of FOPO. There are 17 identified stratotypes located within 48 km (30 mi) of FOPO boundaries, for the Eocene Whiskey Hill Formation (type section and type area) and Muir Sandstone (type locality); Oligocene San Ramon Sandstone (type section); Miocene San Pablo Group (type locality), Cierbo Formation (type section), Sobrante Sandstone (type section), Bald Peak Basalt (type locality), and Mulholland Formation (type section); Miocene–Pliocene Purisima Formation (type section); Pliocene Huichica Formation (type locality), Pinole Tuff (type section), Lobitos Mudstone Member of the Purisima Formation (type section), San Gregorio Sandstone Member of the Purisima Formation (type section), and Tunitas Sandstone Member of the Purisima Formation (type section); and Pleistocene Colma Formation (type locality and reference locality).

Figure 5. Park map of FOPO, California, also showing the locations of GOGA and MUWO (NPS).

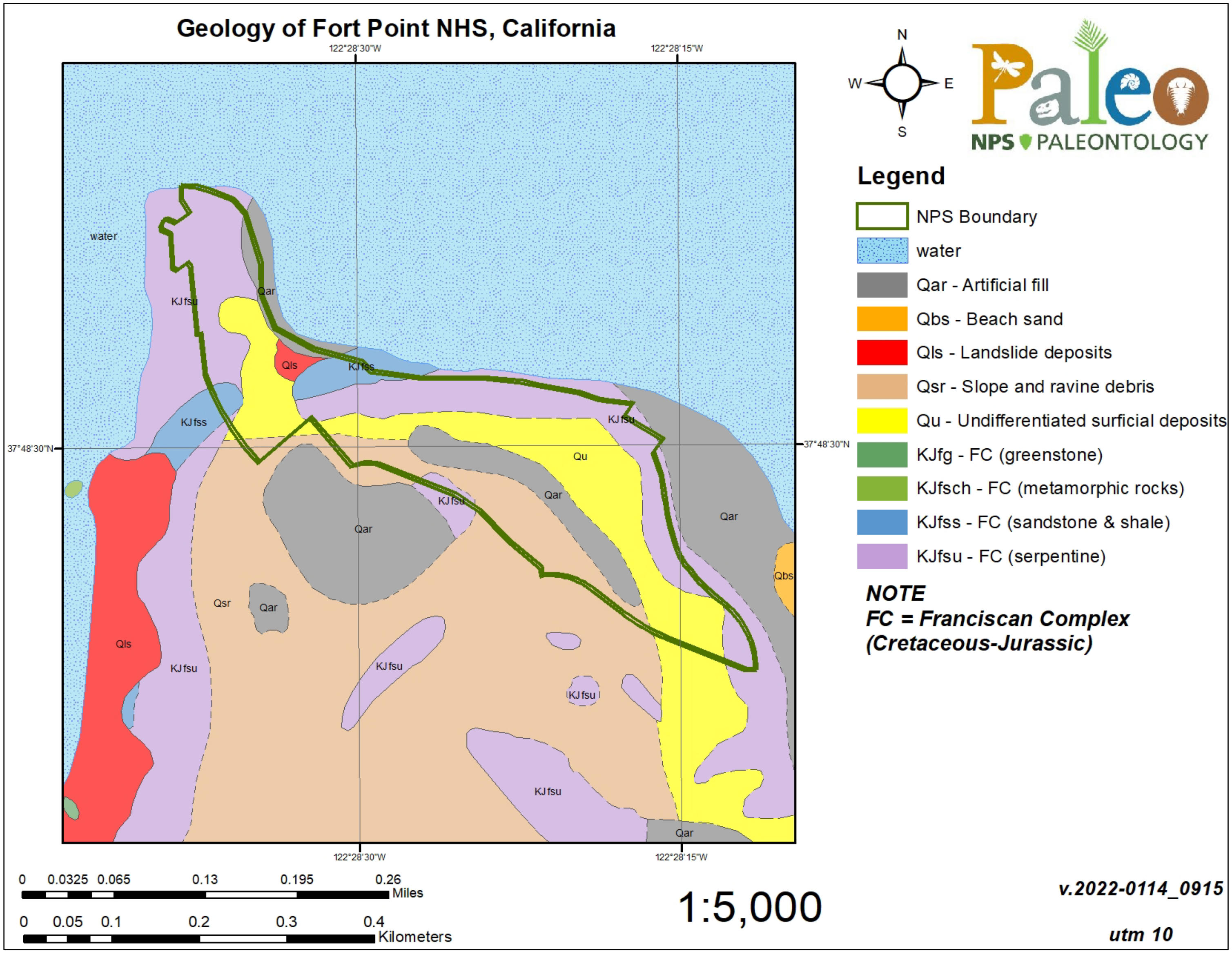


Figure 6. Geologic map of FOPO, California. Data modified from FOPO GRI digital geologic map data at https://irma.nps.gov/DataStore/Reference/Profile/1048292.

Golden Gate National Recreation Area (GOGA)

Golden Gate National Recreation Area (GOGA) is one of the largest urban parks on Earth, stretching across California's San Francisco Bay area in Marin, San Francisco, and San Mateo Counties (Figure 7). Established on October 27, 1972, GOGA encompasses approximately 33,195 hectares (82,027 acres) and preserves iconic coastal scenery (Marin Headlands), beaches, lagoons, more than 160 km (100 mi) of trails, an infamous prison (Alcatraz Island), massive trees (Muir Woods), former U.S. military fortifications, and the site of the initial Spanish fortification in San Francisco (the Presidio). The national recreation area is part of the United Nations (UNESCO)-designated Golden Gate Biosphere Reserve, home to more than 1,250 plant and animal species, including some of the most rare, threatened, and endangered species in the NPS (National Park Service 2017). GOGA's namesake, "Golden Gate," refers to the narrow strait connecting San Francisco Bay to the Pacific Ocean. The bay, isolated islands, and rugged headlands created a valuable landscape that supported commerce and facilitated defense (Port 2016). GOGA consists of a collection of NPS-administered areas that includes two other park units—Fort Point National Historic Site (FOPO) and Muir Woods National Monument (MUWO) (both covered under their own chapters here).

GOGA is situated in one of the most geologically active regions of the United States and serves as an ideal setting to study the geologic processes associated with plate tectonics. Rocks underlying GOGA date back to the Jurassic Period (~160 Ma), when the western margin of North America represented a convergent plate boundary between the ancient Farallon oceanic plate and North American continental plate. Because oceanic crust is denser than continental crust, the Farallon Plate sank beneath the North American Plate and formed what geologists refer to as the "Franciscan subduction zone". Franciscan subduction occurred from about 160 Ma to 50 Ma (Elder 2013). Basement rocks within GOGA and the surrounding area formed (or at least assembled) in various geologic settings (e.g., oceanic trench, forearc basin, and volcanic arc) associated with the Franciscan subduction zone. Formations mapped within GOGA can be broken down into three main groups: (1) rocks of the Jurassic–Eocene Franciscan Complex; (2) Jurassic and Cretaceous-age intrusive and volcanic rocks; and (3) Cenozoic units of the Whiskey Hill Formation, Purisima Formation, Millerton Formation, Olema Creek Formation, Merced Formation, Santa Clara Formation, and Colma Formation (Figures 8 and 9). GOGA is bisected by the San Andreas fault system, a transform boundary between the North American Plate and Pacific Plate. Initiation of the modern transform boundary began in Southern California about 28 Ma and extended through the Bay Area approximately 10 Ma (Atwater 1989; Page and Wahrhaftig 1989; Elder 2013).

Figure 7. Park map of GOGA, California (NPS).

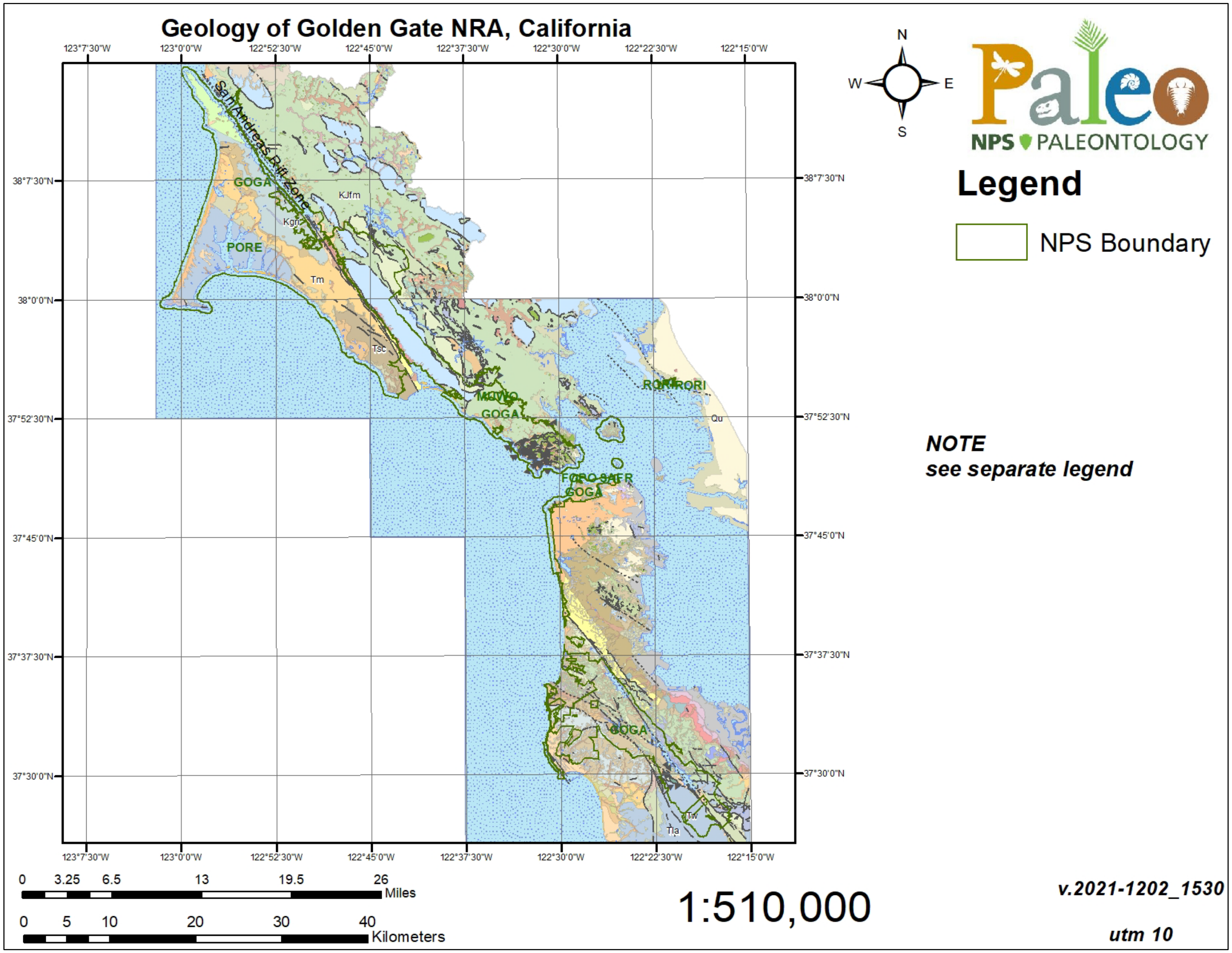


Figure 8. Geologic map of GOGA, California; see Figure 9 for legend. Data modified from GOGA GRI digital geologic map data at https://irma.nps.gov/DataStore/Reference/Profile/1048292.

Figure 9. Geologic map legend of GOGA, California.

GOGA contains five identified stratotypes that are subdivided into one type section and four type localities (Table 2; Figure 10). In addition to the designated stratotypes located within GOGA, stratotypes located within 48 km (30 mi) of GOGA boundaries include the Cretaceous Pigeon Point Formation (type section); Paleocene Locatelli Formation (type section); Eocene Butano Sandstone (type section), Whiskey Hill Formation (type section and type area), and Muir Sandstone (type locality); Eocene–Oligocene San Lorenzo Formation (type section); Oligocene San Ramon Sandstone (type section); Oligocene–Miocene Mindego Basalt (type section) and Lambert Shale (type section); Miocene San Pablo Group (type locality), Cierbo Formation (type section), Sobrante Sandstone (type section), Bald Peak Basalt (type locality), Mulholland Formation (type section), Page Mill Basalt (type section), Ladera Sandstone (type area), and Lompico Sandstone (type section); Miocene–Pliocene Wilson Grove Formation (type locality), Sonoma Volcanics (type area), Purisima Formation (type section), and Tahana Member of the Purisima Formation (type section and two reference sections); Pliocene Lobitos Mudstone Member of the Purisima Formation (type section), Pomponio Mudstone Member of the Purisima Formation (type section and reference section), San Gregorio Sandstone Member of the Purisima Formation (type section), Tunitas Sandstone Member of the Purisima Formation (type section), Huichica Formation (type locality), and Pinole Tuff (type section); Pliocene–Pleistocene Santa Clara Formation (type section) and Glen Ellen Formation (type locality); and the Pleistocene Colma Formation (type locality and reference locality).

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

Unit Name (GRI map symbol)	Reference	Stratotype Location	Age
Olema Creek Formation (Qoc)	Galloway 1977	**Type section**: outcrop in Olema Creek between Boyd Stewart Ranch and Vedanta Retreat, Marin County, CA.	Pleistocene
Millerton Formation (Qml)	Dickerson 1922	**Type locality**: in the headland near Millerton Station, northwest of Inverness on Tomales Bay, Marin County, CA.	Pleistocene
Merced Formation (QTm)	Lawson 1893; Arnold 1906; Glen 1959	**Type locality**: sea-cliffs south of Lake Merced that extend to Mussel Rock about 13 km (8 mi) south of Point Lobos, San Mateo County, CA.	Pliocene–Pleistocene
Calera Limestone, Franciscan Complex	Schlocker 1974	**Type locality**: stated to be along Pacific Ocean shoreline, 15 km (9.5 mi) south of San Francisco North Quadrangle, in Calera Valley adjacent to Rockaway quarry [Montara Mountain 7.5′ Quadrangle], San Mateo County, CA.	Cretaceous
Franciscan Complex (KJf*)	Schlocker et al. 1954	**Type locality**: narrow band of exposures in cliffs along the southern shore of inlet to San Francisco Bay, San Francisco County, CA.	Jurassic–Eocene

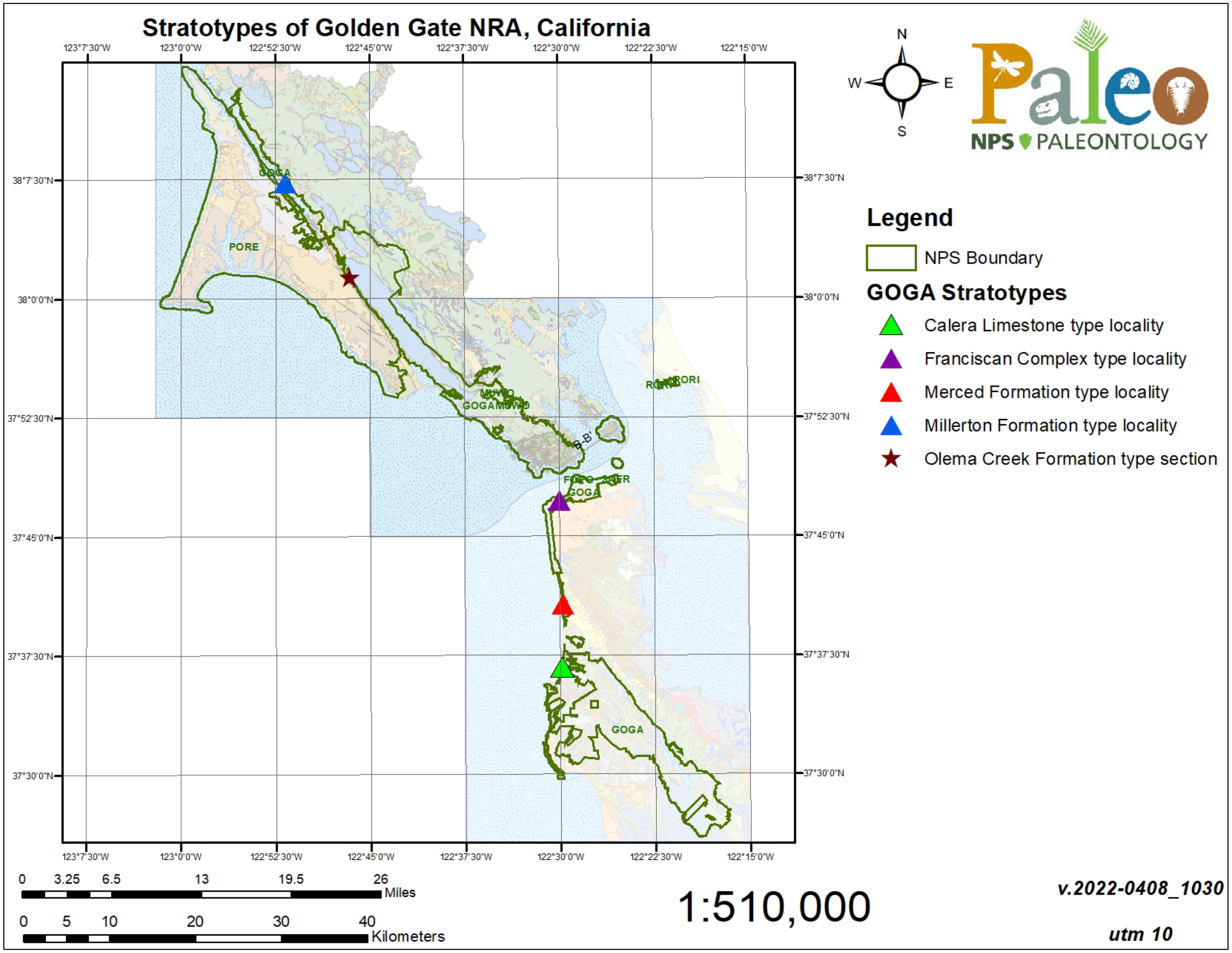


Figure 10. Modified geologic map of GOGA showing stratotype locations. The transparency of the geologic units layer has been increased.

Franciscan Complex

The Jurassic–Eocene Franciscan Complex was originally referred to as the "Franciscan series" by Lawson (1895) who derived the name from its extensive exposures near San Francisco, California. The type locality of the Franciscan Complex is designated as the narrow band of exposures in cliffs along the southern shore of the inlet to San Francisco Bay (Table 2; Figures 10–12; Schlocker et al. 1954). These exposures occur along approximately 3.2 km (2 mi) of precipitous cliffs that extend from the southern end of Baker Beach to a point 244 m (800 ft) south of Point Lobos (Schlocker et al. 1954). In the type locality, the Franciscan Complex is about 716 m (2,350 ft) thick and predominantly consists of greenstone, graywacke, and massive sandstone (Schlocker et al. 1954; Schlocker 1974; Cochrane et al. 2015). Exposures consisting of graywacke at Baker Beach exhibit honeycomb-like cavity structures called tafoni that typically develop in coastal areas (Figure 12). Rocks of the Franciscan Complex are composed of a diverse assemblage of sedimentary, metamorphic, and igneous rocks that represent an accretionary wedge: a complex body of rock that accumulates in a subduction zone (Elder 2013). In the type locality, the Franciscan Complex is overlain in places by Quaternary landslide deposits.

Figure 11. Serpentinite cliffs of the Franciscan Complex in the type locality along the southern shore of the inlet to San Francisco. Several landslide scars are visible and outlined by dashed lines (© 2002–2015 Kenneth & Gabrielle Adelman, California Coastal Records Project, https://www.californiacoastline.org/).

Figure 12. Coastal cliffs consisting of graywacke of the Franciscan Complex in the type locality at Baker Beach (NPS).

Calera Limestone

The Cretaceous Calera Limestone of the Franciscan Complex was originally introduced by Lawson (1914) as a member of the now-abandoned Cahil Sandstone, and derived the name from exposures in the sea cliffs at the lower end of Calera Valley, California. The type locality of the formation is designated along the Pacific Ocean shoreline, 15 km (9.5 mi) south of San Francisco North Quadrangle, in Calera Valley adjacent to Rockaway quarry [Montara Mountain 7.5′ Quadrangle], San Mateo County, western California (Table 2; Figures 10 and 13; Schlocker 1974). Type locality exposures have an average thickness of about 18 m (60 ft) and consist of gray limestone that contains irregular beds of chert ranging from 3–30 cm (1–12 in) thick (Lawson 1914). At the type locality, the Calera Limestone is in fault contact with greenstone rocks of the Franciscan Complex and is partially overlain by Quaternary beach sands and landslide deposits.

Figure 13. Type locality exposures of the Calera Limestone near the Rockaway quarry just north of Calera Valley (© 2002–2015 Kenneth & Gabrielle Adelman, California Coastal Records Project, https://www.californiacoastline.org/).

Merced Formation

The Pliocene–Pleistocene Merced Formation was proposed by Lawson (1893) as the "Merced series" and named after exposures near Lake Merced in western California. The type locality is designated as the sea-cliffs south of Lake Merced that extend to Mussel Rock about 13 km (8 mi) south of Point Lobos in San Mateo County, California (Table 2; Figure 10; Arnold 1906 and Glen 1959 citing Lawson 1893). At the type locality the Merced Formation forms a 1,778 m (5,834 ft)-thick sequence of friable, grayish-brown sandstone and sandy shale interbedded with pebbly conglomerate and well-cemented shell layers (Figure 14; Lawson 1893; Arnold 1906; Glen 1959). The Merced Formation unconformably overlies and is in fault contact with rocks of the Franciscan Complex and underlies both the Colma Formation and Quaternary-age landslide deposits and slope and ravine deposits.

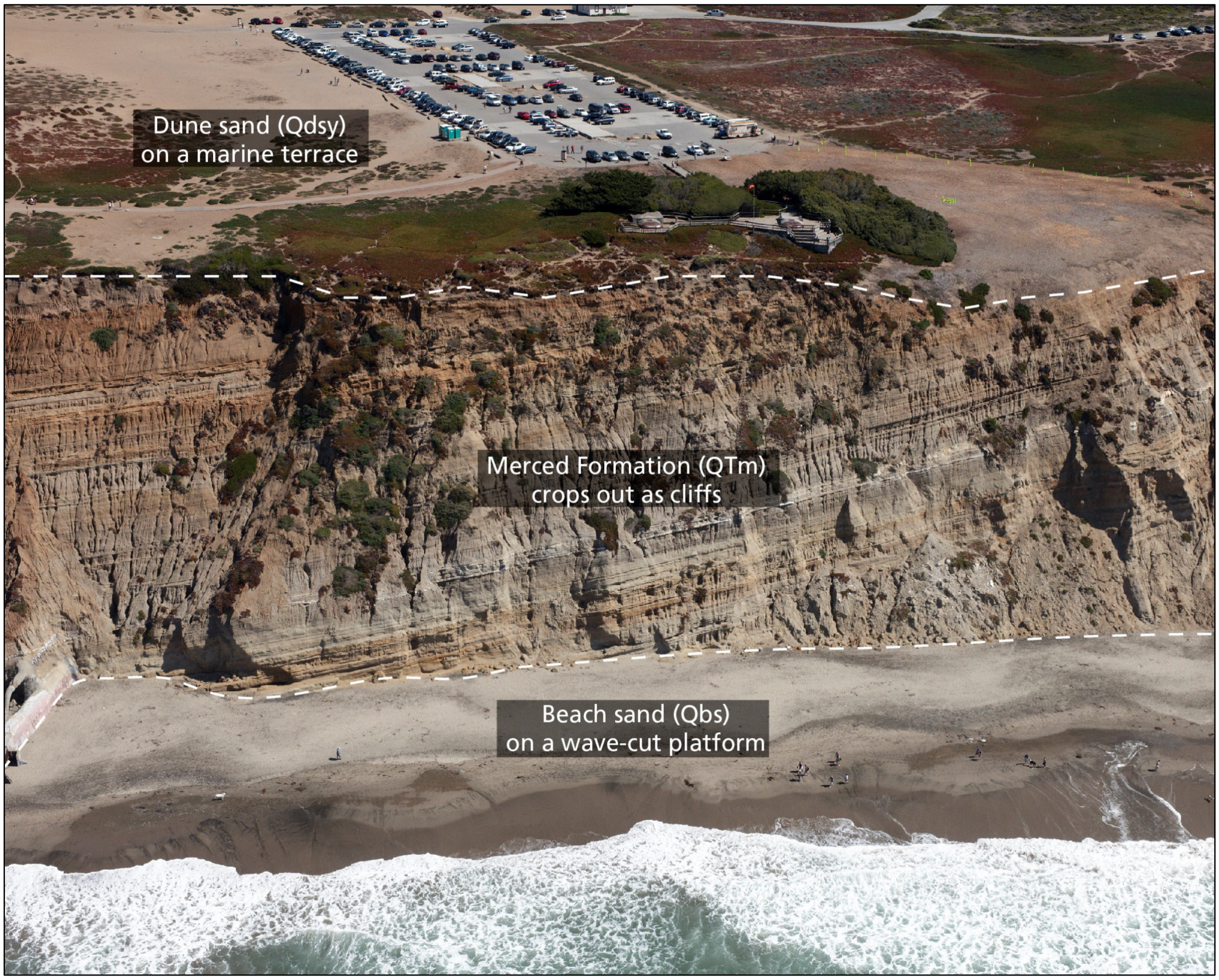


Figure 14. Type locality cliff exposures consisting of fossiliferous marine sandstone, shale (mudstone), and conglomerate of the Merced Formation below Fort Funston (© 2002–2015 Kenneth & Gabrielle Adelman, California Coastal Records Project, https://www.californiacoastline.org/).

Millerton Formation

The Pleistocene Millerton Formation was named by Dickerson (1922) after its type locality exposures in the headland near Millerton Station, northwest of Inverness on Tomales Bay, California (Table 2; Figure 10; Dickerson 1922). Type locality exposures measure approximately 18 m (60 ft) thick and consist of a basal interval of oyster beds and fossiliferous claystone overlain by sandstone and a prominent sequence of conglomerate (Dickerson 1922; Galloway 1977). The Millerton Formation represents an interbedded fossiliferous sequence of marine and non-marine deposits (Weaver 1949; Schlocker 1974). At the type locality the Millerton Formation unconformably overlies mélange of the Franciscan Complex and is partially overlain by Quaternary alluvium and landslide deposits.

Olema Creek Formation

The Pleistocene Olema Creek Formation was named by Galloway (1977) after its type section exposure along Olema Creek between Boyd Stewart Ranch and Vedanta Retreat in Marin County, California (Table 2; Figures 10, 15, and 16). Distribution of the formation is confined to the central part of the San Andreas fault zone between Five Brooks and Olema, where the formation measures more than 200 m (656 ft) thick (Galloway 1977). The Olema Creek Formation predominantly consists of bluish-gray, thin-bedded siltstone or claystone interbedded with coarse granitic gravel. The unit contains both freshwater diatoms and organic material including tree trunks (some preserved in upright growing position), wood, and peat (Galloway 1977). At the type locality the Olema Creek Formation is in fault contact with older sandstone and shale of the Franciscan Complex and is overlain by Quaternary alluvium and marine terrace deposits.

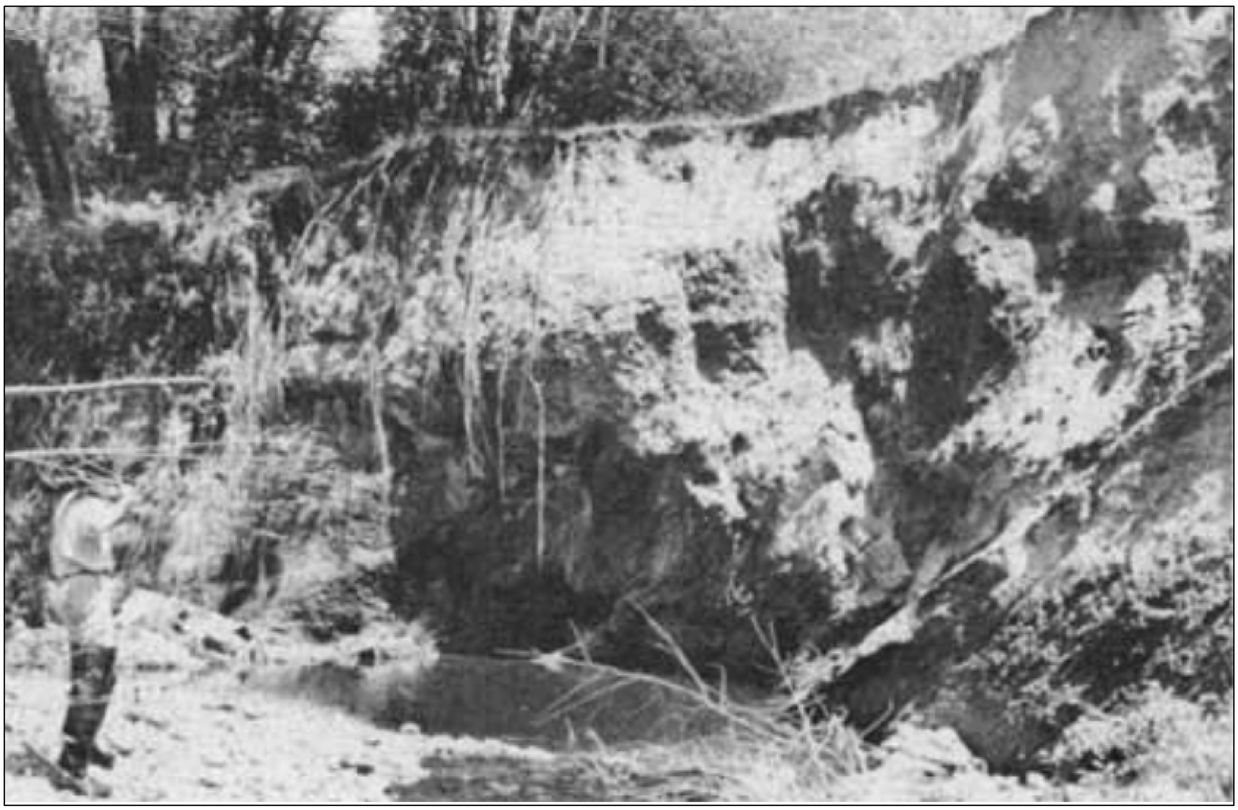


Figure 15. Type locality exposures of the Olema Creek Formation consisting of siltstone interbedded with granitic gravel. Note the person in the left foreground for scale. Photograph 17 from Galloway (1977).

Figure 16. Blocky siltstones of the Olema Creek Formation in the type locality near Olema. Photograph 18 from Galloway (1977).

John Muir National Historic Site (JOMU)

John Muir National Historic Site (JOMU) is situated along the Alhambra Valley in Martinez, Contra Costa County, California (Figure 17). Authorized on August 31, 1964, JOMU encompasses approximately 139 hectares (344 acres) and preserves the home and portions of the agricultural estate where influential naturalist and writer John Muir lived, worked, and is buried (National Park Service 2016). Considered a key advocate and founder of the national park concept, Muir's political leadership and writings helped establish several early national parks and launched an era of environmental activism that continues today. The historic site interprets the entirety of John Muir, beyond his legacy in wilderness conservation, and is uniquely positioned to explore how societal biases were woven into the system from its origins during Muir's time and why they continue today (National Park Service 2015a). The historic site is composed of three non-contiguous properties: 1) House Unit, that contains the 1882 Italianate Victorian house where John Muir lived from 1880 until his death in 1914; 2) Mount Wanda Unit, consisting of 132 hectares (326 acres) of rolling hills and footpaths; and 3) Gravesite Unit, that encompasses the Strentzel-Muir cemetery, including the gravesites of John Muir, his wife Louie, her parents John and Louisiana Strentzel, and Muir's daughter and son-in-law, Wanda and Tom Hanna (National Park Service 2015a; KellerLynn 2021).

The bedrock underlying John Muir National Historic Site is predominantly composed of two sedimentary units: (1) rocks of the Cretaceous Great Valley Sequence; and (2) the Paleocene Martinez Formation. Sediments that comprise these formations were shed from the Sierran magmatic arc to the east and deposited in a marine basin associated with a subduction zone on the western margin of North America between 163.5 Ma and 56 Ma. These rocks were laid down before the modern-day transform plate boundary of California existed, at a time when the oceanic Farallon and Kula Plates were converging with the continental North American Plate (Elder 2013). Sandstone, siltstone, and shale (mudstone) of the Great Valley Sequence are widely mapped throughout the core of JOMU and represent a diverse range of depositional environments that include shallow marine, fluvial-deltaic, basin plain, and deep-sea fan settings (Ingersoll 1979; Cherven 1983; Bartow and Nilsen 1990). Marine sandstone and shale of the Martinez Formation are found along the southwestern and northeastern portions of the historic site (Figure 18; Elder 2013).

John Muir National Historic Site contains one identified stratotype that represents the Paleocene Martinez Formation (Table 3; Figure 19). In addition to the designated stratotype located within JOMU, stratotypes located within 48 km (30 mi) of JOMU boundaries include the Eocene Muir Sandstone (type locality), Meganos Formation (type section), Markley Formation (type locality), and Nortonville Shale Member of the Kreyenhagen Shale (type locality); Oligocene San Ramon Sandstone (type section); Miocene Mulholland Formation (type section), San Pablo Group (type locality), Cierbo Formation (type section), Sobrante Sandstone (type section), and Bald Peak Basalt (type locality); Pliocene Huichica Formation (type locality) and Pinole Tuff (type section); and the Pleistocene Colma Formation (type locality and reference locality).

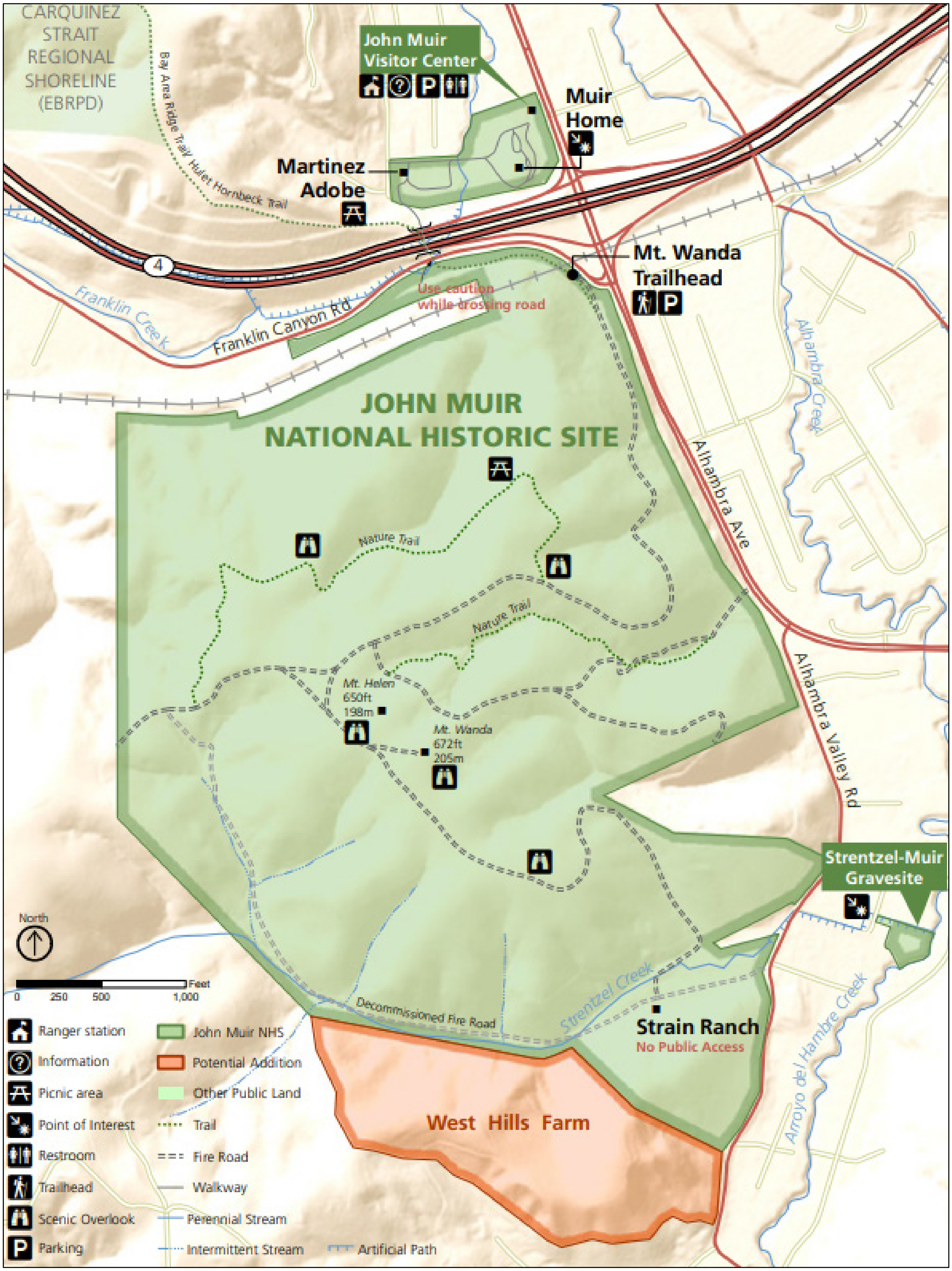


Figure 17. Park map of JOMU, California (NPS).

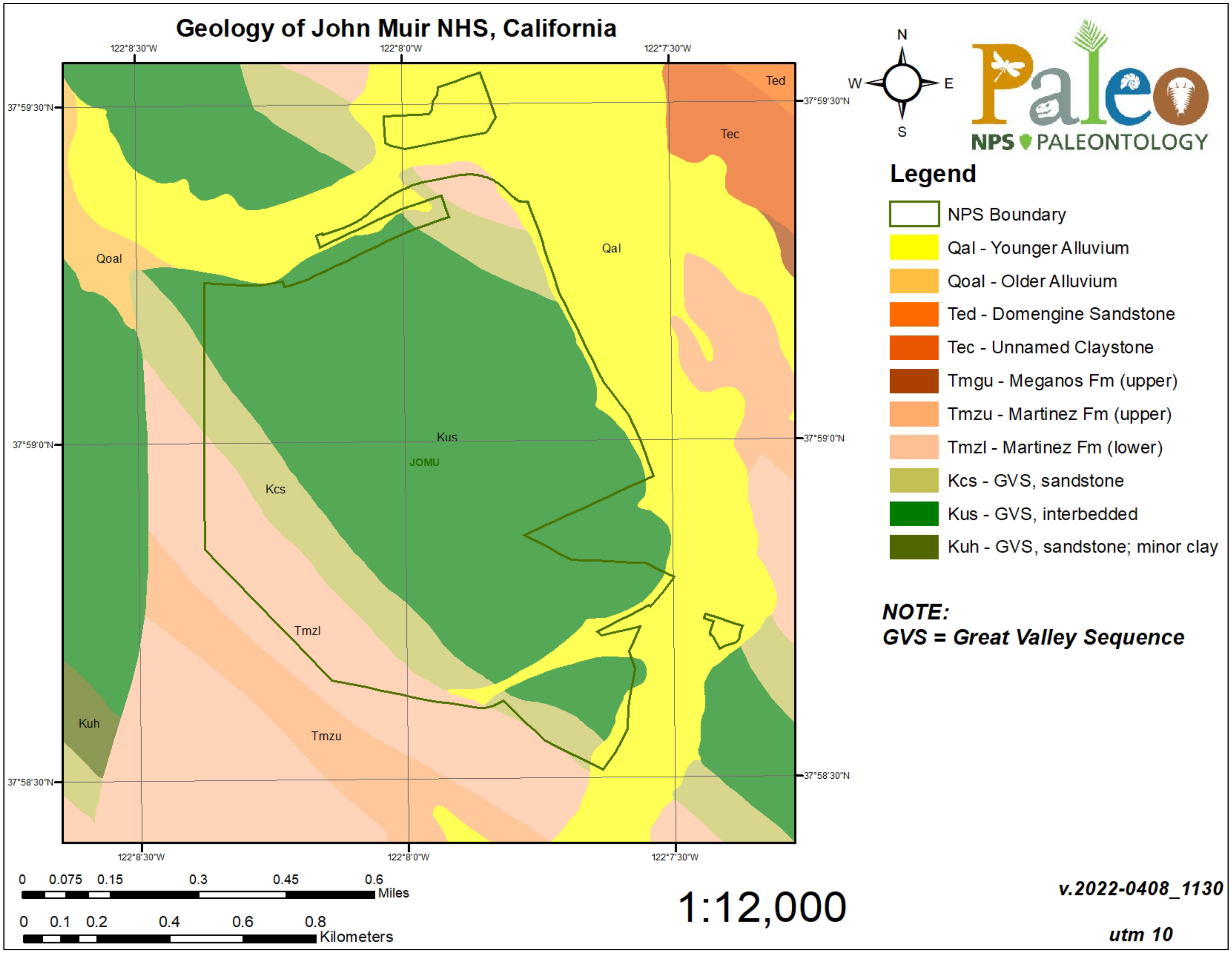


Figure 18. Geologic map of JOMU, California. Data modified from JOMU GRI digital geologic map data at https://irma.nps.gov/DataStore/Reference/Profile/1046887.

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

Unit Name (GRI map symbol)	Reference	Stratotype Location	Age
Martinez Formation (Tmz, Tmzu, Tmzl)	Merriam 1897; Arnold 1906	**Type locality**: designated as exposures south of town of Martinez, Contra Costa County, CA.	Paleocene

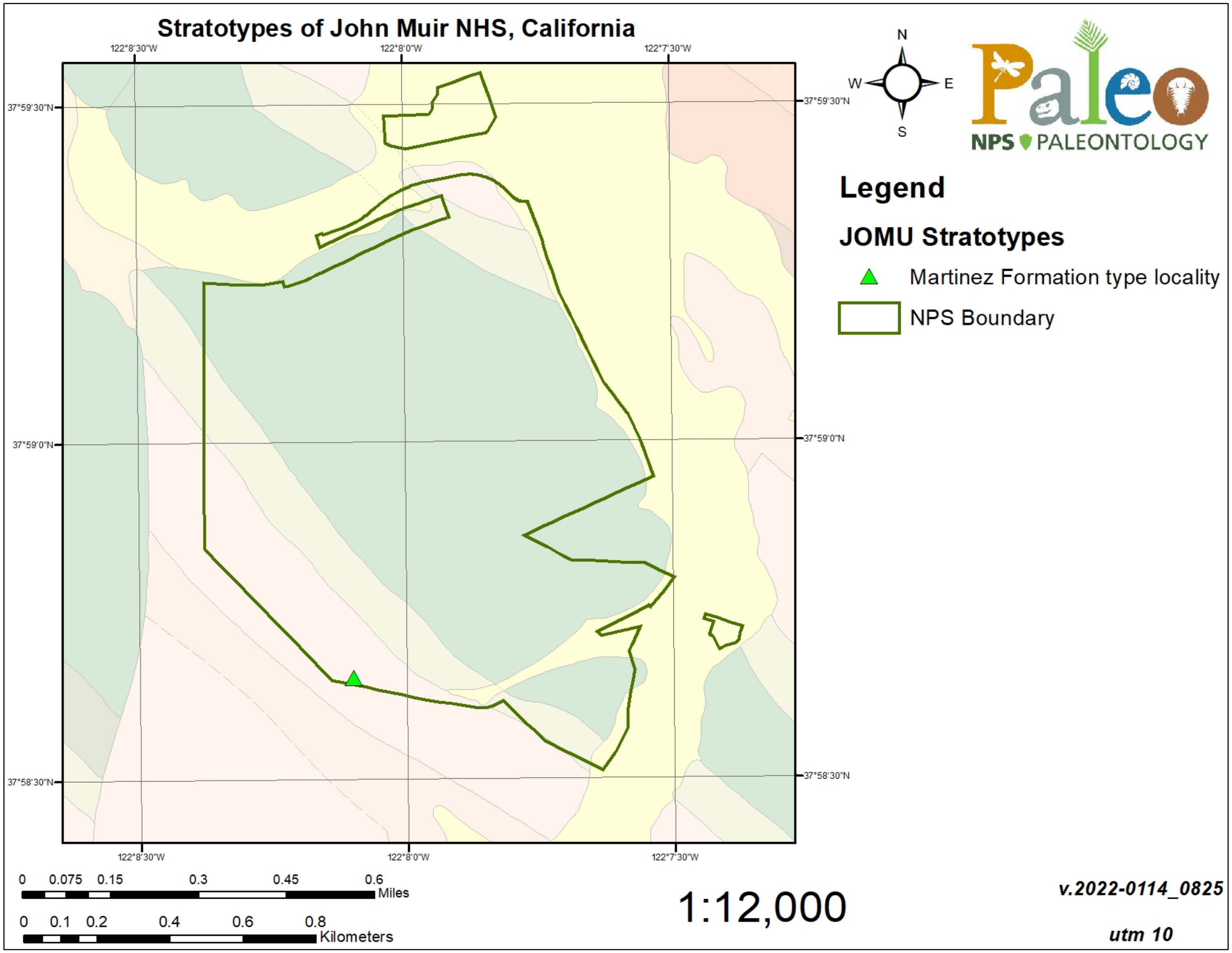


Figure 19. Modified geologic map of JOMU showing stratotype locations. The transparency of the geologic units layer has been increased.

Martinez Formation

The Paleocene Martinez Formation was introduced by Gabb (1869) and defined by Merriam (1897) as a fossiliferous sequence of marine sedimentary rocks that form the hills south of Martinez, California. The type locality of the formation is designated south of the town of Martinez in Contra Costa County, California (Table 3; Figure 19; Merriam 1897; Arnold 1906). At the type locality the Martinez Formation has a thickness of about 305–610 m (1,000–2,000 ft) and consists of sandstone, shale, and glauconitic sand (Merriam 1897; Arnold 1906; Dickerson 1914). The Martinez Formation conformably occurs between the overlying Tejon Formation and underlying Chico Formation.

Muir Woods National Monument (MUWO)

Muir Woods National Monument (MUWO) is located just a few miles northwest of San Francisco in Marin County, California (Figure 20). Proclaimed on January 9, 1908, MUWO contains about 224 hectares (554 acres) and protects the last remnant of old-growth redwood forest in proximity to the Bay Area (National Park Service 2016, 2017). The monument is named after influential naturalist and writer John Muir, considered to be a key advocate and founder of the national park concept. The establishment of MUWO is regarded as an important demonstration of early 20th century American conservation history, as the virgin redwood tract reaches heights of more than 76 m (250 ft) and has an average age between 600 and 800 years, with the oldest trees being at least 1,200 years old (Port 2016; National Park Service 2017). MUWO is encompassed by and managed as a distinct park unit within Golden Gate National Recreation Area.

The bedrock geology of MUWO consists entirely of rocks associated with the Jurassic–Eocene Franciscan Complex. The Franciscan Complex is composed of a diverse suite of lithologies that formed in an ancient subduction zone along the western coast of the United States (Elder 2013). Convergence between the oceanic Farallon Plate and continental North American Plate sheared and faulted some of the Franciscan rocks into a “mélange” (a French word for “mixture”) or broken blocks ranging in size from a few meters or yards across to many square kilometers or miles in area (Sloan 2006). The soft and sheared mélange of the Franciscan Complex is the predominant bedrock of MUWO, and forms rounded hills among more resistant Franciscan rocks in the Bay Area (Figure 21; Sloan 2006). Mapped in the easternmost portion of the monument are chert and metachert of the Franciscan Complex that occur as a large, fault-bounded block surrounded by mélange. Young surficial units within MUWO include Quaternary-age alluvium located along lower Redwood Creek.

There are no designated stratotypes identified within the boundaries of MUWO. There are 12 identified stratotypes located within 48 km (30 mi) of MUWO boundaries, for the Eocene Muir Sandstone (type locality); Oligocene San Ramon Sandstone (type section); Miocene San Pablo Group (type locality), Cierbo Formation (type section), Sobrante Sandstone (type section), Bald Peak Basalt (type locality), and Mulholland Formation (type section); Miocene–Pliocene Sonoma Volcanics (type area); Pliocene Huichica Formation (type locality) and Pinole Tuff (type section); and the Pleistocene Colma Formation (type locality and reference locality).

Figure 20. Park map of MUWO, California, also showing portions of GOGA (NPS).

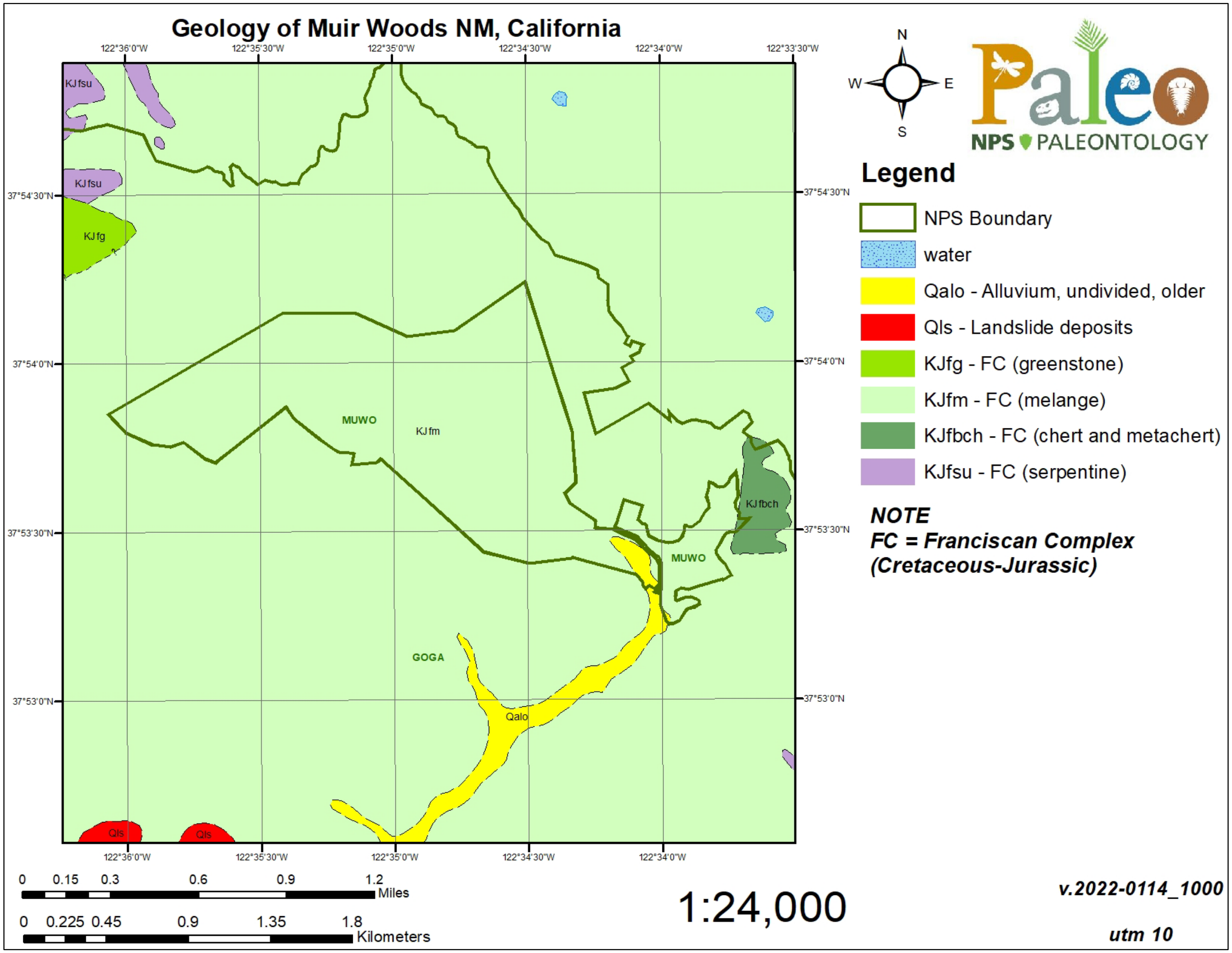


Figure 21. Geologic map of MUWO, California. Data modified from MUWO GRI digital geologic map data at https://irma.nps.gov/DataStore/Reference/Profile/1048292.

Pinnacles National Park (PINN)

Pinnacles National Park (PINN) is located in the southern Gabilan Range, about 64 km (40 mi) inland from the Pacific Ocean and about 129 km (80 mi) south of the San Francisco Bay Area in Monterey and San Benito Counties, California (Figure 22). Originally proclaimed as a national monument on January 16, 1908, it was re-designated as a national park on January 10, 2013 (National Park Service 2016). PINN encompasses approximately 10,799 hectares (26,686 acres) and protects valuable geologic resources that include spire-like rock formations standing 152–366 m (500–1,200 ft) high, an extensive assemblage of rare talus caves, and a variety of volcanic features associated with the Neenach Volcanic Field (National Park Service 2015b). Volcanic rocks of the Neenach Volcanic Field are believed to have formed ~23 Ma near present-day Lancaster, California, and have been transported to their current location some 315 km (196 mi) northwest by the extensive San Andreas fault system (Turner et al. 1970; Matthews 1973b; Sims 1993). Over the course of millions of years, the forces of wind and water have slowly sculpted the volcanic rocks to form a unique landscape of deep narrow gorges, caves, colonnades, and monoliths.

Situated along the San Andreas Fault, the geology of PINN has been heavily influenced by transform plate motion and contains rocks that have been transported hundreds of kilometers or miles from where they were formed. The geology of PINN can be subdivided into three main groups of rocks: (1) Cretaceous-age intrusive rocks; (2) volcanic rocks of the Oligocene–Miocene Pinnacles Volcanics; and (3) Neogene and younger rocks of the Monterey Formation, Pancho Rico Formation, and Paso Robles Formation (Figures 23 and 24). Older Cretaceous units are mapped along the western boundary and southeastern portion of PINN and include quartz monzonite of Bickmore Canyon and quartz diorite-granodiorite of Johnson Canyon. The Pinnacles Volcanics consist of rhyolite, dacite, andesite, agglomerate, breccia, and pumice lapilli-tuff that underlie the central core of the park between the Pinnacles Fault to the west and Chalone Creek Fault to the east. The Pinnacles Volcanics are correlative with the Neenach Volcanics, two igneous units that are now separated 315 km (196 mi) along strike of the San Andreas Fault (Turner et al. 1970; Sims 1993). Over the course of geologic time, the San Andreas Fault has split and slowly offset the Neenach Volcanic Field, leaving petrologically similar lithologies on either side of the transform boundary. Rocks of the Miocene Monterey Formation and Pliocene Pancho Rico Formation are located east of the Chalone Creek Fault in northeastern PINN. The youngest bedrock is represented by the Pliocene–Pleistocene Paso Robles Formation along the southwestern margin of the park.

PINN contains one identified stratotype that represents the Oligocene–Miocene Pinnacles Volcanics (Table 4; Figure 25). In addition to the designated stratotype located within PINN, stratotypes located within 48 km (30 mi) of PINN boundaries include the Cretaceous Butts Ranch Shale Member of the Panoche Formation (type locality) and Call Sandstone Member of the Panoche Formation (type locality); Paleocene Cerros Shale Member of the Lodo Formation (type locality); Paleocene–Eocene Lodo Formation (type locality); Eocene Bear Canyon Member of the Kreyenhagen Shale (type locality), Tumey Sandstone Lentil of the Kreyenhagen Shale (type locality), and Capita Shale Member of the Domengine Formation (type locality); Oligocene–Miocene Vaqueros Formation (type section and type locality); and the Miocene Hames Member of the Monterey Shale (two reference localities) and Los Laureles Sandstone Member of the Monterey Shale (type section).

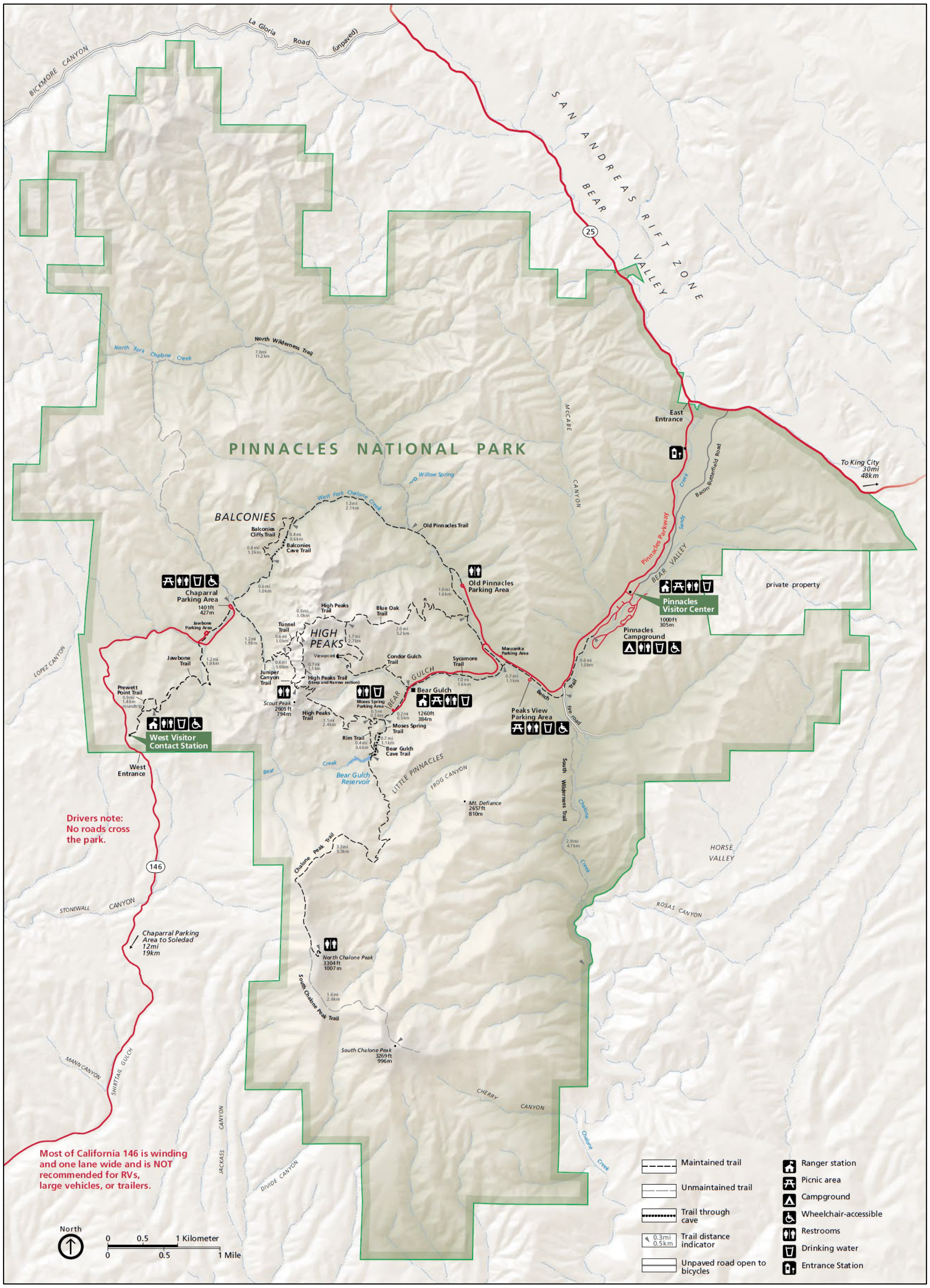


Figure 22. Park map of PINN, California (NPS).

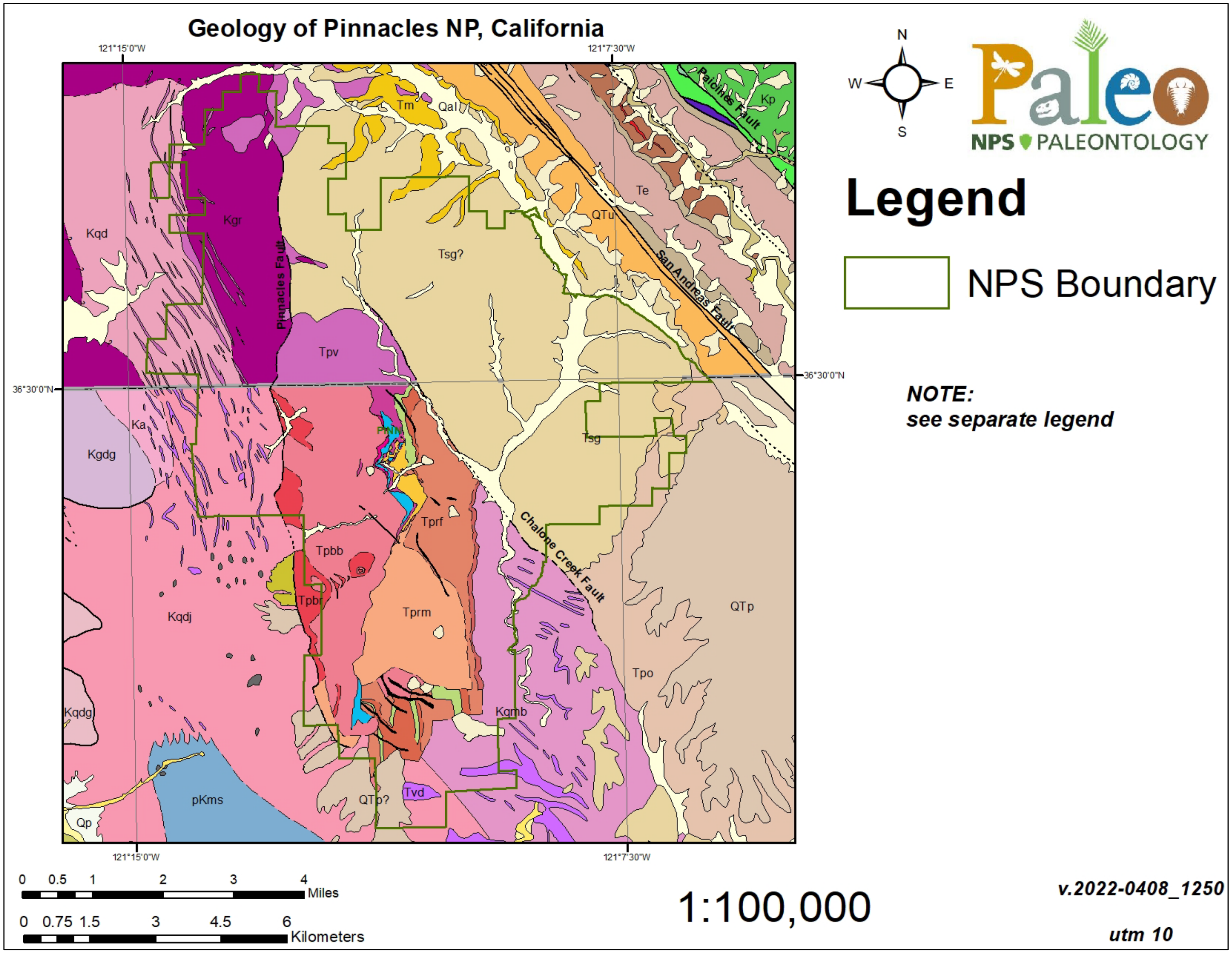


Figure 23. Geologic map of PINN, California; see Figure 24 for legend. Data modified from PINN GRI digital geologic map data at https://irma.nps.gov/DataStore/Reference/Profile/2165382.

Legend

- Qal - Alluvial deposits, undifferentiated
- Qsc - Stream channel deposits
- Qmz - Metz terrace
- Qas - Arroyo Seco fan surfaces and associated deposits
- Qch - Chualar fan surfaces and associated deposits
- Qp - Placentia alluvial fan surfaces and associated deposits
- Qoa - Older alluvium
- Qls - Landslide deposits
- QTp - Paso Robles Formation, undifferentiated
- QTu - Plio-Pleistocene continental deposits, includes Paso Robles Formation
- Tpo - Pancho Rico Formation, mudstone
- Tucm - Unnamed Pliocene continental mudstone
- Tas - Unnamed arkosic sandstone
- Te - Etchegoin Formation
- Tsm - Santa Margarita Sandstone
- Tsg - Unnamed conglomerate and sandstone
- Tm - Monterey Formation
- Tvu - Unnamed Miocene volcanic rocks
- Tpv - Pinnacles Volcanic Formation, undivided
- Tdi - Pinnacles Volcanic Formation, dikes
- Tpbr - Pinnacles Volcanic Formation, Breccia Member, white, aphanitic rhyolite flows
- Tpbb - Pinnacles Volcanic Formation, Breccia Member, breccia and tuff-breccia
- Tpbt - Pinnacles Volcanic Formation, Breccia Member, predominantly tuff
- Tppr - Pinnacles Volcanic Formation, Porphyritic Rhyolite Member
- Tpd - Pinnacles Volcanic Formation, Dacite Member
- Tpa - Pinnacles Volcanic Formation, Andesite Member
- Tpag - Pinnacles Volcanic Formation, Agglomerate Member
- Tppl - Pinnacles Volcanic Formation, Pumice Lapilli-Tuff Member
- Tprm - Pinnacles Volcanic Formation, Rhyolite Member-massive gray to pink aphanitic rhyolite
- Tprf - Pinnacles Volcanic Formation, Rhyolite Member-flow-banded rhyolite
- Tprv - Pinnacles Volcanic Formation, Rhyolite Member-vitric lapilli tuff
- Tprp - Pinnacles Volcanic Formation, Rhyolite Member-perlite
- Tvd - Dacitic felsite
- Kp - Panoche Formation
- Kgr - Granitic rocks
- Ka - Aplite, alaskite, and pegmatite
- Kqmb - Quartz monzonite of Bickmore Canyon
- Kgdg - Granodiorite of Gloria Road
- Kqdj - Quartz diorite-granodiorite of Johnson Canyon
- Kqdg - Gneissic quartz diorite of Stonewall Canyon
- Kqd - Quartz diorite
- KJfm - Franciscan Complex (includes melange)
- KJfum - Franciscan Complex, serpentinized ultramafic rock
- KJu - Jurassic-Cretaceous sedimentary rocks
- pKms - Mica schist
- pKm - Marble

Figure 24. Geologic map legend of PINN, California.

Table 4. List of PINN stratotype units sorted by age with associated reference publications and locations.

Unit Name (GRI map symbol)	Reference	Stratotype Location	Age
Pinnacles Volcanics (Tpv, Tpbr, Tpbb, Tpbt, Tppr, Tpd, Tpa, Tpag, Tppl, Tprm, Tprf, Tprv, Tprp, Tdi)	Matthews 1973a; Sims 1993	**Type section**: exposures along High Peaks Trail west of Chalone Creek Campground in Pinnacles National Monument, from SW/4 SE/4 sec. 35 to SW/4 SE/4 sec. 34, T. 16 S., R. 7 E., North Chalone Peak 7.5′ Quadrangle, San Benito County, CA. The campground no longer exists but was located at latitude 36°29′35″ N., longitude 121°10′27″ W., about 200 m (650 ft) south of the Old Pinnacles Trailhead parking area.	Oligocene–Miocene

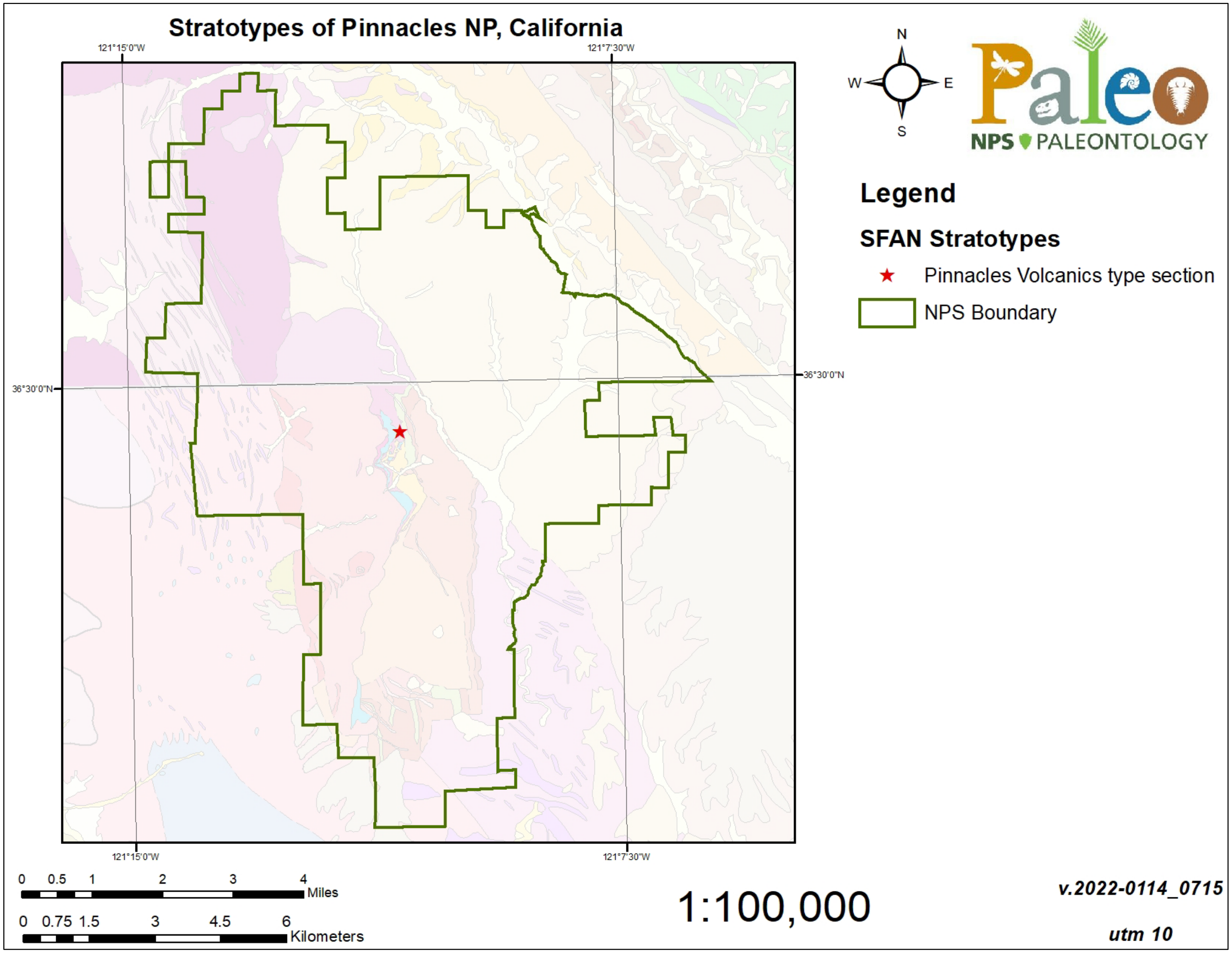


Figure 25. Modified geologic map of PINN showing stratotype locations. The transparency of the geologic units layer has been increased.

Pinnacles Volcanics

The Oligocene–Miocene Pinnacles Volcanics was originally introduced as the "Pinnacles Formation" by Andrews (1936) and named for a sequence of volcanic rocks exposed in Pinnacles National Monument. Matthews (1973a) more fully described the formation, which he called the "Pinnacles Volcanic Formation", and divided the unit into seven informal members with an overall thickness of approximately 2,185 m (7,169 ft). Sims (1993) renamed the unit the Pinnacles Volcanics and accepted the type section Matthews (1973a) designated along the High Peaks Trail west of Chalone Creek Campground in PINN, San Benito County, California (Table 4; Figures 25–28). The campground does not exist today but was located about 200 m (650 ft) south of the Old Pinnacles Trailhead parking area along Chalone Creek. The Pinnacles Volcanics represent a complex assemblage of flow-banded rhyolite, andesite, dacite, and pyroclastic deposits that are petrologically and temporally correlative with the Neenach Volcanics in the northwestern Mojave Desert (Matthews 1973b; Sims 1993). Rocks of the Pinnacles Volcanics rest unconformably on granitic basement and are unconformably overlain by strata assigned to the Santa Margarita Formation (Matthews 1973a; Sims 1993).

Figure 26. Exposures of the Pinnacles Volcanics near the type section along the High Peaks Trail. Photo courtesy of Arman Sabouri (@armansabouriphoto).

Figure 27. Panoramic view from the High Peaks Trail showing volcanic rocks consisting of rhyolite and pyroclastic deposits of the Pinnacles Volcanics (NPS/REUVEN BANK).

Figure 28. Spire-like rock formations of the Pinnacles Volcanics seen along the High Peaks Trail (NPS).

Point Reyes National Seashore (PORE)

Point Reyes National Seashore (PORE) is located on Point Reyes Peninsula near the San Francisco Bay metropolitan area in Marin County, California (Figure 29). Authorized on September 13, 1962, PORE preserves approximately 28,755 hectares (71,055 acres) of geologically unique peninsular terrane that includes beaches, lagoons, coastal cliffs and headlands, marine terraces, coastal uplands, open grasslands, brushy hillsides, forested ridges, and all tidal and submerged lands up to 0.4 km (0.25 mi) offshore (National Park Service 2016, 2020). PORE contains more than 129 km (80 mi) of undeveloped coastline, 237 km (147 mi) of hiking trails, backcountry campgrounds, and many scenic beaches. PORE supports a diverse assemblage of biota, including more than 900 plant species, more than 490 avian species, and at least 28 threatened and endangered species. More than 120 archeological sites in PORE document an extensive 5,000-year human occupation and provide insight into the long history of the Coast Miwok people in the Bay Area. PORE contains about 400 historic structures including the historic Point Reyes Lighthouse built in 1870 and two national historic landmarks: the Point Reyes Lifeboat Station and the Drakes Bay Historic and Archaeological District (National Park Service 2020).

The geology of PORE provides an exceptional opportunity to study plate tectonics, allowing geologists to reconstruct portions of Earth history along strike of the San Andreas Fault. Geologic units in PORE can be broken down into three main groups of rock: (1) Paleozoic and/or Mesozoic metamorphic rocks that occur along Inverness Ridge; (2) Cretaceous-age intrusive rocks; and (3) Cenozoic sedimentary deposits (Figures 30 and 31; Clark and Brabb 1997). Plutonic igneous rocks form the Point Reyes Headlands and portions of Inverness Ridge, and include several informal units including the granodiorite of Inverness Ridge, granodiorite of Point Reyes, and tonalite of Tomales Point. These intrusive rocks originated from a massive batholith in southern California and were subsequently displaced by lateral fault motion to their current location (Port 2018). Cenozoic-age units are widely mapped across PORE and include marine sedimentary rocks of the Eocene Point Reyes Conglomerate; Miocene Laird Sandstone, Monterey Formation, Santa Cruz Mudstone, and Santa Margarita Formation; Miocene–Pliocene Purisima Formation; and Pliocene–Pleistocene Merced Formation. Young surficial deposits mapped within PORE include Quaternary-age landslide deposits, alluvium, marine terrace deposits, dune sand, beach sand, and bay mud. The landscape of PORE contains valleys, ridges, rolling grasslands, sandy beaches, and rocky promontories whose physiography is largely controlled by the underlying Point Reyes syncline.

PORE contains five identified stratotypes that are subdivided into two type sections, one type locality, and two type areas (Table 5; Figure 32). In addition to the designated stratotypes located within PORE, stratotypes located within 48 km (30 mi) of PORE boundaries include the Miocene San Pablo Group (type locality), Cierbo Formation (type section), Sobrante Sandstone (type section), and Bald Peak Basalt (type locality); Miocene–Pliocene Wilson Grove Formation (type locality) and Sonoma Volcanics (type area); Pliocene Huichica Formation (type locality) and Pinole Tuff (type section); Pliocene–Pleistocene Glen Ellen Formation (type locality); and the Pleistocene Colma Formation (type locality and reference locality).

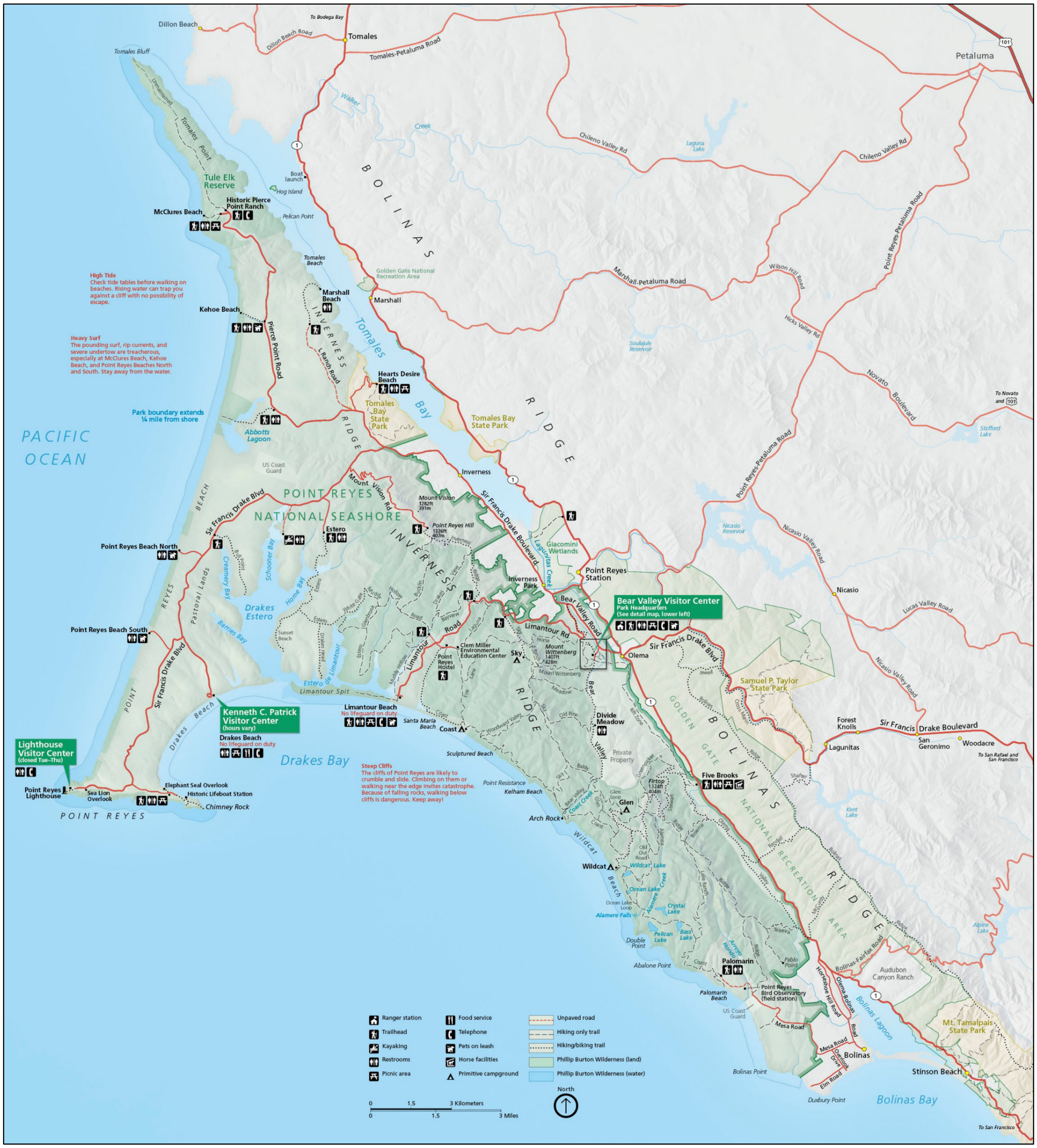


Figure 29. Park map of PORE, California (NPS).

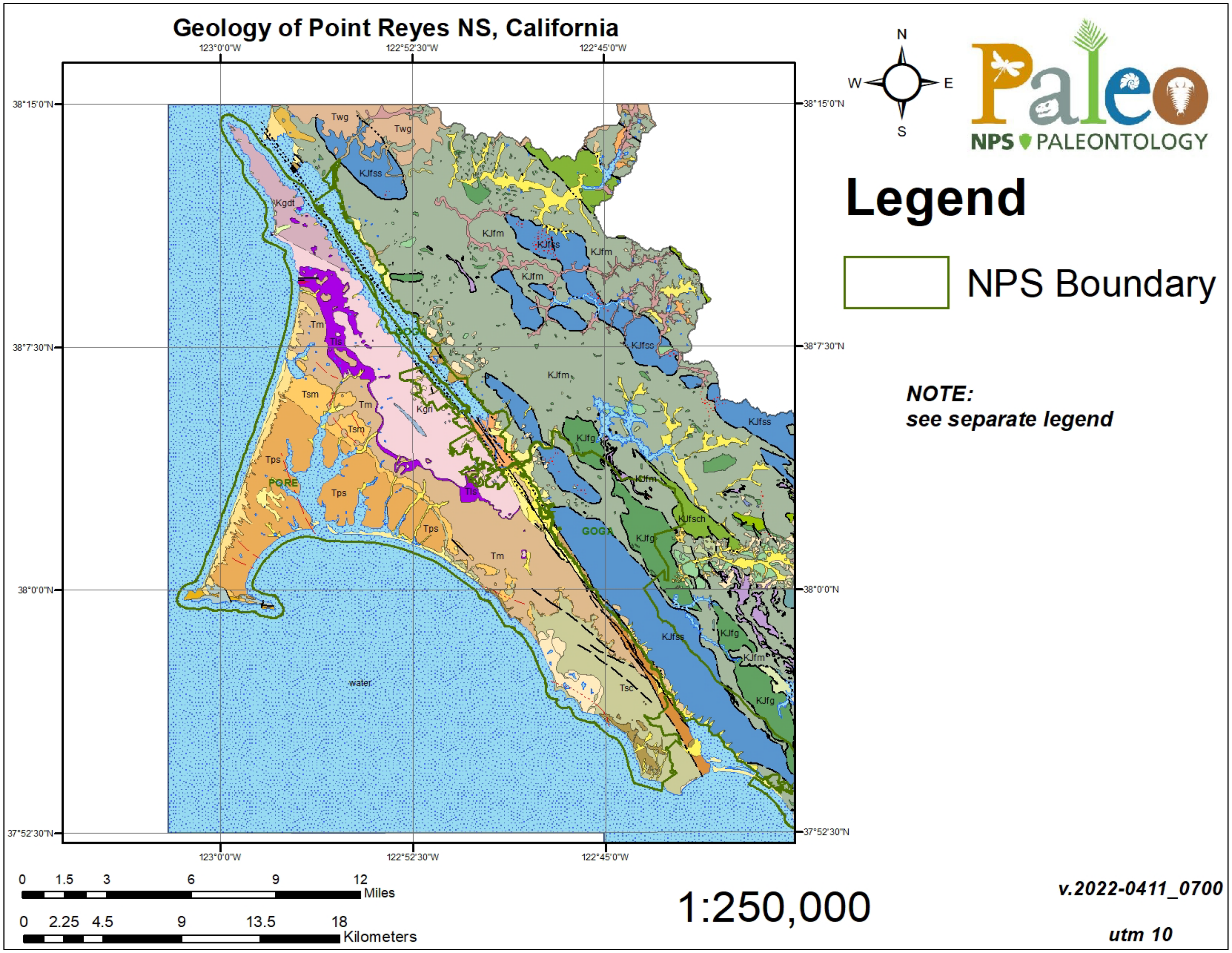


Figure 30. Geologic map of PORE, California; see Figure 31 for legend. Data modified from PINN GRI digital geologic map data at https://irma.nps.gov/DataStore/Reference/Profile/1048293.

Legend

- water
- Qar - Artificial fill (Quaternary)
- Qbs - Beach sand (Quaternary)
- Qsc - Stream channel deposits (Holocene)
- Qdsy - Dune sand, younger (Quaternary)
- Qbmy - Bay mud, younger (Holocene < 10,000 years)
- Qst - Stream terrace deposits (latest Holocene)
- Qafy - Holocene alluvial fan deposits (Holocene)
- Qaly - Alluvium, undivided, younger (Holocene)
- Qalo - Alluvium, undivided, older (Quaternary)
- Qdso - Dune sand, older (latest Pleistocene to Holocene)
- Qbmo - Bay mud, older (Quaternary)
- Qafo - Alluvial fan deposits (latest Pleistocene (<~30,000 years) to Holocene)
- Qls - Landslide deposits (Quaternary)
- Qcl - Colluvium (latest Pleistocene to Holocene)
- Qpf - Pleistocene alluvial fan deposits (Pleistocene)
- Qobs - Older beach sand (late Pleistocene?)
- Qoal - Older alluvium (Quaternary)
- Qtmr - Marine terrace deposits (Quaternary)
- Qmst - Marine and stream terrace deposits (Quaternary)
- Qoc - Olema Creek Formation (late Pleistocene)
- Qml - Millerton Formation (Pleistocene)
- QTm - Merced Formation (Quaternary and late Pliocene)
- Tps - Purisima Formation (Pliocene and Miocene)
- Twg - Wilson Grove Formation (Pliocene and late Miocene)
- Tsc - Santa Cruz Mudstone (upper/late Miocene)
- Tsm - Santa Margarita Sandstone (upper/late Miocene)
- Tm - Monterey Formation (late and middle Miocene)
- Tls - Laird Sandstone (middle Miocene)
- Tpr - Point Reyes Conglomerate of Galloway (1977) (lower Eocene)
- Kg - Porphyritic granodiorite of Point Reyes (Late Cretaceous)
- Kgri - Granodiorite of Inverness Ridge (Late Cretaceous)
- Kgdt - Tonalite of Tomales Point (Late Cretaceous)
- Kfl - Franciscan Complex, limestone and chert (Cretaceous)
- Kfgwy - Franciscan Complex, graywacke, shale and some metagraywacke (Cretaceous)
- KJfg - Franciscan Complex, greenstone (Cretaceous and Jurassic)
- KJfsch - Franciscan Complex, metamorphic rocks (Cretaceous and/or Jurassic)
- KJfss - Franciscan Complex, sandstone and shale (Cretaceous and Jurassic)
- KJfm - Franciscan Complex, melange (Cretaceous and Jurassic)
- KJfbss - Franciscan Complex, sandstone, shale and conglomerate (Cretaceous and Jurassic)
- KJfbsch - Franciscan Complex, schist and semischist (Cretaceous and Jurassic)
- KJfbch - Franciscan Complex, chert and metachert (Cretaceous and Jurassic)
- KJfbmg - Franciscan Complex, metagraywacke and graywacke (Cretaceous and Jurassic)
- KJfmgs - Franciscan Complex, metagreenstone (Cretaceous and Jurassic)
- KJfbsc - Franciscan Complex, silica carbonate rocks (Cretaceous and Jurassic)
- KJfsu - Franciscan Complex, serpentine (Cretaceous and Jurassic)
- KJfgs - Franciscan Complex, greenstone (small discrete masses) (Cretaceous and Jurassic)
- MZPZmx - Metamorphic rocks (Mesozoic and/or Paleozoic)

Figure 31. Geologic map legend of PORE, California.

Table 5. List of PORE stratotype units sorted by age with associated reference publications and locations.

Unit Name (GRI map symbol)	Reference	Stratotype Location	Age
Drakes Bay Formation (unit is now considered obsolete)	Galloway 1977	**Type section**: Drakes Bay sea cliff extending from Drakes Estero [southwest about 6 km] to granitic outcrop at east end of Point Reyes ridge, Marin County, CA. **Type locality**: the syncline lying between the granitic ridges of Inverness Ridge and Point Reyes, CA.	Miocene–Pliocene
Laird Sandstone (Tls)	Weaver 1949; Galloway 1977	**Type area**: exposures west of Laird's Landing on Tomales Bay, Marin County, CA.	Miocene
Point Reyes Conglomerate (Tpr)	Galloway 1977	**Type section**: the westernmost fault block at the Point Reyes lighthouse on west end of Point Reyes Peninsula, Marin County, CA. **Type area**: Point Reyes, CA.	Eocene

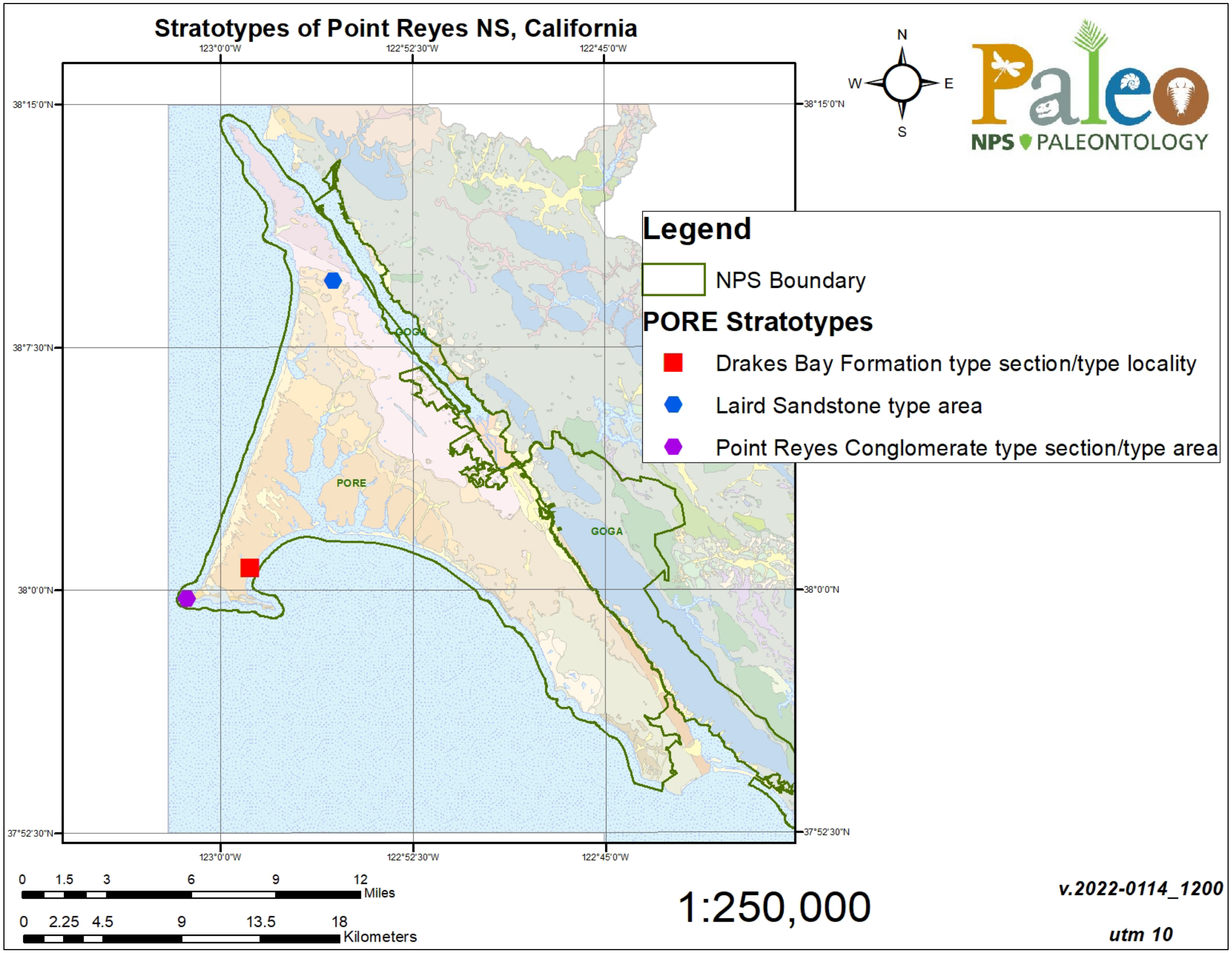


Figure 32. Modified geologic map of PORE showing stratotype locations. The transparency of the geologic units layer has been increased.

Point Reyes Conglomerate

The Eocene Point Reyes Conglomerate was proposed by Galloway (1977) and named after its type area exposures at Point Reyes, California (Table 5; Figures 32 and 33). Galloway (1977) designated the type section of the formation to be the westernmost fault block at the Point Reyes lighthouse on the west end of Point Reyes Peninsula in Marin County, California (Table 5; Figures 32, 34, and 35). Type area exposures measure about 213 m (700 ft) thick and consist of marine conglomerate and sandstone that form craggy or stack-like outcrops that display vertical jointing and crossbedding (Galloway 1977). Conglomerate beds are typically separated by thin shale (mudstone) and silty micaceous sand layers that contain carbonized plant remains and foraminifera (Galloway 1977). The Point Reyes Conglomerate unconformably overlies the granitic basement at Point Reyes and is overlain unconformably by the Drakes Bay Formation.

Figure 33. Jagged cliffs consisting of the Point Reyes Conglomerate at the type area near the west end of Point Reyes Peninsula at the Point Reyes lighthouse (NPS/A. KOPSHEVER).

Figure 34. Type section cliff exposures consisting of marine conglomerate and sandstone of the Point Reyes Conglomerate at the Point Reyes lighthouse (NPS). Note the people for scale.

Figure 35. Type section exposures of the Point Reyes Conglomerate consisting of conglomerate and sandstone near the Point Reyes lighthouse (left photograph). Conglomerate clasts (right photograph) were derived from weathered intrusive rocks as well as now-absent volcanic terrane or older conglomerate (USGS/PHIL STOFFER).

Laird Sandstone

The Miocene Laird Sandstone was introduced by Weaver (1949) who named the formation after Laird's Landing on Point Reyes Peninsula, California. The type area of the Laird Sandstone is assigned to the exposures west of Laird's Landing on Tomales Bay in Marin County, California (Table 5; Figures 32 and 36; Galloway 1977 citing Weaver 1949). Type area exposures are more than 61 m (200 ft) thick and consist of light brown, massive, medium- to coarse-grained sandstone with pebbly or conglomeratic sandstone at its base (Weaver 1949; Galloway 1977). The upper part of the

Laird Sandstone grades upward into the Monterey Shale, with interbeds of shale appearing with increasing frequency higher in the section (Galloway 1977). At the type area the Laird Sandstone unconformably overlies granitic basement and conformably underlies the Monterey Shale.

Figure 36. Type area cliff exposure of the Laird Sandstone (Tls) in fault contact with older granodiorite of Inverness Ridge (Kgri) north of Kehoe Beach. The approximate location of a high-angle fault is represented by the black dashed line with arrows showing relative displacement direction. Folding within the Laird Sandstone is depicted with the red dashed line. The massive beds of Laird Sandstone are offset about 40 m (130 ft) by the fault (© 2002–2015 Kenneth & Gabrielle Adelman, California Coastal Records Project, https://www.californiacoastline.org/).

Drakes Bay Formation

The Miocene–Pliocene Drakes Bay Formation was proposed by Galloway (1977) and named for Drakes Bay, California. Galloway (1977) designated the type locality as the syncline lying between the granitic ridges of Inverness Ridge and Point Reyes, California (Table 5; Figure 32). A more precise type section location is designated in the sea cliffs of Drakes Bay extending from Drakes Estero to granitic outcrops at the east end of Point Reyes ridge in Marin County, California (Table 5; Figure 32; Galloway 1977). At the type locality the Drakes Bay Formation measures several hundred meters or feet thick and is subdivided into the following lithologies: 1) a basal green to grayish-green, glauconitic-bearing sandstone about 30 m (100 ft) thick; 2) thin-bedded chocolate brown shale 15–30 m (50–100 ft) thick; and 3) an upper main body consisting of fine-grained, brown- to cream siltstones interbedded with massive, gray- to yellowish silty mudstones (Galloway 1977). The Drakes Bay Formation unconformably overlies granitic basement rocks, Point Reyes Conglomerate, or Monterey Shale, and unconformably underlies Quaternary-age sediments (Galloway 1977). Although Clark et al. (1984) replaced the Drakes Bay Formation with the Santa Margarita Sandstone, Santa Cruz Mudstone, and Purisima Formation, the unit is included here as a historical stratotype reference.

Recommendations

See also protocols in Brocx et al. (2019), from which several of these recommendations were adapted:

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). *Stratotypes represent unique geologic exposures and should be considered extremely important to protect for the advancement of the scientific community for future generations.*
2. Once the SFAN Geologic Type Section Inventory report is finalized, the NPS Geologic Resources Division should schedule a briefing for the staff of the SFAN and respective network parks.
3. The NPS Geologic Resources Division should work with park and network staff to ensure they are aware of the location of stratotypes in park areas. This information would be important to ensure that proposed park activities or development would not adversely impact the stability and condition of these geologic exposures. Preservation of stratotypes should not limit availability for future scientific research, but help safeguard these exposures from infrastructure development.
4. The NPS Geologic Resources Division should work with park and network staff, the U.S. Geological Survey, state geological surveys, academic geologists, and other partners to formally assess potential new stratotypes as to their significance (international, national, or statewide), based on lithology, stratigraphy, fossils or notable features using procedural code outlined by the North American Commission on Stratigraphic Nomenclature (after Brocx et al. 2019).
5. From the assessment in (4), 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 (after Brocx et al. 2019).
6. The NPS Geologic Resources Division should work with park and network staff to compile and update a central inventory of all designated stratotypes and potential future nominations (after Brocx et al. 2019).
7. The NPS Geologic Resources Division should ensure the park-specific Geologic Type Section Inventory Reports are widely distributed and available online.
8. The NPS Geologic Resources Division should work with park and network staff to regularly monitor geologic type sections to identify any threats or impacts to these geologic heritage features in parks.
9. The NPS Geologic Resources Division should work with park and network staff to obtain good photographs of each geologic type section within the parks. In some cases, where there may be active geologic processes (rock falls, landslides, coastal erosion, etc.), the use of

photogrammetry may be considered for monitoring of geologic type sections. GPS locations should also be recorded and kept in a database when the photographs are taken.

10. The NPS Geologic Resources Division should work with park and network staff to consider the collection and curation of geologic samples from type sections within NPS areas. Samples collected from type section exposures can be useful as reference specimens to support future studies, especially where stratotypes may be lost through natural processes or human activities.
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 (after Brocx et al. 2019).
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) (after Brocx et al. 2019).

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Appendix A: Source Information for GRI Maps of SFAN Parks

FOPO–GOGA–MUWO–PORE

- GMAP 2522: Schlocker, J., M. G. Bonilla, and D. H. Radbruch. 1958. Geology of the San Francisco North Quadrangle, California. U.S. Geological Survey, Washington, D.C. Miscellaneous Geologic Investigations Map 272. Scale 1:24,000. Available at: http://ngmdb.usgs.gov/Prodesc/proddesc_466.htm (accessed April 12, 2022).
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JOMU

- GMAP 46591: Haydon, W. D. 1995. Landslide hazards in the Martinez-Orinda-Walnut Creek area, Contra Costa County, California. Relative Landslide Susceptibility Map. Division of Mines and Geology, California Department of Conservation, Sacramento, California. Landslide Hazard Identification Map 32, Open-File Report 95-12, plate 32A. Scale 1:24,000.

- GMAP 46592: Haydon, W. D. 1995. Landslide hazards in the Martinez-Orinda-Walnut Creek area, Contra Costa County, California. Landslide and Related Slope-Failure Features Map. Division of Mines and Geology, California Department of Conservation, Sacramento, California. Landslide Hazard Identification Map 32, Open-File Report 95-12, plate 32B. Scale 1:24,000.
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Appendix B: Geologic Time Scale

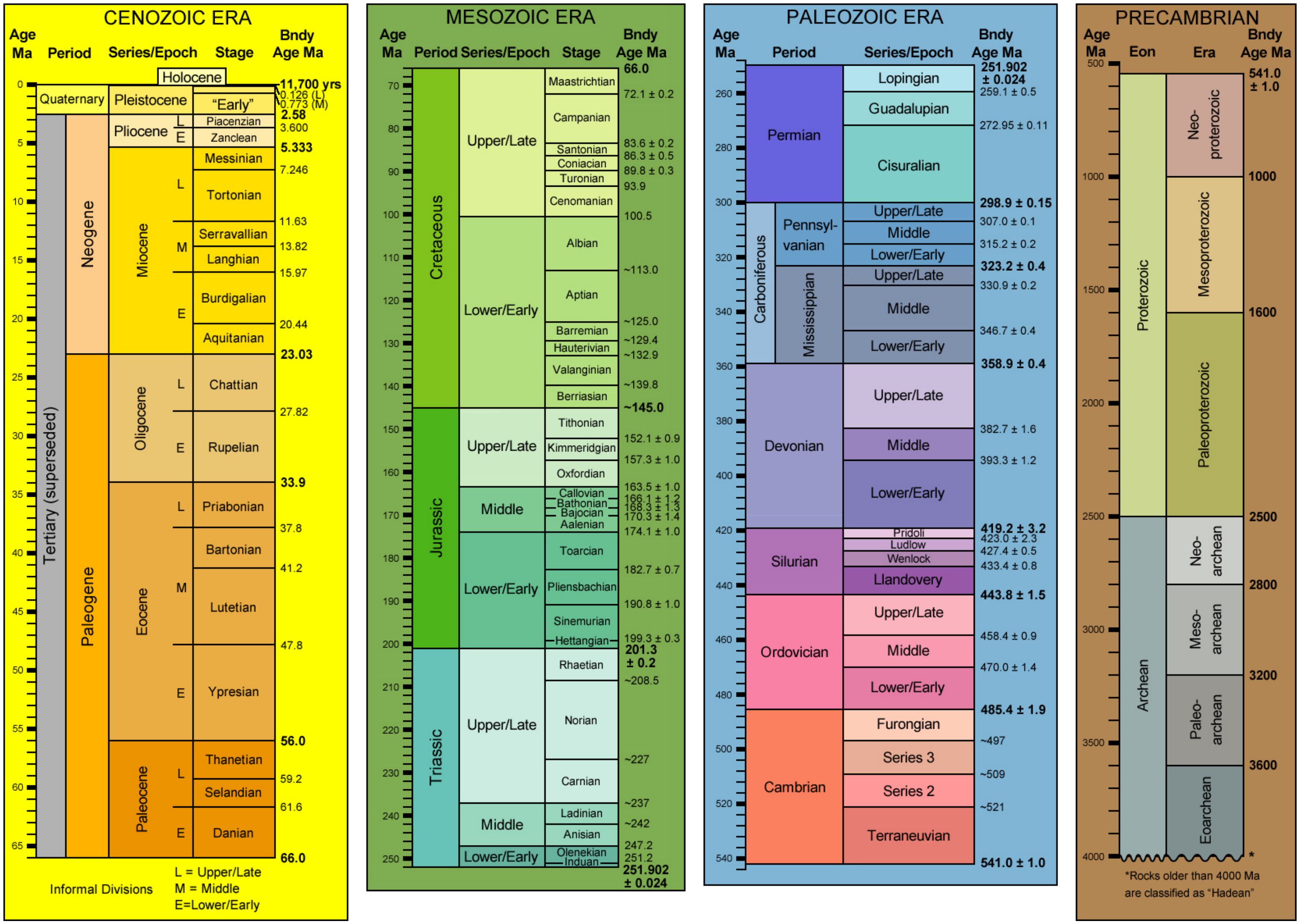

Figure B1. Geologic Time Scale. **Ma**=Millions of years old. **Bndy Age**=Boundary Age. Layout after 1999 Geological Society of America Time Scale (https://www.geosociety.org/documents/gsa/timescale/timescl-1999.pdf). Dates after Gradstein et al. (2020).

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