National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

National Park Service Geologic Type Section Inventory

Klamath Inventory & Monitoring Network

Natural Resource Report NPS/KLMN/NRR—2021/2286

ON THE COVER
Type locality cliff exposures of the Holocene Wineglass Welded Tuff at Skell Head, Crater Lake National Park. Photo by Charles Bacon (USGS).

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July 2021

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

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

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

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

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

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Please cite this publication as:

Henderson, T., V. L. Santucci, T. Connors, and J. S. Tweet. 2021. National Park Service geologic type section inventory: Klamath Inventory & Monitoring Network. Natural Resource Report NPS/KLMN/NRR—2021/2286. National Park Service, Fort Collins, Colorado. https://doi.org/10.36967/nrr- 2286915.

NPS 925/176899, July 2021

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Executive Summary

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

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

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

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

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

The goal of this project is to consolidate information pertaining to geologic type sections which occur within NPS-administered areas, in order that this information is available throughout the NPS to inform park managers and to promote the preservation and protection of these important geologic landmarks and geologic heritage resources. The review of stratotype occurrences for the KLMN shows there are currently no designated stratotypes for Lassen Volcanic National Park, Lava Beds National Monument, Oregon Caves National Monument, or Whiskeytown National Recreation Area; Crater Lake National Park has two type sections; and Redwood National and State Parks has one type locality.

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

Acknowledgments

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

We 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 Michael Clynne and Charles Bacon (USGS) for their review of this report and for their professional input related to the stratigraphy of LAVO and CRLA. 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 Klamath Inventory and Monitoring Network and various network parks, including Alice Chung-MacCoubrey (KLMN), Vicki Ozaki (REDW), Eric Dinger, Sean Smith, Sonya Daw, Allison Snyder, and Marsha Davis. Additional thanks to Denise Louie and Marsha Davis for continued support for this and other important geology projects in the Pacific-West Region of the NPS.

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

Dedication

The Klamath Inventory and Monitoring Network Geologic Type Section Inventory is dedicated to Katie KellerLynn (Colorado State University) and Greg Mack (retired NPS Pacific West Region). Katie and Greg have supported the development of geologic maps and geologic resource inventory reports for NPS areas, including parks within the Klamath Inventory & Monitoring Network. Katie began working on NPS Geologic Resource Inventory reports in 2002 and has authored many of these valuable reports during her career. Greg worked on GIS projects and geologic mapping between 2004 and 2014. We are pleased to recognize Katie and Greg for their important work helping us all better understand and appreciate the geology of the National Parks.

Left: Katie KellerLynn at Crater Lake National Park; Right: Greg Mack at work in his office.

Introduction

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

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

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

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

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

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

Geology and Stratigraphy of the KLMN I&M Network Parks

The Klamath Inventory & Monitoring Network (KLMN) consists of six national park units in northern California and southwestern Oregon (Figure 1). The parks include Crater Lake National Park (CRLA), Lassen Volcanic National Park (LAVO), Lava Beds National Monument (LABE), Oregon Caves National Monument (ORCA), Redwood National and State Parks (REDW) and Whiskeytown National Recreation Area (WHIS). Elevations within the network range from sea level at REDW to 3,187 m (10,456 ft) above sea level at LAVO. The following paragraphs are summarized from Santucci and Kenworthy (2009).

Figure 1. Map of Klamath I&M Network parks including: Crater Lake National Park (CRLA), Lassen Volcanic National Park (LAVO), Lava Beds National Monument (LABE), Oregon Caves National Monument and Preserve (ORCA), Redwood National and State Parks (REDW), and Whiskeytown National Recreation Area (WHIS) (NPS).

Sarr et al. (2007) divided the Klamath region into two subregions with fundamentally different geological character. An approximate boundary from Redding to Yreka, California and from Ashland to Roseburg, Oregon can be used to separate the complex and varied Klamath–Coastal subregion from the volcanic Cascades–Modoc subregion.

The Klamath–Coastal subregion, including REDW, ORCA, and WHIS, is notable for its rugged, non-volcanic topography and complex geology. The Klamath Mountains are a classic example of a mountain belt formed from repeated accretion and compression of island arc terranes, oceanic crust, and upper mantle material. This accretion occurred during the last 150 million years along an active continental margin on the westward edge of North America (Norris and Webb 1990). The Klamath Mountains province has been divided into four arc-shaped belts of rock of varying age that include (from east to west) the Eastern Klamath, central metamorphic, western Paleozoic and Triassic, and western Jurassic belts (Snoke and Barnes 2006). The Middle Jurassic (about 160 million years ago) was characterized by many igneous intrusions and metamorphism (see Appendix B for a geologic time scale).

The Cascades–Modoc subregion formed during relatively recent volcanism. The Cascades Range is a classic example of subduction zone volcanism where oceanic crust is forced beneath less dense continental crust. As the oceanic crust descends into the mantle, it is heated by surrounding rocks which force water-bearing minerals to break down. This water lowers the melting temperature of the surrounding rocks so that they partially melt. This buoyant molten material rises toward the surface, fueling volcanoes. The volcanic features of the Cascades within the KLMN include Crater Lake (CRLA) and the numerous volcanoes that form the Lassen volcanic center (LAVO). Crater Lake, a spectacular 8 x 10 km (5 x 6 mi) caldera, formed in a major eruption about 7,700 years ago from the collapse of a complex of overlapping shield and stratovolcanoes known as Mount Mazama. Lassen Peak represents the southernmost extent of the Cascades Range. A 1914–1917 explosive eruption there inspired its designation as a national park.

East of the Cascades, volcanism formed the Modoc Plateau, which is comprised of Miocene volcanic arc rocks (6–12 million years old) that formed when the axis of the Cascade arc was farther east. These Miocene volcanic units have been progressively buried by basalt lava flows related to volcanism in the Basin and Range Province (M. Clynne, U.S. Geological Survey, pers. comm., 2021). LABE, in the northern flank of Medicine Lake shield volcano, contains hundreds of lava-tube caves displaying a variety of spectacular lava-flow features (Waters et al. 1990; Venzke et al. 2002). Volcanic rocks from the Cascades represent the full compositional spectrum from basalt (~47% silica) to andesite to dacite to rhyolite (~77% silica) (Norris and Webb 1990). Some of the largest rhyolitic lava flows in the Cascades are just outside LAVO and at Medicine Lake. The eastern edge of the Cascades is bordered by the Modoc Plateau basalt flows. Continued volcanism in the eastern Cascades created geomorphic and geothermal features, including cinder cones, small shield volcanoes, lava tubes, and hot springs.

Precambrian

Precambrian rocks are not mapped within the parks of the KLMN.

Paleozoic

The only park within the KLMN that has Paleozoic strata is WHIS. Lower–Middle Devonian through Mississippian rocks within WHIS include metavolcanic rocks of the Copley Greenstone, extrusive igneous rocks of the Balaklala Rhyolite, the Mule Mountain Stock, and the Bragdon Formation of sedimentary origin.

Mesozoic

The oldest Mesozoic rocks in the KLMN occur at ORCA and are represented by the Triassic Rattlesnake Creek Terrane marble and other metamorphic rocks. The Grayback Pluton, an Upper Jurassic pluton, is also mapped at ORCA. The Middle Jurassic–Upper Cretaceous Franciscan Complex is mapped at REDW. Additionally, the Upper Jurassic–Lower Cretaceous Shasta Bally Batholith occurs at WHIS.

Cenozoic

Upper Miocene–lower Pliocene sedimentary units are represented by the Wimer Formation, St. George Formation, and Prairie Creek Formation at REDW. Upper Pliocene–Holocene volcanic flows are mapped at LAVO and are in association with alluvial, colluvial, glacial, and lacustrine deposits in the park.

Pleistocene units are widespread in the parks of the KLMN. At CRLA, sequences of extrusive volcanic rocks, including those associated with the eruption of Mount Mazama, are associated with Pleistocene–Holocene glacial and lacustrine deposits. Extensive volcanic flows of the Medicine Lake Volcanics at LABE are associated with some glacial and lacustrine units. The Battery and Falor Formations are Pleistocene units mapped at REDW.

National Park Service Geologic Resource Inventory

The Geologic Resources Inventory (GRI) provides digital geologic map data and pertinent geologic information on park-specific features, issues, and processes to support resource management and science-informed decision-making in more than 270 natural resource parks throughout the National Park System. The GRI is one of 12 inventories funded by the National Park Service (NPS) Inventory and Monitoring Program. The Geologic Resources Division (GRD) of the NPS Natural Resource Stewardship and Science Directorate administers the GRI. The GRI team consists of a partnership between the GRD and the Colorado State University Department of Geosciences to produce GRI products.

GRI Products

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

Scoping meetings bring together park staff and geologic experts to review and assess available geologic maps, develop a geologic mapping plan, and discuss geologic features, processes, and resource management issues that should be addressed in the GRI report. Scoping sessions were held on the following dates for the KLMN parks: LAVO on March 1, 2004; WHIS on March 2, 2004; REDW on March 2–3, 2004; CRLA on March 3, 2004; and LABE and ORCA on March 4, 2004.

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 May 2021, GRI reports have been completed for all of the KLMN parks except REDW. 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 KLMN parks follows the selected source maps and includes components such as: faults, mine area features, mine point features, geologic contacts, geologic units (bedrock, surficial, glacial), geologic line features, structure contours, and so forth. These are commonly acceptable geologic features to include in a geologic map.

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

Geologic Maps

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

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

Source Maps

The GRI team does not conduct original geologic mapping. The team digitizes paper maps and compiles and converts digital data to conform to the GRI GIS data model. The GRI GIS dataset includes essential elements of the source maps such as map unit descriptions, a correlation chart of units, a map legend, map notes, cross sections, figures, and references. These items are typically included in a master geology document (PDF) for a specific park. The GRI team uses a unique "GMAP ID" value for each geologic source map, and all sources used to produce the GRI GIS datasets for the KLMN 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 WHIS was compiled using data model version 2.3, which is available at http://www.nps.gov/articles/gri-geodatabase-model.htm; data for CRLA, LABE, LAVO, ORCA and REDW are based on older data model version 2.1. This data model dictates GIS data structure, including layer architecture, feature attribution, and relationships within ESRI ArcGIS software. The GRI website (https://www.nps.gov/subjects/geology/gri.htm) provides more information about the program's products.

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

The following components are part of the data set:

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

GRI Map Posters

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

Use Constraints

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

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

Methods

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

There are a number of considerations to be addressed throughout this inventory. The most up-to-date information available is necessary, either found online or in published articles and maps. Occasionally, there is a lack of specific information that limits the information contained in the final report. This inventory does not include any field work and is dependent on the existing information related to individual park geology and stratigraphy. Additionally, this inventory does not attempt to resolve any unresolved or controversial stratigraphic interpretations, which is beyond the scope of the project.

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

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

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

Methodology

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

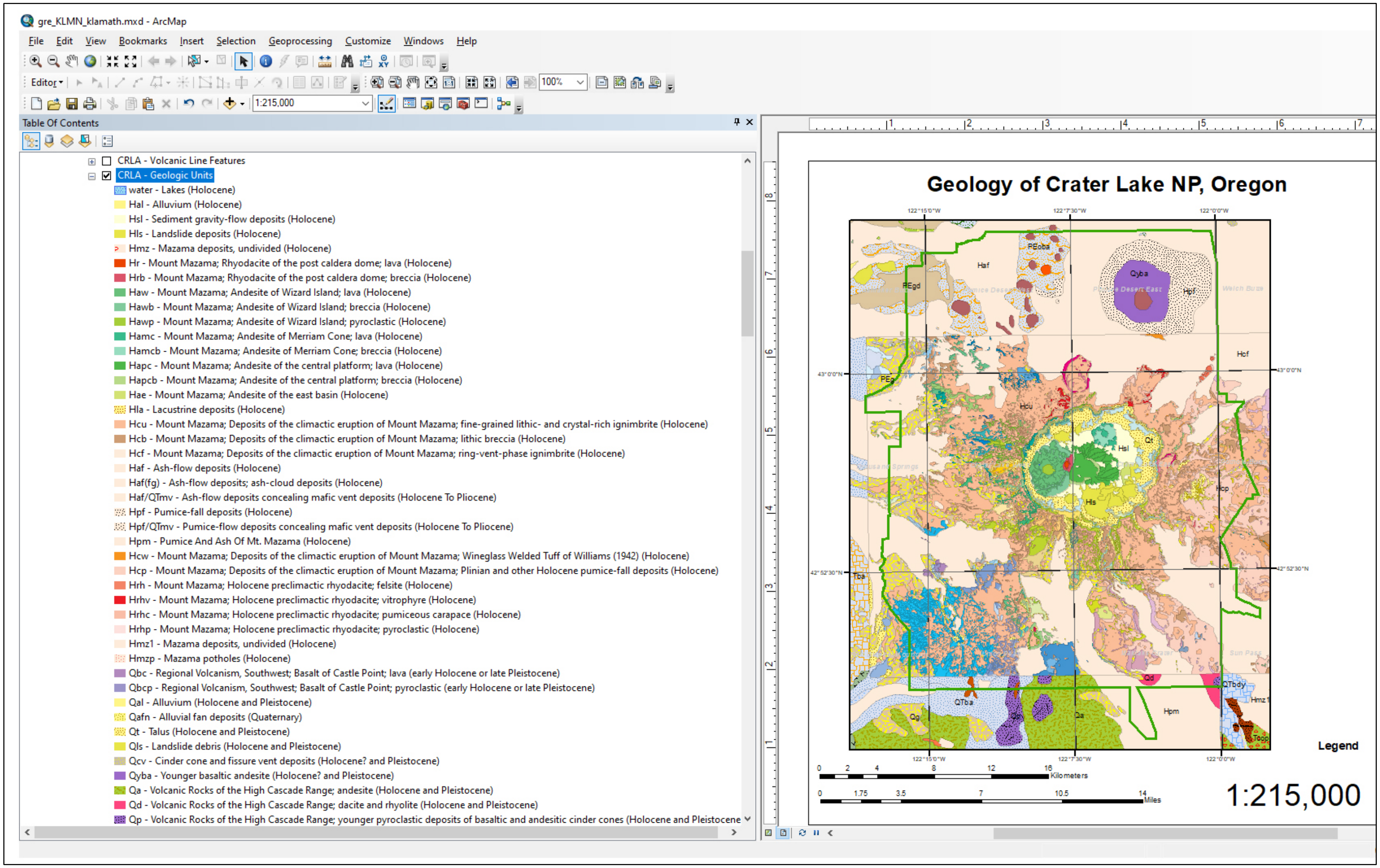


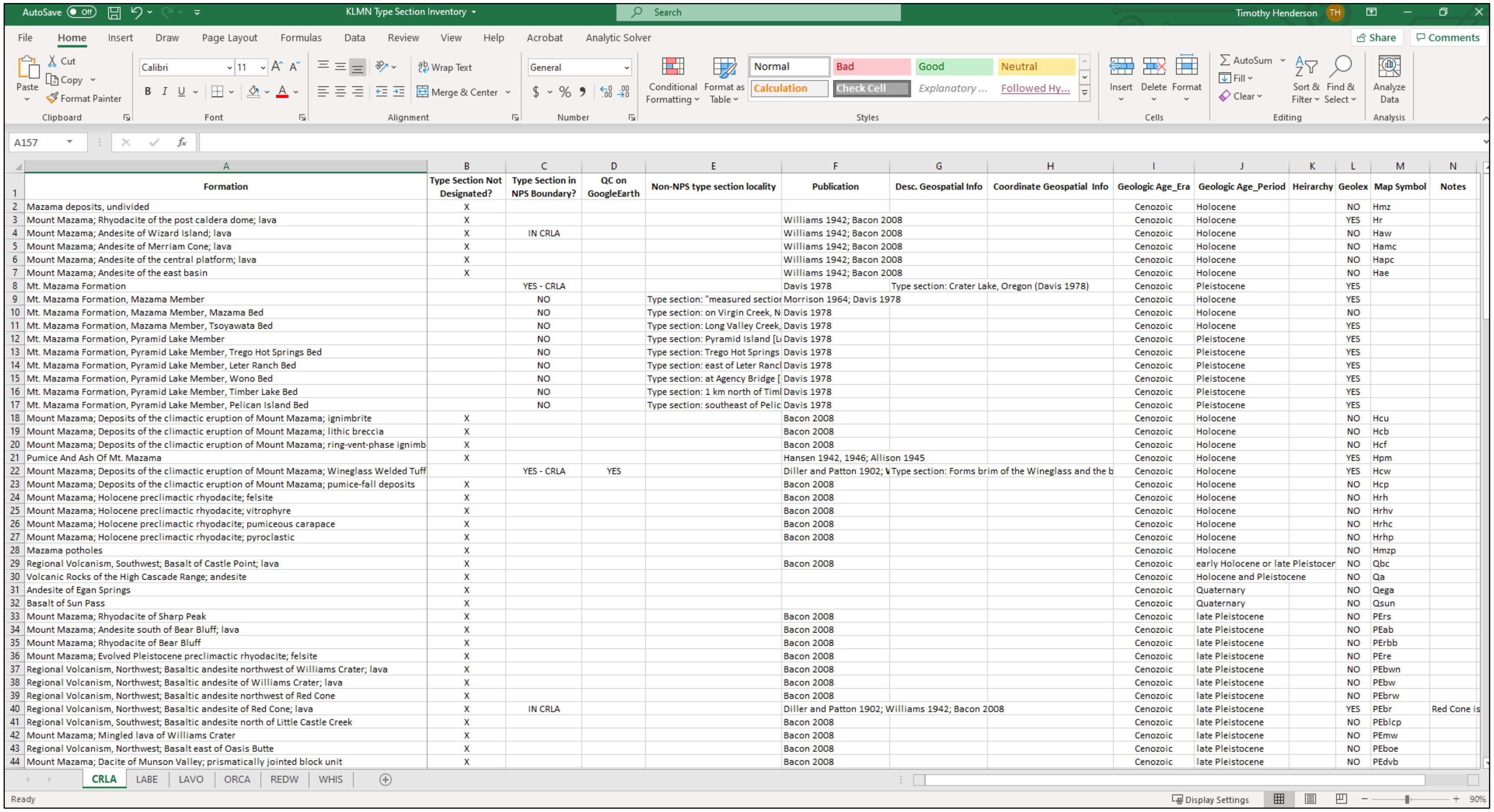
Figure 2. Screenshot of digital geologic map of Crater Lake National Park showing mapped units.

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

Figure 3. GEOLEX search result for Prairie Creek Formation 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 on subdivisions of a single 93.2 km^2 (36 mi^2) township into 36 individual 2.59 km^2 (1 mi^2) sections, and were converted into Google Earth (.kmz file) locations using Earth Point (https://www.earthpoint.us/TownshipsSearchByDescription.aspx). The most accurate GEOLEX descriptions using TRS coordinates can help locate features within 0.1618 km^2 (0.0625 mi^2). Once stratotype locality information provided for a given unit is geolocated using Google Earth, a GRI digital geologic map of the national park is draped over it. This step serves two functions: to improve accuracy in locating the stratotype, and validating the geologic polygon for agreement with GEOLEX nomenclature. Geolocations in Google Earth are then converted into an ArcGIS format using a "KML to Layer" conversion tool in ArcMap.

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



	Formation	Type Section Not Designated?	Type Section in NPS Boundary?	QC on GoogleEarth	Non-NPS type section locality	Publication	Desc. Geospatial Info	Coordinate Geospatial Info	Geologic Age_Era	Geologic Age_Period	Heirarchy	Geolex	Map Symbol	Notes
2	Mazama deposits, undivided	X							Cenozoic	Holocene		NO	Hmz	
3	Mount Mazama; Rhyodacite of the post caldera dome; lava	X				Williams 1942; Bacon 2008			Cenozoic	Holocene		YES	Hr	
4	Mount Mazama; Andesite of Wizard Island; lava	X	IN CRLA			Williams 1942; Bacon 2008			Cenozoic	Holocene		NO	Haw	
5	Mount Mazama; Andesite of Merriam Cone; lava	X				Williams 1942; Bacon 2008			Cenozoic	Holocene		NO	Hamc	
6	Mount Mazama; Andesite of the central platform; lava	X				Williams 1942; Bacon 2008			Cenozoic	Holocene		NO	Hapc	
7	Mount Mazama; Andesite of the east basin	X				Williams 1942; Bacon 2008			Cenozoic	Holocene		NO	Hae	
8	Mt. Mazama Formation		YES - CRLA			Davis 1978	Type section: Crater Lake, Oregon (Davis 1978)		Cenozoic	Pleistocene		YES		
9	Mt. Mazama Formation, Mazama Member		NO		Type section: "measured sectior	Morrison 1964; Davis 1978			Cenozoic	Holocene		YES		
10	Mt. Mazama Formation, Mazama Member, Mazama Bed		NO		Type section: on Virgin Creek, N	Davis 1978			Cenozoic	Holocene		NO		
11	Mt. Mazama Formation, Mazama Member, Tsoyawata Bed		NO		Type section: Long Valley Creek,	Davis 1978			Cenozoic	Holocene		YES		
12	Mt. Mazama Formation, Pyramid Lake Member		NO		Type section: Pyramid Island [L	Davis 1978			Cenozoic	Pleistocene		YES		
13	Mt. Mazama Formation, Pyramid Lake Member, Trego Hot Springs Bed		NO		Type section: Trego Hot Springs	Davis 1978			Cenozoic	Pleistocene		YES		
14	Mt. Mazama Formation, Pyramid Lake Member, Leter Ranch Bed		NO		Type section: east of Leter Rancl	Davis 1978			Cenozoic	Pleistocene		YES		
15	Mt. Mazama Formation, Pyramid Lake Member, Wono Bed		NO		Type section: at Agency Bridge [	Davis 1978			Cenozoic	Pleistocene		YES		
16	Mt. Mazama Formation, Pyramid Lake Member, Timber Lake Bed		NO		Type section: 1 km north of Timl	Davis 1978			Cenozoic	Pleistocene		YES		
17	Mt. Mazama Formation, Pyramid Lake Member, Pelican Island Bed		NO		Type section: southeast of Pelic	Davis 1978			Cenozoic	Pleistocene		YES		
18	Mount Mazama; Deposits of the climactic eruption of Mount Mazama; ignimbrite	X				Bacon 2008			Cenozoic	Holocene		NO	Hcu	
19	Mount Mazama; Deposits of the climactic eruption of Mount Mazama; lithic breccia	X				Bacon 2008			Cenozoic	Holocene		NO	Hcb	
20	Mount Mazama; Deposits of the climactic eruption of Mount Mazama; ring-vent-phase ignimb	X				Bacon 2008			Cenozoic	Holocene		NO	Hcf	
21	Pumice And Ash Of Mt. Mazama	X				Hansen 1942, 1946; Allison 1945			Cenozoic	Holocene		YES	Hpm	
22	Mount Mazama; Deposits of the climactic eruption of Mount Mazama; Wineglass Welded Tuff		YES - CRLA	YES		Diller and Patton 1902;	Type section: Forms brim of the Wineglass and the b		Cenozoic	Holocene		YES	Hcw	
23	Mount Mazama; Deposits of the climactic eruption of Mount Mazama; pumice-fall deposits	X				Bacon 2008			Cenozoic	Holocene		NO	Hcp	
24	Mount Mazama; Holocene preclimactic rhyodacite; felsite	X				Bacon 2008			Cenozoic	Holocene		NO	Hrh	
25	Mount Mazama; Holocene preclimactic rhyodacite; vitrophyre	X				Bacon 2008			Cenozoic	Holocene		NO	Hrhv	
26	Mount Mazama; Holocene preclimactic rhyodacite; pumiceous carapace	X				Bacon 2008			Cenozoic	Holocene		NO	Hrhc	
27	Mount Mazama; Holocene preclimactic rhyodacite; pyroclastic	X				Bacon 2008			Cenozoic	Holocene		NO	Hrhp	
28	Mazama potholes	X							Cenozoic	Holocene		NO	Hmzp	
29	Regional Volcanism, Southwest; Basalt of Castle Point; lava	X				Bacon 2008			Cenozoic	early Holocene or late Pleistocer		NO	Qbc	
30	Volcanic Rocks of the High Cascade Range; andesite	X							Cenozoic	Holocene and Pleistocene		NO	Qa	
31	Andesite of Egan Springs	X							Cenozoic	Quaternary		NO	Qega	
32	Basalt of Sun Pass	X							Cenozoic	Quaternary		NO	Qsun	
33	Mount Mazama; Rhyodacite of Sharp Peak	X				Bacon 2008			Cenozoic	late Pleistocene		NO	PErs	
34	Mount Mazama; Andesite south of Bear Bluff; lava	X				Bacon 2008			Cenozoic	late Pleistocene		NO	PEab	
35	Mount Mazama; Rhyodacite of Bear Bluff	X				Bacon 2008			Cenozoic	late Pleistocene		NO	PErbb	
36	Mount Mazama; Evolved Pleistocene preclimactic rhyodacite; felsite	X				Bacon 2008			Cenozoic	late Pleistocene		NO	PEre	
37	Regional Volcanism, Northwest; Basaltic andesite northwest of Williams Crater; lava	X				Bacon 2008			Cenozoic	late Pleistocene		NO	PEbwn	
38	Regional Volcanism, Northwest; Basaltic andesite of Williams Crater; lava	X				Bacon 2008			Cenozoic	late Pleistocene		NO	PEbw	
39	Regional Volcanism, Northwest; Basaltic andesite northwest of Red Cone	X				Bacon 2008			Cenozoic	late Pleistocene		NO	PEbrw	
40	Regional Volcanism, Northwest; Basaltic andesite of Red Cone; lava	X	IN CRLA			Diller and Patton 1902; Williams 1942; Bacon 2008			Cenozoic	late Pleistocene		YES	PEbr	Red Cone is
41	Regional Volcanism, Southwest; Basaltic andesite north of Little Castle Creek	X				Bacon 2008			Cenozoic	late Pleistocene		NO	PEblcp	
42	Mount Mazama; Mingled lava of Williams Crater	X				Bacon 2008			Cenozoic	late Pleistocene		NO	PEmw	
43	Regional Volcanism, Northwest; Basalt east of Oasis Butte	X				Bacon 2008			Cenozoic	late Pleistocene		NO	PEboe	
44	Mount Mazama; Dacite of Munson Valley; prismatically jointed block unit	X				Bacon 2008			Cenozoic	late Pleistocene		NO	PEdvb	

Figure 4. Stratotype inventory spreadsheet of the KLMN 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 (original or subsequently designated) for a named geologic unit or boundary and constitutes the basis for definition or recognition of that unit or boundary (North American Commission on Stratigraphic Nomenclature 2005). There are several variations of stratotype referred to in the literature and this report, and they are defined as following:

(1) **Unit stratotype**: the **type section** for a stratified deposit or the **type area** for a non-stratified body that serves as the standard for recognition and definition of a geologic unit (North American Commission on Stratigraphic Nomenclature 2005). Once a unit stratotype is assigned, it is never changed. The term “unit stratotype” is commonly referred to as “type section” and “type area” in this report.

(2) **Type locality**: the specific geographic locality encompassing the unit stratotype of a formally recognized and defined unit. On a broader scale, a type area is the geographic territory encompassing the type locality. Before development of the stratotype concept, only type localities and type areas were designated for many geologic units that are now long- and well-established (North American Commission on Stratigraphic Nomenclature 2005).

(3) **Reference sections**: for well-established geologic units for which a type section was never assigned, a reference section may serve as an invaluable standard in definitions or revisions. A principal reference section may also be designated for units whose stratotypes have been destroyed, covered, or are otherwise inaccessible (North American Commission on Stratigraphic Nomenclature 2005). Multiple reference sections can be designated for a single unit to help illustrate heterogeneity or some critical feature not found in the stratotype. Reference sections can help supplement unit stratotypes in the case where the stratotype proves inadequate (North American Commission on Stratigraphic Nomenclature 2005).

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

Crater Lake National Park (CRLA)

Crater Lake National Park (CRLA) is located in the Cascades Range in Klamath County, southwestern Oregon (Figure 5). Established as an NPS unit on May 22, 1902, CRLA preserves approximately 74,148 hectares (183,224 acres) of pristine forest and alpine terrain (Anderson 2017). The iconic Crater Lake lies within the caldera of Mount Mazama which climactically erupted 7,700 years ago (Bacon 1983). The caldera is an 8 x 10 km (5 x 6 mi) basin more than 1 km (0.6 mi) deep, making Crater Lake the deepest lake in the United States (KellerLynn 2013). Prior to eruption, Mount Mazama consisted of several overlapping volcanic edifices in the immediate vicinity of Crater Lake. Visitors to CRLA can enjoy fishing, bicycling, hiking the over 145 km (90 mi) of trails, or taking in the spectacular views of the clear, blue waters of Crater Lake.

The eruption of Mount Mazama and the formation of the Crater Lake caldera created excellent geologic exposures of volcanic deposits. Many of the distinctive features at CRLA consist of hundreds of Pleistocene volcanic units 420,000 years old and younger (Figures 6, 7a, and 7b). Remnants of Mount Mazama can be found in and surrounding Crater Lake and include: Phantom Ship (420,000–400,000 years old), Sentinel Rock (340,000–300,000 years old), Llao Rock (170,000–120,000 years old), Roundtop (159,000 ± 13,000 years old), Pumice Castle (70,000 years old), The Watchman (55,000 ± 3,000 years old), and Devils Backbone (50,000–40,000 years old) (Bacon 2008; KellerLynn 2013). Since the climactic eruption 7,700 years ago, all post-caldera volcanic activity within CRLA has occurred within the caldera and includes the formation of the Wizard Island volcano. In addition to the park's volcanic history, CRLA is also noted for many glacial features that include U-shaped valleys, cirques (on Mount Scott and Union Peak), and glacial horns (The Watchman and Union Peak).

CRLA contains two identified stratotypes: the type sections of the Holocene Mount Mazama Formation and Wineglass Welded Tuff (Table 1; Figure 8). In addition, numerous geologic units exist within CRLA that are unique to the region but currently lack stratotype designation. These are addressed in the 'Recommendations' section. There are no identified stratotypes located within 48 km (30 mi) of CRLA boundaries.

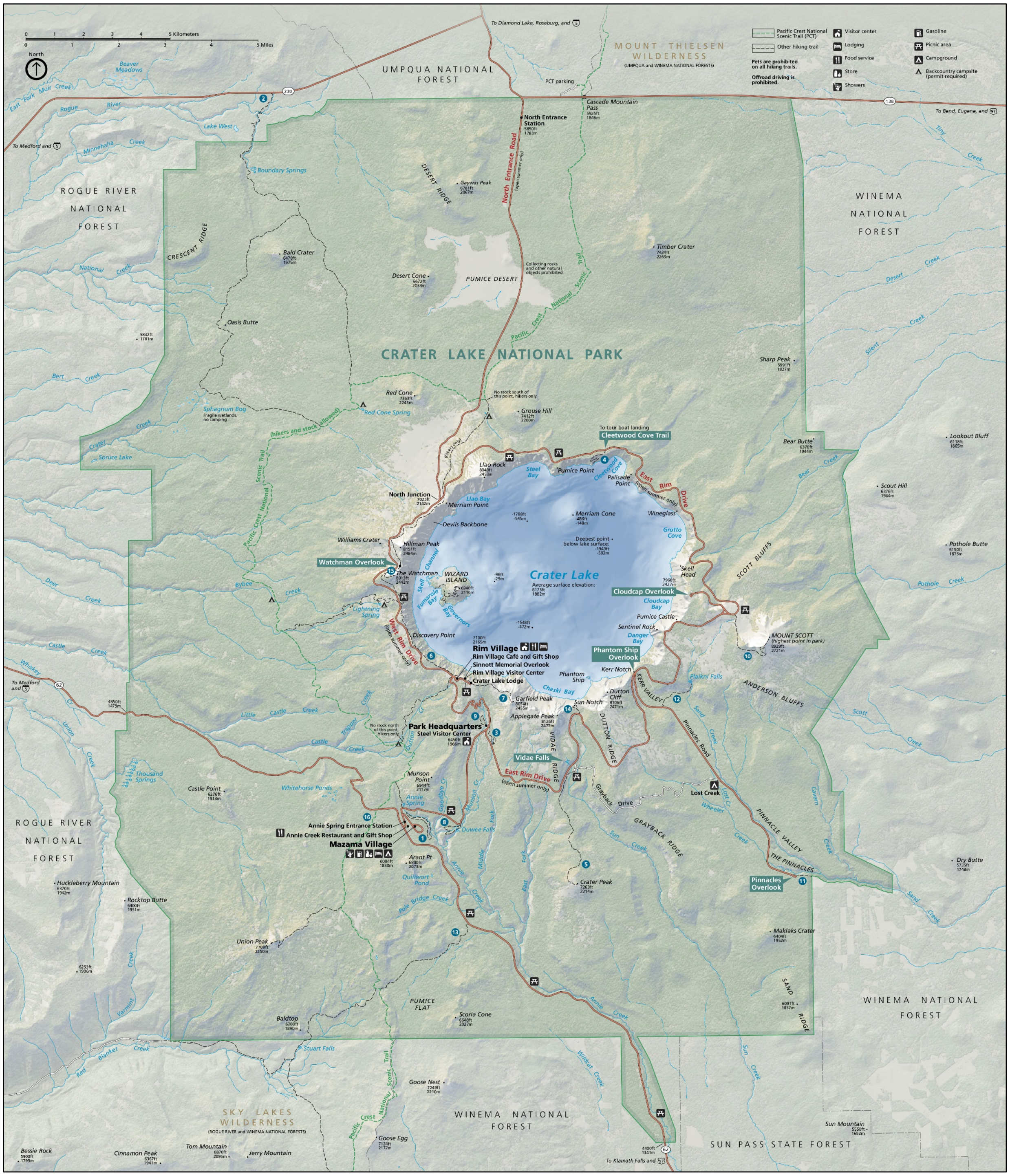


Figure 5. Park map of CRLA, Oregon (NPS).

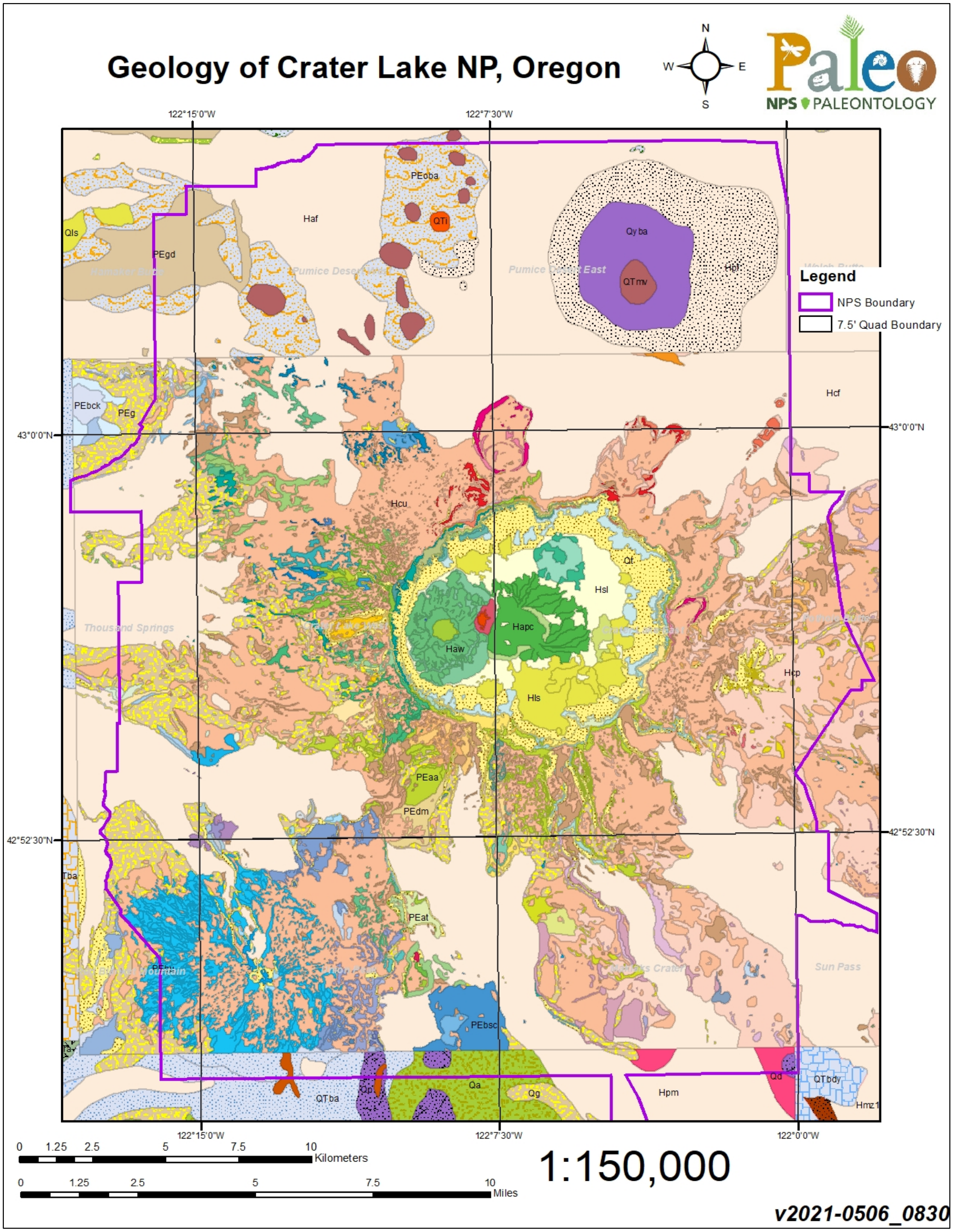


Figure 6. Geologic map of CRLA, Oregon; full legend is included as Figures 7a and 7b.

Figure 7a. Geologic map legend of CRLA, Oregon (for Figure 6) (part 1).

PEs - Sedimentary deposits, undivided (late and middle Pleistocene)
PEasl - Mount Mazama; Andesite east of Spruce Lake (late or middle Pleistocene)
PEdpt - Mount Mazama; Dacite of Palisade Point (late or middle Pleistocene)
PEall - Mount Mazama; Andesite of Llao Bay, lower unit (middle Pleistocene)
PEar - Mount Mazama; Andesite of Roundtop (middle Pleistocene)
PEbu - Regional Volcanism, Southwest; Basaltic andesite of Union Peak; lava (middle Pleistocene)
PEbui - Regional Volcanism, Southwest; Basaltic andesite of Union Peak; intrusive (middle Pleistocene)
PEbup - Regional Volcanism, Southwest; Basaltic andesite of Union Peak; pyroclastic (middle Pleistocene)
PEamv - Mount Mazama; Andesite east of Munson Valley (middle Pleistocene)
PEags - Mount Mazama; Andesite of the gaging station (middle Pleistocene)
PEboi - Regional Volcanism, Northwest; Basaltic andesite of Oasis Butte; intrusive (middle Pleistocene)
PEbo - Regional Volcanism, Northwest; Basaltic andesite of Oasis Butte; lava (middle Pleistocene)
PEbop - Regional Volcanism, Northwest; Basaltic andesite of Oasis Butte; pyroclastic (middle Pleistocene)
PEdcn - Mount Mazama; Dacite north of Castle Creek; lava (middle Pleistocene)
PEdcnp - Mount Mazama; Dacite north of Castle Creek; pyroclastic (middle Pleistocene)
PEbsw - Regional Volcanism, East; Basalt west of Sun Creek (middle Pleistocene)
PEbmc - Regional Volcanism, East; Basaltic andesite of Maklaks Crater; lava (middle Pleistocene)
PEbmcp - Regional Volcanism, East; Basaltic andesite of Maklaks Crater; pyroclastic (middle Pleistocene)
PEag - Mount Mazama; Andesite of Garfield Peak (middle Pleistocene)
PEdg - Mount Mazama; Dacite south of Garfield Peak (middle Pleistocene)
PEaa - Mount Mazama; Andesite of Applegate Peak; lava (middle Pleistocene)
PEaai - Mount Mazama; Andesite of Applegate Peak; intrusive (middle Pleistocene)
PEbn - Regional Volcanism, Northwest; Basaltic andesite north of Red Cone (middle? Pleistocene)
PEawe - Mount Mazama; Andesite east of Wineglass (middle Pleistocene)
PEac - Mount Mazama; Andesite of Cloudcap Bay (middle Pleistocene)
PEdm - Mount Mazama; Dacite of Munson Ridge (middle Pleistocene)
PEaf - Mount Mazama; Andesite west of Fumarole Bay (middle Pleistocene)
PEao - Regional Volcanism, Northwest; Andesite southwest of Oasis Butte (middle Pleistocene)
PEbx - Regional Volcanism, Southwest; Basaltic andesite of Whitehorse Bluff; lava (middle Pleistocene)
PEbxi - Regional Volcanism, Southwest; Basaltic andesite of Whitehorse Bluff; intrusive (middle Pleistocene)
PEbxp - Regional Volcanism, Southwest; Basaltic andesite of Whitehorse Bluff; pyroclastic (middle Pleistocene)
PEat - Regional Volcanism, Southwest; Andesite of Arant Point; lava (middle Pleistocene)
PEatg - Regional Volcanism, Southwest; Andesite of Arant Point; vitric (middle Pleistocene)
PEati - Regional Volcanism, Southwest; Andesite of Arant Point; intrusive (middle Pleistocene)
PEarv - Mount Mazama; Andesite below Rim Village (middle Pleistocene)
PEdr - Mount Mazama; Dacite of Sentinel Rock (middle Pleistocene)
PEbxn - Regional Volcanism, Southwest; Basalt northwest of Whitehorse Bluff; lava (middle? Pleistocene)
PEbxni - Regional Volcanism, Southwest; Basalt northwest of Whitehorse Bluff; intrusive (middle? Pleistocene)
PEbaw - Regional Volcanism, Southwest; Basaltic andesite west of Arant Point (middle Pleistocene)
PEak - Mount Mazama; Andesite of Kerr Notch (middle Pleistocene)
PEdb - Mount Mazama; Dacite of Chaski Bay (middle Pleistocene)
PEams - Mount Mazama; Andesite south of Mount Scott (middle Pleistocene)
PEbsr - Regional Volcanism, East; Basalt of Sand Ridge; lava (middle Pleistocene)
PEbsrp - Regional Volcanism, East; Basalt of Sand Ridge; pyroclastic (middle Pleistocene)
PEdpn - Mount Mazama; Dacite of phantom cone (middle Pleistocene)
PEbow - Regional Volcanism, Northwest; Basaltic andesite west of Oasis Butte (middle? Pleistocene)
PEbbi - Regional Volcanism, Southwest; Basaltic andesite west of Bear Bluff; intrusive (middle? Pleistocene)
PEbbp - Regional Volcanism, Southwest; Basaltic andesite west of Bear Bluff; pyroclastic (middle? Pleistocene)
PEbcw - Regional Volcanism, Southwest; Basaltic andesite west of Mazama Campground (middle? Pleistocene)
PEds - Mount Mazama; Dacite of Mount Scott; lava (middle Pleistocene)
PEdsf - Mount Mazama; Dacite of Mount Scott; mudflow breccia (middle Pleistocene)
PEdsp - Mount Mazama; Dacite of Mount Scott; pyroclastic (middle Pleistocene)
PEdcc - Mount Mazama; Dacite of Cavern Creek (middle? Pleistocene)
PEapn - Mount Mazama; Andesite of phantom cone; lava (middle Pleistocene)
PEapni - Mount Mazama; Andesite of phantom cone; intrusive (middle Pleistocene)
PEbwc - Regional Volcanism, Southwest; Basaltic andesite of Whitehorse Creek; lava (middle? Pleistocene)
PEbwci - Regional Volcanism, Southwest; Basaltic andesite of Whitehorse Creek; intrusive (middle? Pleistocene)
PEbwcp - Regional Volcanism, Southwest; Basaltic andesite of Whitehorse Creek; pyroclastic (middle? Pleistocene)
PErpb - Pre-Mazama Volcanism; Rhyodacite of Pothole Butte; felsite (middle Pleistocene)
PErcs - Pre-Mazama Volcanism; Rhyodacite south of Crater Peak (middle Pleistocene)
PErsc - Pre-Mazama Volcanism; Rhyodacite of Scott Creek (middle Pleistocene)
PEaq - Regional Volcanism, East; Andesite of Sand Creek quarry (middle? Pleistocene)
PEaco - Regional Volcanism, Southwest; Andesite north of Castle Creek; lava (middle Pleistocene)
PEacop - Regional Volcanism, Southwest; Andesite north of Castle Creek; pyroclastic (middle Pleistocene)
PEaaf - Regional Volcanism, East; Andesite northeast of Annie Falls (middle Pleistocene)
PEbep - Regional Volcanism, East; Basaltic andesite east of Cavern Creek (middle? Pleistocene)
PEacs - Regional Volcanism, East; Andesite south of Sand Creek; lava (middle? Pleistocene)
PEacsp - Regional Volcanism, East; Andesite south of Sand Creek; pyroclastic (middle? Pleistocene)
PEas - Regional Volcanism, East; Andesite of Sun Creek (middle Pleistocene)
PEdw - Pre-Mazama Volcanism; Dacite west of The Pinnacles (middle Pleistocene)
PEasw - Regional Volcanism, East; Andesite west of Sand Creek (middle Pleistocene)
PEbaf - Regional Volcanism, East; Basaltic andesite east of Annie Falls (middle Pleistocene)
PErcc - Pre-Mazama Volcanism; Rhyodacite west of Cavern Creek (middle Pleistocene)
PEbcc - Regional Volcanism, Southwest; Basalt of Castle Creek (middle or early Pleistocene)
PEbbf - Pre-Mazama Volcanism; Basaltic andesite of Bert Creek; mudflow (early Pleistocene)
PEbln - Regional Volcanism, Southwest; Basaltic andesite northwest of Little Castle Creek (early? Pleistocene)
PEbcn - Regional Volcanism, Southwest; Basalt north of Castle Creek
PEbac - Regional Volcanism, Southwest; Basaltic andesite of Castle Point (early? Pleistocene)
PEbbc - Pre-Mazama Volcanism; Basaltic andesite of Bert Creek; lava (early Pleistocene)
PEbck - Regional Volcanism, Northwest; Basaltic andesite north of Crater Creek; regional volcanism, Northwest (early Pleistocene)
PEsu - Mount Mazama; Submerged outcrops of the caldera walls, undivided (Pleistocene)
PEgd - Glaciogenic deposits (Pleistocene)
PEoba - Older basaltic andesite (Pleistocene)
PEob - Older basalt (Pleistocene)
PEoa - Older andesite (Pleistocene)
QTmv - Mafic vent deposits (Holocene? To Pliocene)
QTb - Regional Volcanism, Southwest; Basaltic andesite, undivided; lava (Pleistocene or Pliocene)
QTbuc - Regional Volcanism, Southwest; Basaltic andesite of Union Creek; lava (Pleistocene or Pliocene)
QTbuci - Regional Volcanism, Southwest; Basaltic andesite of Union Creek; intrusive (Pleistocene or Pliocene)
QTba - Volcanic Rocks of the High Cascade Range; basaltic andesite (Pleistocene and Pliocene)
QTmi - Volcanic Rocks of the High Cascade Range; mafic intrusive rocks (Pleistocene and Pliocene)
QTi - Intrusive rocks (Pleistocene and Pliocene)
QTbdy - Basaltic andesite of Boundary Butte (Quaternary/Tertiary)
Tcop - Basalt of Copeland Canyon (Pliocene)
Twod - Basaltic andesite of Wood River Spring (Pliocene)
Td - Diatomite and volcaniclastic sediments (Pliocene and Miocene)
Tba - Volcanic Rocks of the High Cascade Range; basaltic andesite (Pliocene and Upper Miocene)
Ta - Volcanic Rocks of the High Cascade Range; andesite (Pliocene and Upper Miocene)
Tii - Volcanic Rocks of the High Cascade Range; intermediate intrusive rocks (Pliocene and Upper Miocene)
Twa - Basalt and andesite of the Western Cascades; andesite (Miocene)

Figure 7b. Geologic map legend of CRLA, Oregon (for Figure 6) (part 2).

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

Unit Name (map symbol)	Reference	Stratotype Location	Age
Wineglass Welded Tuff (Hcw)	Williams 1942	Type section: forms brim of the Wineglass and the brick-red layer near top of the long slide above Grotto Cove near Crater Lake.	Holocene
Mount Mazama Formation	Davis 1978	Type section: Crater Lake, Oregon	Holocene

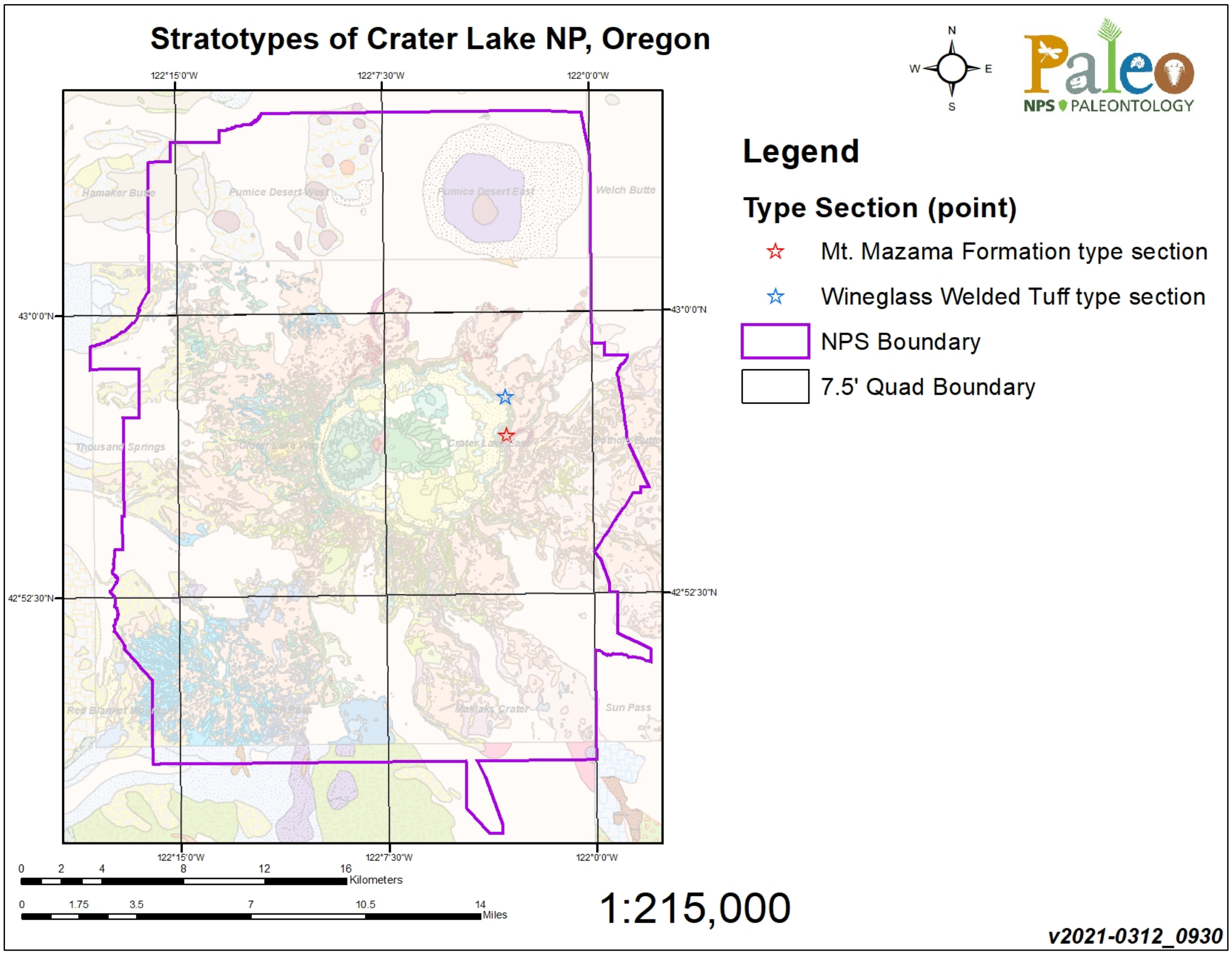


Figure 8. Modified geologic map of CRLA showing stratotype locations. The transparency of the geologic units layer has been increased.

The Holocene Mount Mazama Formation was named by Davis (1978) after Mount Mazama, Oregon. Davis (1978) defines the type section of the formation to be Crater Lake, Oregon (Table 1; Figure 8). It is important to note that the type section designation of Davis (1978) would better represent the geographic scope of a type area by modern definition (North American Commission on Stratigraphic Nomenclature 2005). The formation is subdivided into two members, the Mazama Member and Pyramid Lake Member, consisting of seven individual tephra layers (Davis 1978).

The Holocene-age Wineglass Welded Tuff was first described by Diller and Patton (1902) as the Wineglass dacite flow and was later renamed by Williams (1942) for exposures near the top of the Crater Lake caldera between Pumice Point and Grotto Cove. The unit is named after the Wineglass, a scree chute located to the right of Palisades and Roundtop (Figure 9; Bacon and Wright 2017). Williams (1942) designated the type section of the tuff as exposures that form the brim of the Wineglass along the northeast caldera rim of Crater Lake (Table 1; Figures 8 and 9). The type section of the Wineglass Welded Tuff consists of pinkish-orange to light-brown, partly welded to densely welded rhyodacitic ignimbrite (volcanic deposit consisting mostly of pumice fragments that formed from a dense, fast-moving flow of hot gas, lava pieces, and volcanic ash) that forms a cliff approximately 7.6 m (25 ft) thick (Williams 1942; Bacon 2008). As many as four flow units of ignimbrite form a single cooling unit (Bacon and Wright 2017). Other notable exposures of the tuff occur at Skell Head, where the most complete section of the climactic eruption of Mount Mazama is preserved (Figure 10). The Wineglass Welded Tuff overlies the climactic pumice fall deposits of the single vent phase and underlies the climactic ignimbrite deposits of the ring-vent phase (Bacon and Wright 2017).

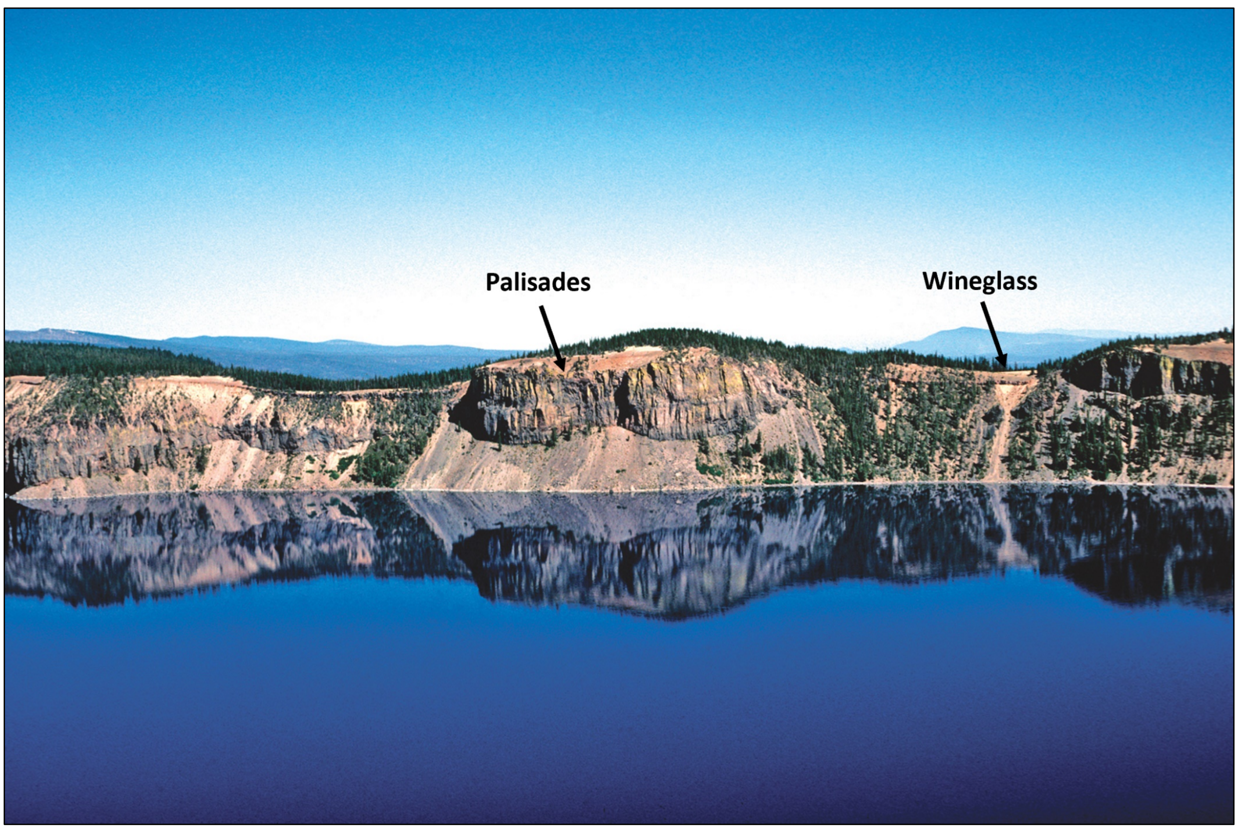


Figure 9. The Palisades and Wineglass, northeastern wall of Crater Lake caldera, CRLA. The central topographic high in this aerial view is Roundtop, and the tall cliffs below Roundtop are the Palisades. To the right of the Palisades is the scree chute known as the Wineglass. The type section of the Wineglass Welded Tuff forms the brim of the Wineglass. Figure modified from U.S. Geological Survey photograph by Charles R. Bacon.

Figure 10. View to the north showing deposits of the climactic eruption of Mount Mazama above Skell Head, the most complete section exposed on the caldera rim. Climactic pumice fall forms pinkish-white slope and two prominent beds by and above person (below red dashed line). Four flow units of Wineglass Welded Tuff (denoted by black arrows) make up the orangish-brown cliff and are marked by recesses and dark lithic fragments. The lower three flow units are partly welded and the highest one is densely welded, grading up into black vitrophyre. Figure modified from Bacon and Wright (2017).

Lassen Volcanic National Park (LAVO)

Lassen Volcanic National Park (LAVO) is located in the southern Cascades Range in Lassen, Plumas, Shasta, and Tehama Counties, northern California (Figure 11). Initially proclaimed as Lassen Peak and Cinder Cone National Monuments on May 6, 1907, the two separate monuments were combined to form LAVO on August 9, 1916 (Anderson 2017). The park preserves approximately 43,135 hectares (106,589 acres) of diverse volcanic landforms and associated hydrothermal features that include composite volcanoes, shield volcanoes, cinder cones, lava domes, lava flows, pyroclastic flows (hot, dense currents of volcanic gas, ash, and rock), tephra (rock fragments and particles ejected by a volcanic eruption), steaming fumaroles, mudpots, and boiling springs. The Lassen volcanic center is the southernmost active volcanic region in the Cascades Range and last erupted intermittently from 1914 to 1917 (Anderson 2017).

The geology of LAVO is dominated by hundreds of volcanic deposits that range in age from the Pleistocene (~2.4 million–900,000 years old) to the most recent 1914–1917 eruption of Lassen Peak (Figures 12 and 13). Most of the southeastern part of LAVO consists of units belonging to the Dittmar volcanic center, active from 2.4 to 1.3 million years. Much of the southwestern corner of LAVO is part of the Maidu volcanic center, active from 2.4 to 1.1 million years ago (Clynne and Muffler 2010). The currently active volcanic center at LAVO, the Lassen volcanic center, has an 825,000-year lifespan and is superimposed upon a volcanic platform created by regional volcanoes (KellerLynn 2014a). The Lassen volcanic center is composed of a collapsed caldera complex filled by the heavily eroded Brokeoff Volcano and the Lassen domefield. Although LAVO is popular for its volcanic terrain, the park's landscape has been modified by hydrothermal alteration and glaciation. Glaciers advanced over the mountainous terrain of the park several times during the ice ages of the recent past, eroding away bedrock and forming glacial landforms such as U-shaped valleys, moraines, till, and outwash deposits that blanket much of the underlying volcanic units. Volcanic rocks in LAVO that have been altered by hydrothermal processes helped facilitate glacial erosion, creating features such as cirques and arêtes that occur throughout the park (KellerLynn 2014a).

As of the writing of this paper, there are no designated stratotypes identified within the boundaries of LAVO. Numerous geologic units exist within LAVO that are unique to the region but currently lack stratotype designation and are addressed under "Recommendations". There are four identified stratotypes located within 48 km (30 mi) of LAVO boundaries, for the Cretaceous Chico Formation (type locality), Kingsley Cave Member of the Chico Formation (type section), South Fork Mountain Schist of the Franciscan Complex (type locality), and the Pleistocene Burney Basalt (type locality).

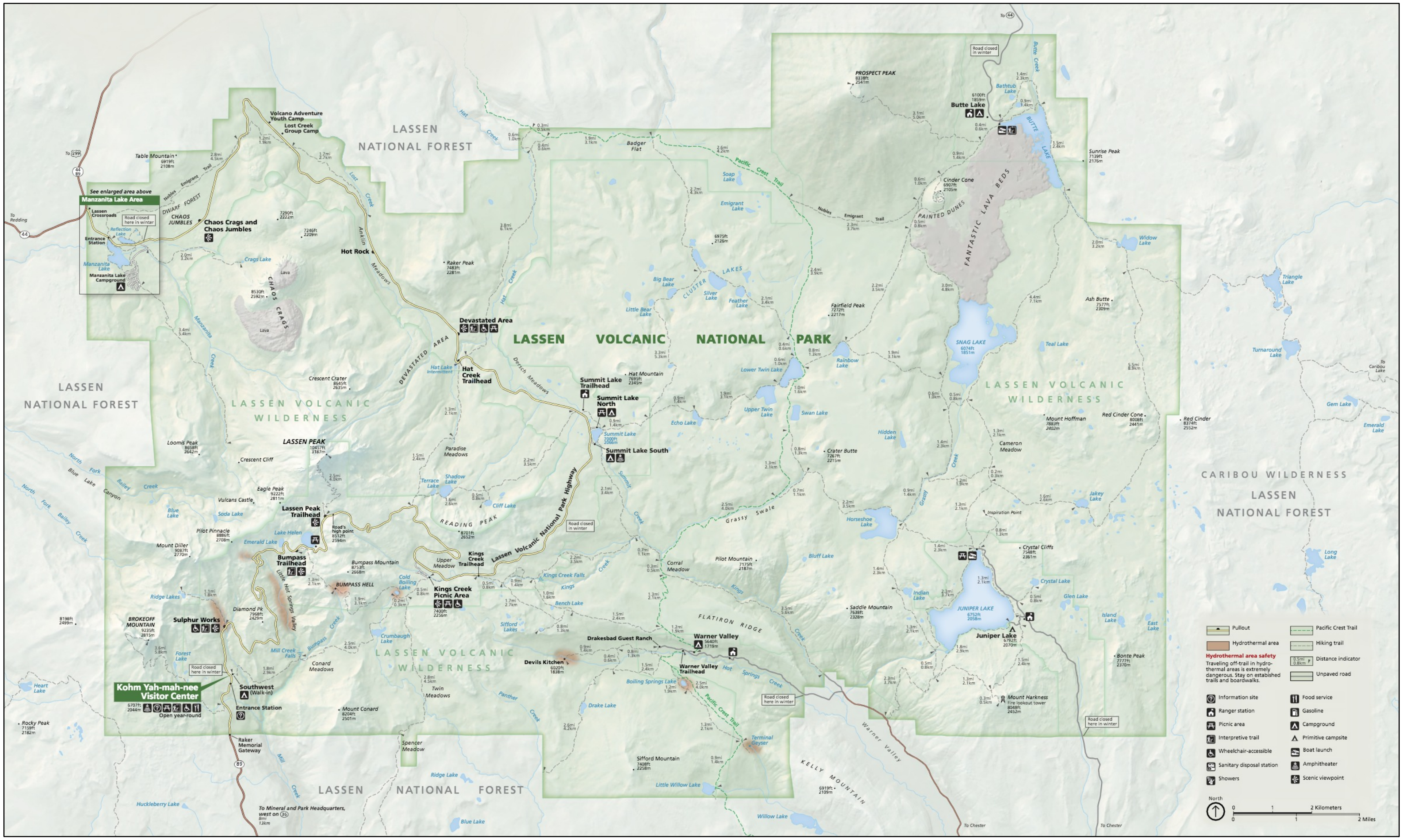


Figure 11. Park map of LAVO, California (NPS).

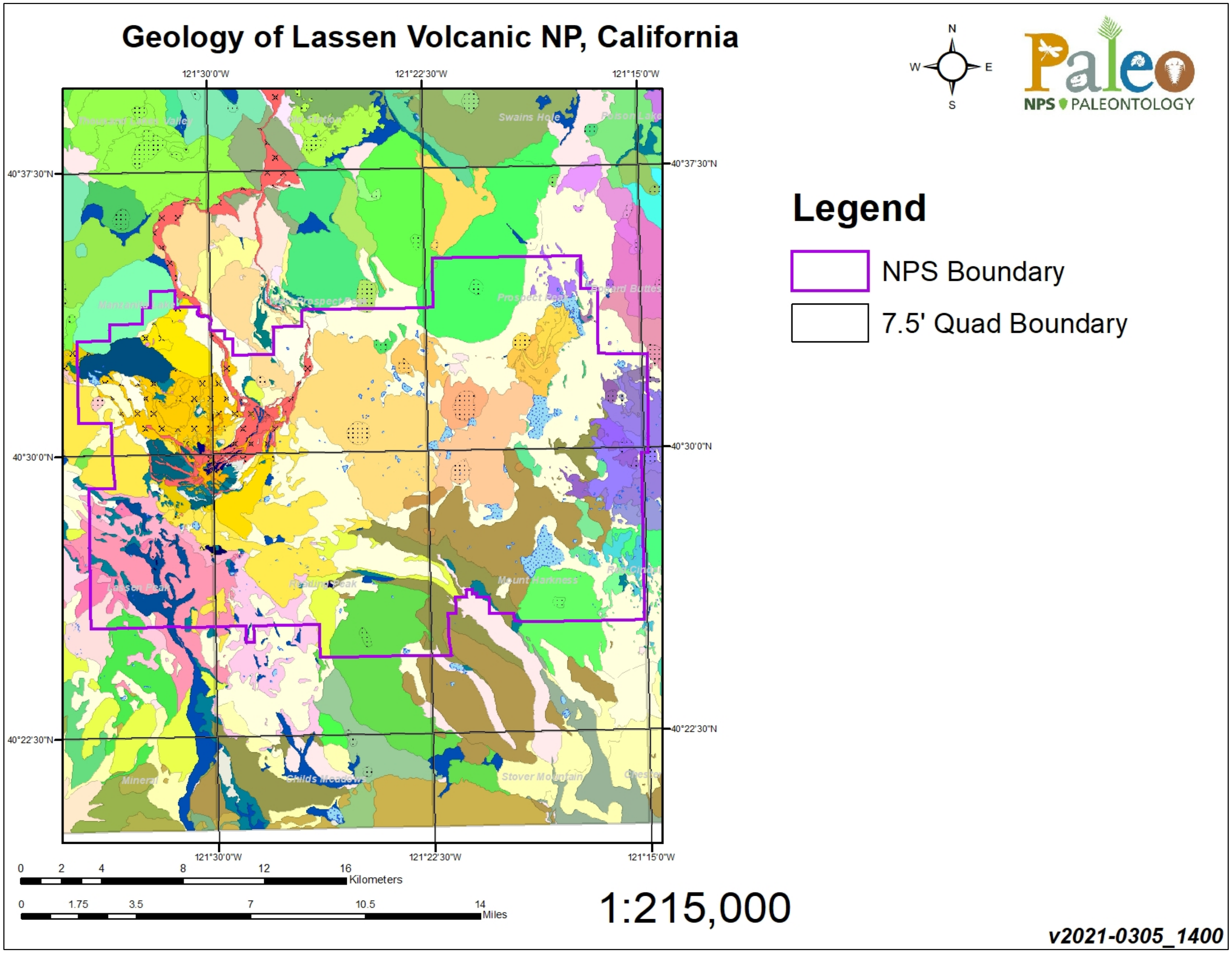


Figure 12. Geologic map of LAVO, California; full legend is included as Figure 13.

Figure 13. Geologic map legend of LAVO, California (for Figure 12).

Lava Beds National Monument (LABE)

Lava Beds National Monument (LABE) is located in the Cascades Range about 16 km (10 mi) south of the California–Oregon border in Modoc and Siskiyou Counties, northeastern California (Figure 14). Established on November 21, 1925, LABE was initially administered by the U.S. Forest Service before it transferred to the NPS on August 10, 1933 (Anderson 2017). The monument encompasses approximately 18,896 hectares (46,692 acres) of rugged, volcanic landscape situated on the northern flank of Medicine Lake volcano. Medicine Lake volcano is the largest volcano by volume in the Cascades Range at 600 km^3 (150 mi^3) and is the primary volcanic source for the monument's namesake lava beds (KellerLynn 2014b). To date, there are 208 recorded volcanic events associated with the volcano's 500,000-year history, 36 of which are preserved in LABE (Donnelly-Nolan 2010).

The geology of LABE is dominated by hundreds of well-preserved lava features that range in composition from rhyolite to basalt (Figures 15 and 16). The monument is decorated by a diverse array of volcanic features that include vents, craters, cinder cones, spatter cones, lava flows, and lava tubes. Thirty-six eruption events associated with Medicine Lake volcano are situated within the monument, the oldest of which is the Pleistocene basalt of Hovey Point (445,000 ± 25,000 years old) (KellerLynn 2014b). The youngest volcanic unit in LABE is the Holocene basaltic andesite of Callahan Flow (1,120 years old) (KellerLynn 2014b). In addition to the monument's diverse volcanic deposits, LABE contains lake deposits, glacial outwash deposits, paleontological resources, and cultural resources. Petroglyph Point is an American Indian rock art site with more than 5,000 individual rock carvings dating back to the early Holocene (11,700 years) (KellerLynn 2014b).

As of the writing of this paper, there are no designated stratotypes identified within the boundaries of LABE. Numerous geologic units exist within LABE that are unique to the region but currently lack stratotype designation and are addressed under "Recommendations". There is one identified stratotype located within 48 km (30 mi) of LABE boundaries, for the Pleistocene Lake Basalt (type locality).

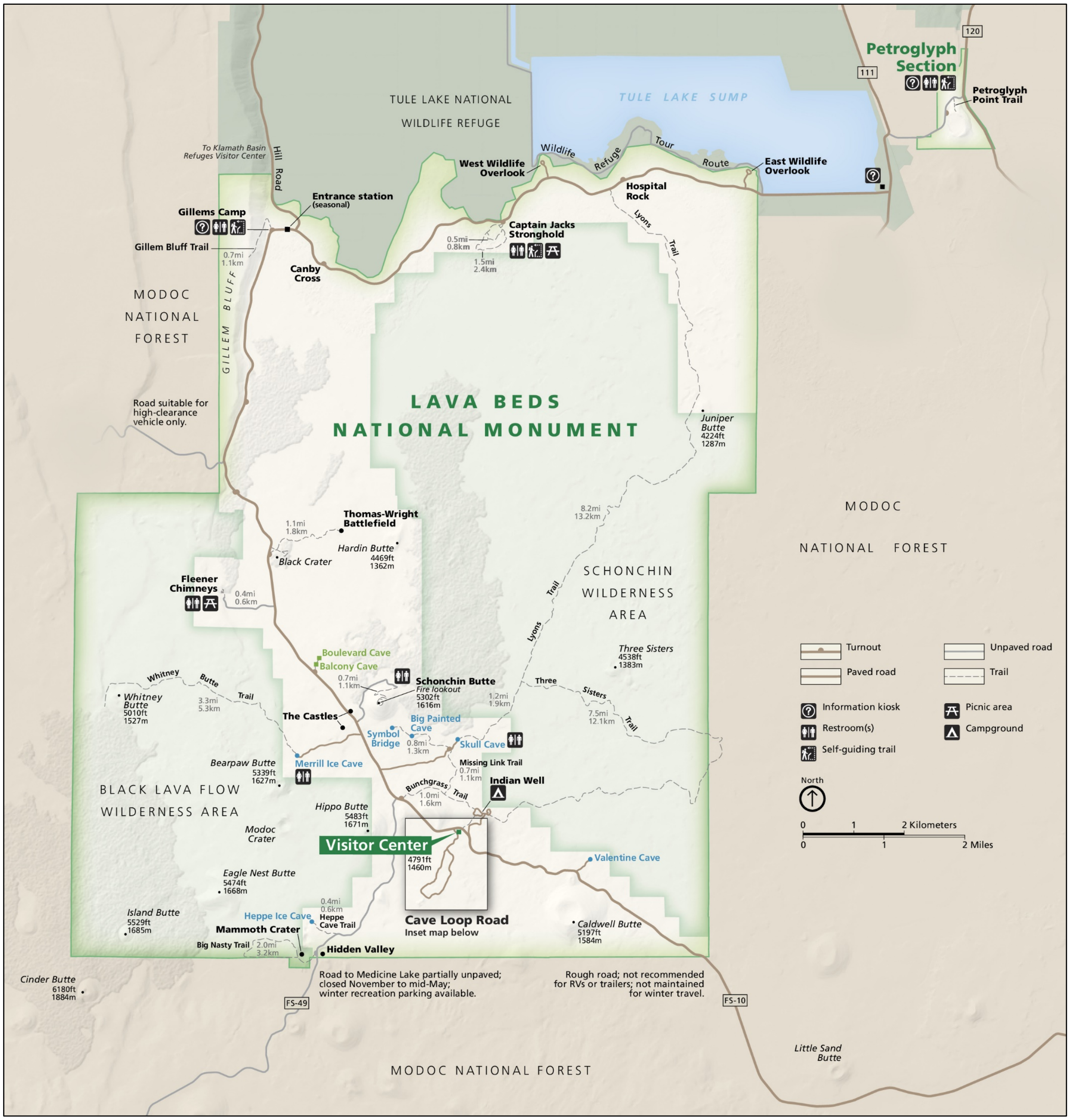


Figure 14. Park map of LABE, California (NPS).

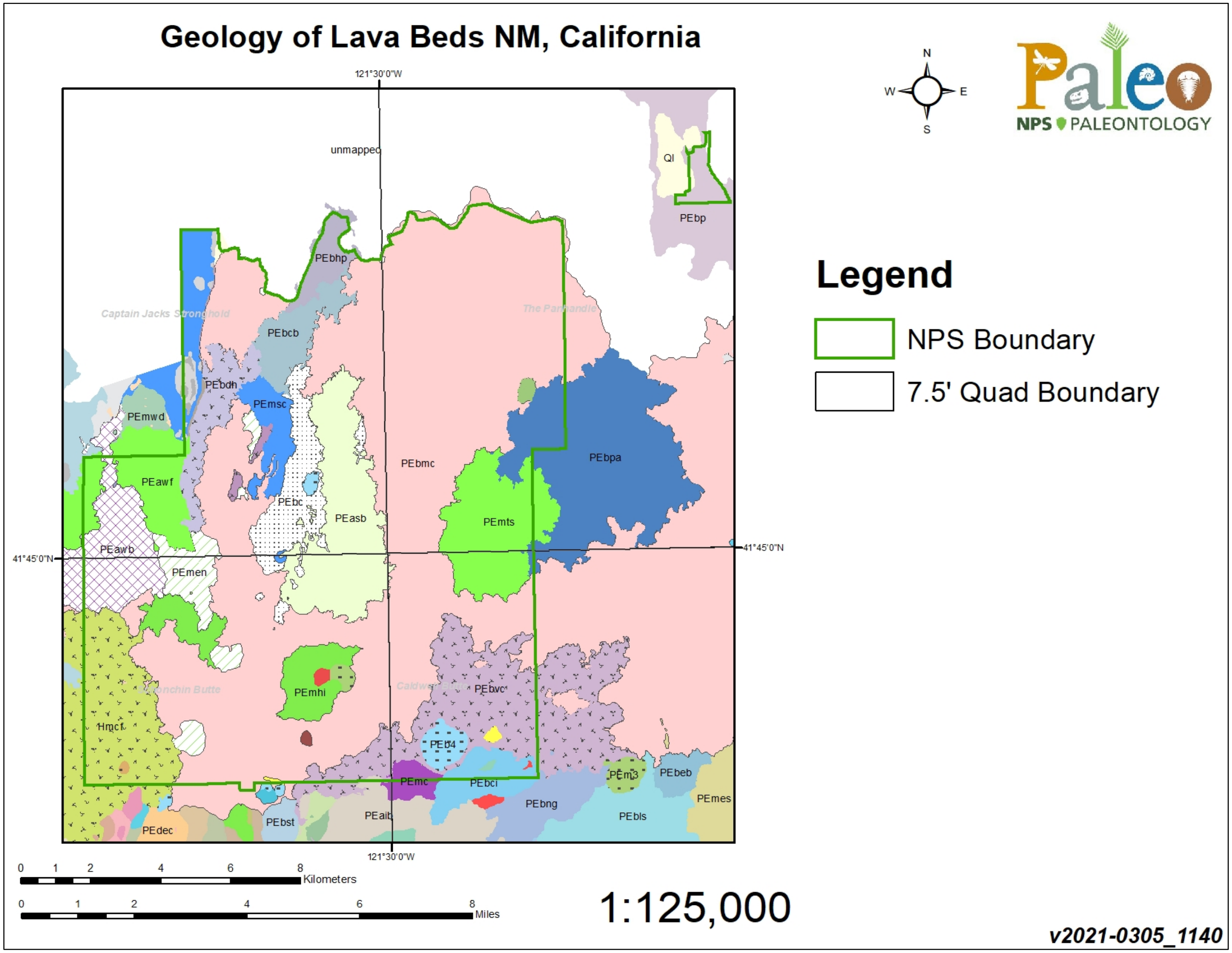


Figure 15. Geologic map of LABE, California; full legend is included as Figure 16.

Figure 16. Geologic map legend of LABE, California (for Figure 15).

Oregon Caves National Monument and Preserve (ORCA)

Oregon Caves National Monument and Preserve (ORCA) is located in the northern Klamath Mountains approximately 10 km (6 mi) north of the California–Oregon border in Josephine County, southwestern Oregon (Figure 17). The monument was proclaimed on July 12, 1909 and originally administered by the U.S. Forest Service. Stewardship of ORCA was transferred to the NPS on August 10, 1933. Encompassing approximately 1,843 hectares (4,554 acres), ORCA protects remnant old-growth Douglas fir forest, numerous glacial features, and the longest marble solution cave in the Siskiyou Mountains (Anderson 2017). Although its name is confusingly pluralized, Oregon Caves is a single cave with 4.8 km (3 mi) of interconnected passages (KellerLynn 2011). The entrance to the cave is located on the side of Mt. Elijah, named after the 24-year-old hunter Elijah Davidson who accidentally made the first recorded discovery of the cave in 1874.

The geologic history of ORCA spans millions of years and involved the slow dissolution of rock by acidic waters to create a long, continuous marble cave nestled within an unusually diverse array of rock types. The bedrock at ORCA consists of the Triassic–Jurassic Rattlesnake Creek terrane (207–193 million years old; Wright and Wyld 1994) and Jurassic Josephine ophiolite (157 million years old; Harper 1984), rocks that originated elsewhere and were transported to their current location by plate tectonic processes. The assemblage of rocks consists of complete ophiolite (seafloor) sequences, broken formations (rock units disrupted by faults but retaining continuous strata), and mélange (units of fragmented rock) that were added to the western margin of North America and welded in place by igneous intrusions of the Jurassic-age Grayback pluton (160 million years old; Johnson and Barnes 2006) (KellerLynn 2011). A diverse suite of rock types and minerals is present in ORCA and includes rocks derived from the upper mantle, submarine lavas, terrestrial sediments, plutons, and marble metamorphosed from marine limestone (Figure 18; KellerLynn 2011).

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

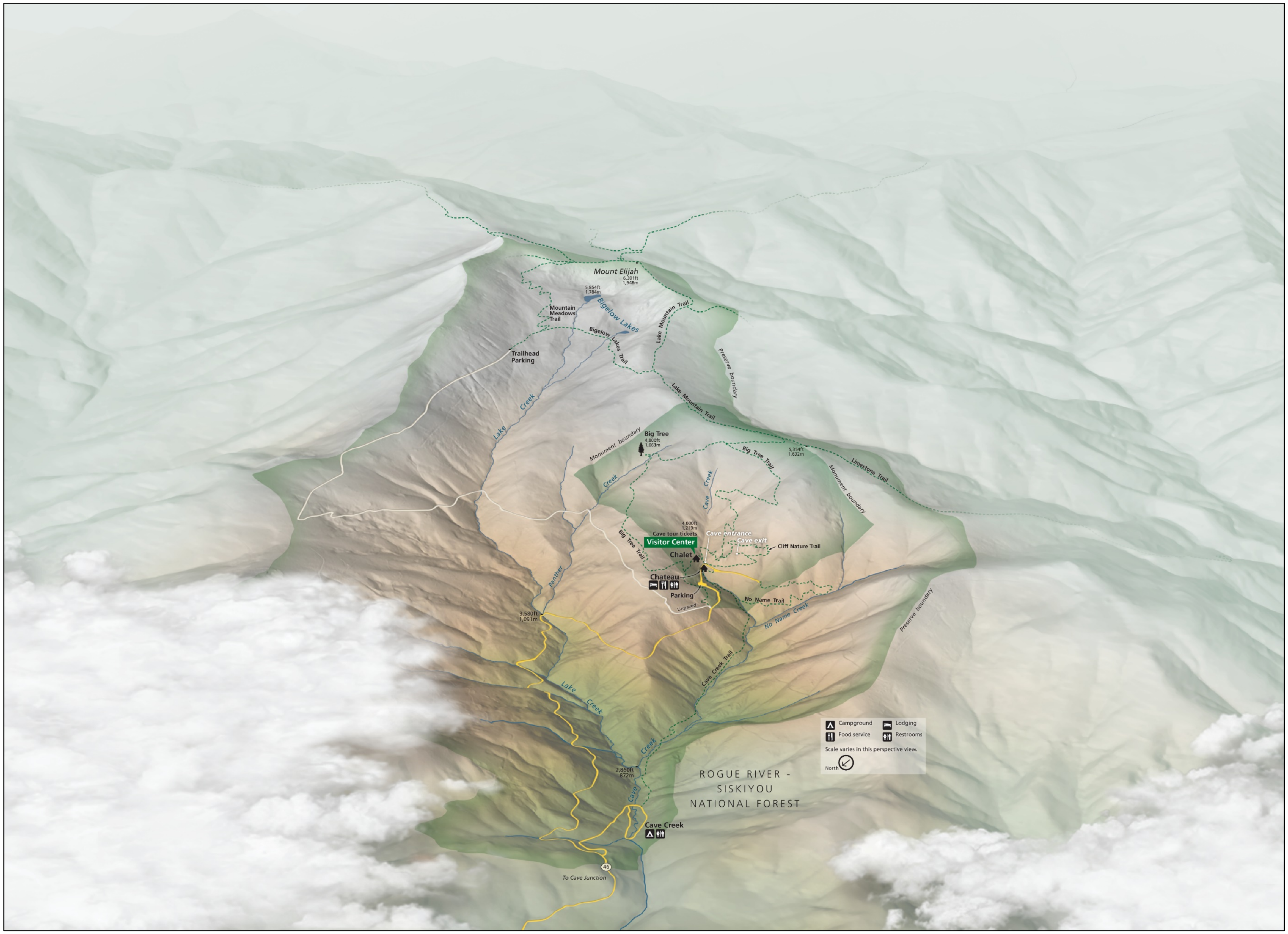


Figure 17. Park map of ORCA, Oregon (NPS).

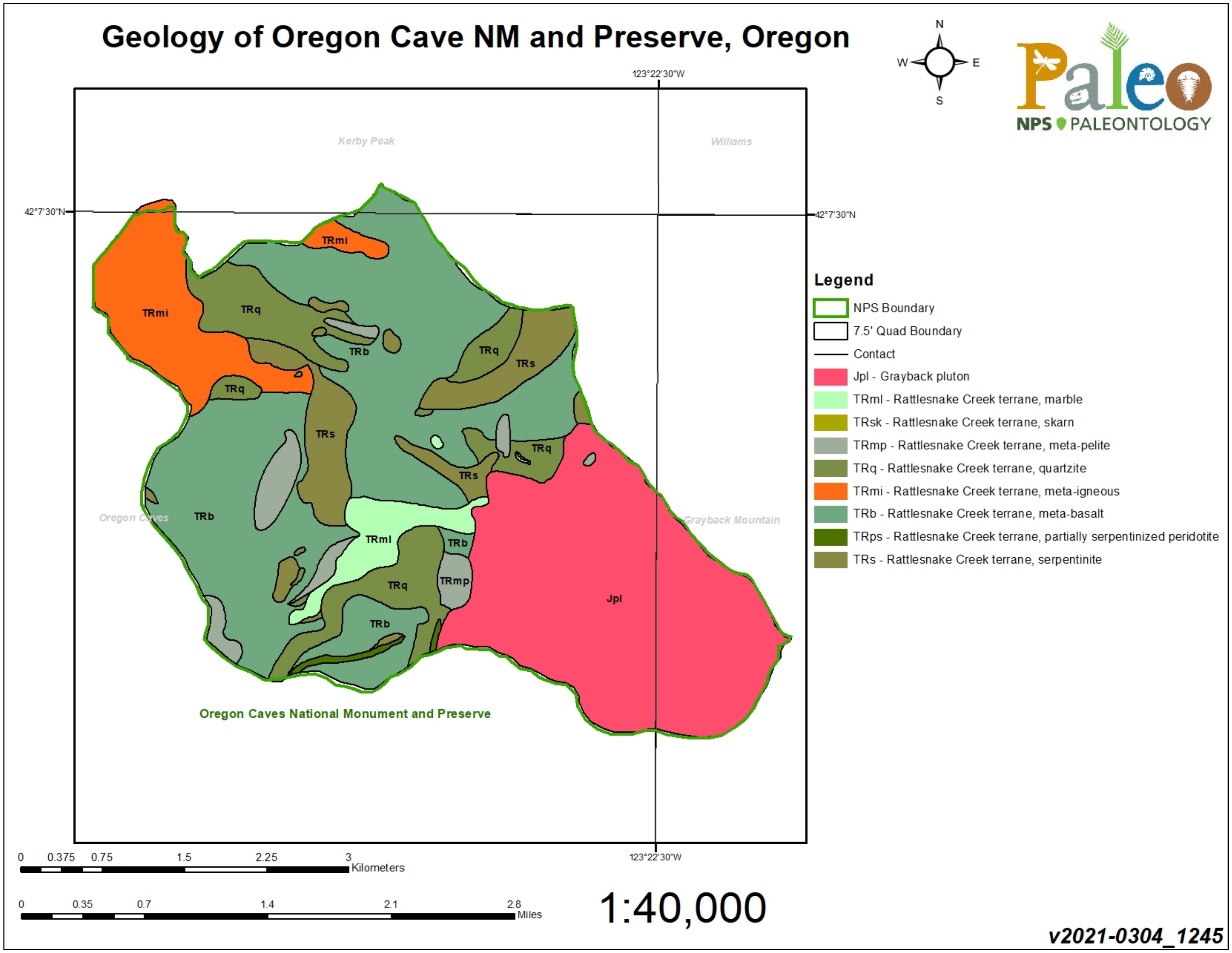


Figure 18. Geologic map of ORCA, Oregon.

Redwood National and State Parks (REDW)

Redwood National and State Parks is located in the western Klamath Mountains approximately 18 km (11 mi) south of the California–Oregon border in Del Norte and Humboldt Counties, northwestern California (Figure 19). Established on October 2, 1968, REDW protects approximately 56,251 hectares (138,999 acres) of vast prairies, oak woodlands, wild riverways, coastal redwood forests with virgin groves of ancient trees, and nearly 56 km (35 mi) of rugged, scenic Pacific coastline (Anderson 2017). The North Coast region that is home to REDW is one of the most seismically active regions of the United States, experiencing frequent earthquakes and rapid uplift rates that have led to landslides, shifting rivers, and rapid coastal erosion. The park supports rich biodiversity and was designated a World Heritage Site on September 2, 1980 (Anderson 2017).

The geology of REDW is predominantly composed of the Jurassic–Cretaceous Franciscan Complex, an accretionary (material tectonically added to an existing landmass) assemblage of rocks that have been sheared and uplifted from the ocean floor as a result of plate tectonic processes (Figure 20; Bero et al. 2020). Younger units of the park include the Miocene St. George Formation, Wimer Formation, Pliocene–Pleistocene Prairie Creek Formation, Pleistocene marine terrace deposits, and the late Pleistocene Battery Formation. The three large river systems within REDW (Smith River, Klamath River, and Redwood Creek) have eroded down through the bedrock to form deep gorges through the forest and mountainous terrain. In the southern section of the park, Redwood Creek follows the trace of the Grogan Fault in a northwest direction. The river basin is long and narrow with many small, steep tributaries.

REDW contains one identified stratotype: the type locality of the Pliocene–Pleistocene Prairie Creek Formation (Table 2; Figure 21). There are three identified stratotypes located within 48 km (30 mi) of REDW boundaries, for the Jurassic–Cretaceous Kerr Ranch Schist (type locality), Lacks Creek Unit of the Franciscan Complex (type locality), and the Cretaceous Houstenaden Creek Formation (type section).

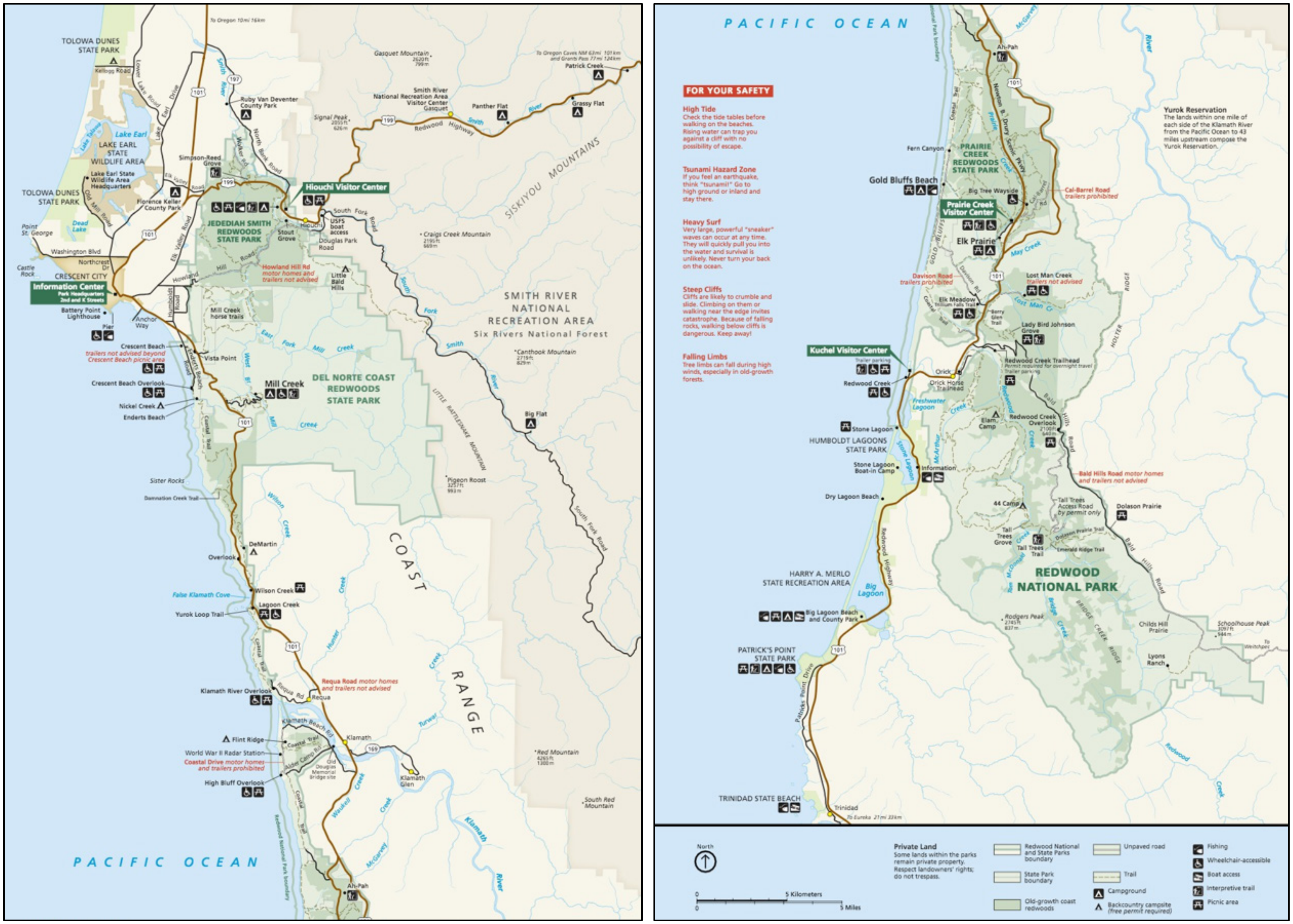


Figure 19. Park map of REDW, California (NPS).

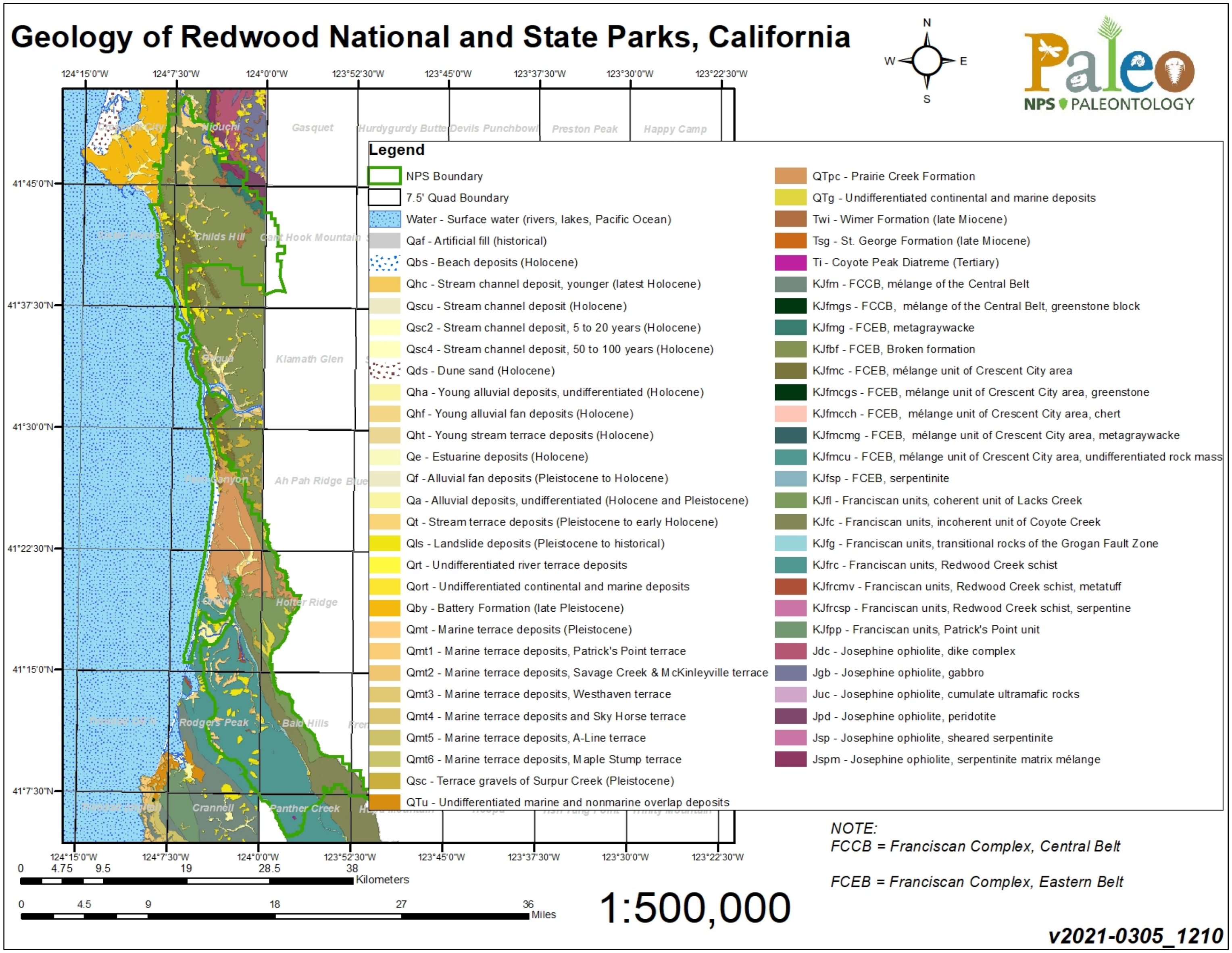


Figure 20. Geologic map of REDW, California.

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

Unit Name (map symbol)	Reference	Stratotype Location	Age
Prairie Creek Formation (QTpc)	Cashman et al. 1995	Type locality: coastal bluffs, Gold Bluffs Beach, Section 4, Township 11 N, Range 1 E, Orick Quadrangle, Humboldt County, California.	late Pliocene–early Pleistocene

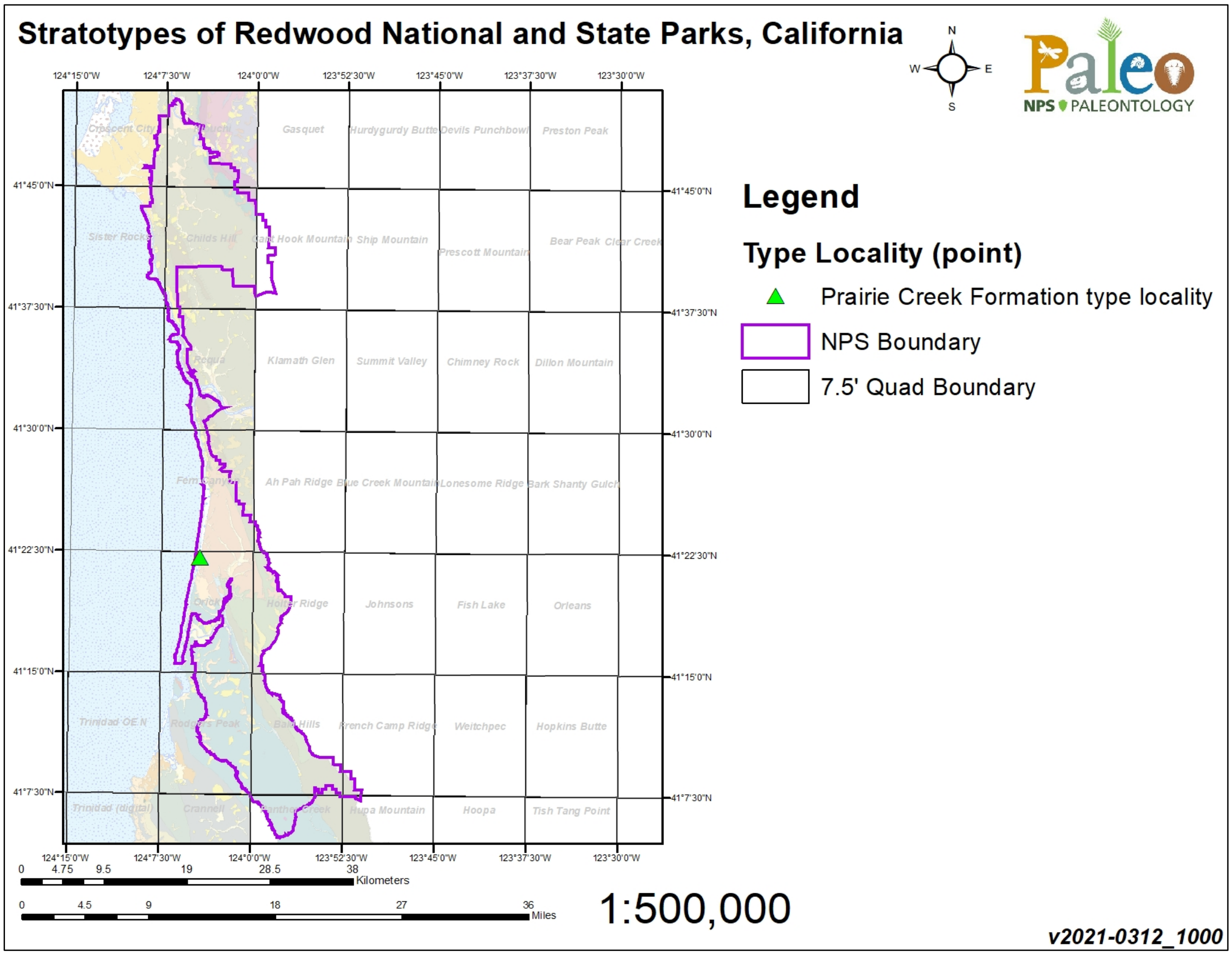


Figure 21. Modified geologic map of REDW showing stratotype location. The transparency of the geologic units layer has been increased.

The Pliocene–Pleistocene Prairie Creek Formation was named by Kelsey and Trexler (1989) after Prairie Creek in Humboldt County, California. The best exposures of the formation occur at the type locality along the well-exposed coastal bluffs at Gold Bluffs Beach in Section 4, Township 11 N, Range 1 E (Table 2; Figures 21 and 22; Cashman et al. 1995). Type locality exposures are 550 m (1,800 ft) thick and consist of basal tan shallow marine sands that grade upward to estuarine and coarse alluvial sequences consisting of sand, pebbles, and cobbles of mixed metamorphic and igneous rocks (Cashman et al. 1995). The formation unconformably overlies the Jurassic–Cretaceous Franciscan Complex (Cashman et al. 1995).

Figure 22. Type locality exposures of the Prairie Creek Formation at Gold Bluffs Beach campground (NPS).

Whiskeytown National Recreation Area (WHIS)

Whiskeytown National Recreation Area (WHIS) lies within the Klamath Mountains approximately (90 mi) south of the California–Oregon border in Shasta and Trinity Counties, northern California (Figure 23). Established on October 21, 1972, WHIS preserves approximately 17,200 hectares (42,503 acres) of mountainous backcountry, the popular man-made Whiskeytown Lake, and historic sites related to the 1849 Gold Rush. Created by the impoundment of Clear Creek behind the Whiskeytown Dam, Whiskeytown Lake provides a multitude of outdoor recreation opportunities including fishing, kayaking, sailing, swimming, and waterskiing (Anderson 2017).

The geology of WHIS is dominated by igneous and metamorphic rocks that played an important role in the early mining history of the region (Figure 24). Prospectors and miners of the Gold Rush were attracted to the area by the gold and sulfide deposits associated with igneous intrusions (Thornberry-Ehrlich 2007). The oldest geologic units in WHIS are the Devonian Copley Greenstone and Balaklala Rhyolite that occur throughout the central portion of WHIS. Some of the youngest geologic units of the park include the Pleistocene Red Bluff Formation and more recent landslide and talus deposits. One of the most prominent geologic features within the recreation area is the peak of Shasta Bally with an elevation of 1,893 m (6,209 ft) (Thornberry-Ehrlich 2007).

As of the writing of this paper, there are no designated stratotypes identified within the boundaries of WHIS. There are two identified stratotypes located within 48 km (30 mi) of WHIS boundaries, for the Devonian Grouse Ridge Formation (type area) and the Permian–Triassic Stuart Fork Formation (type area).

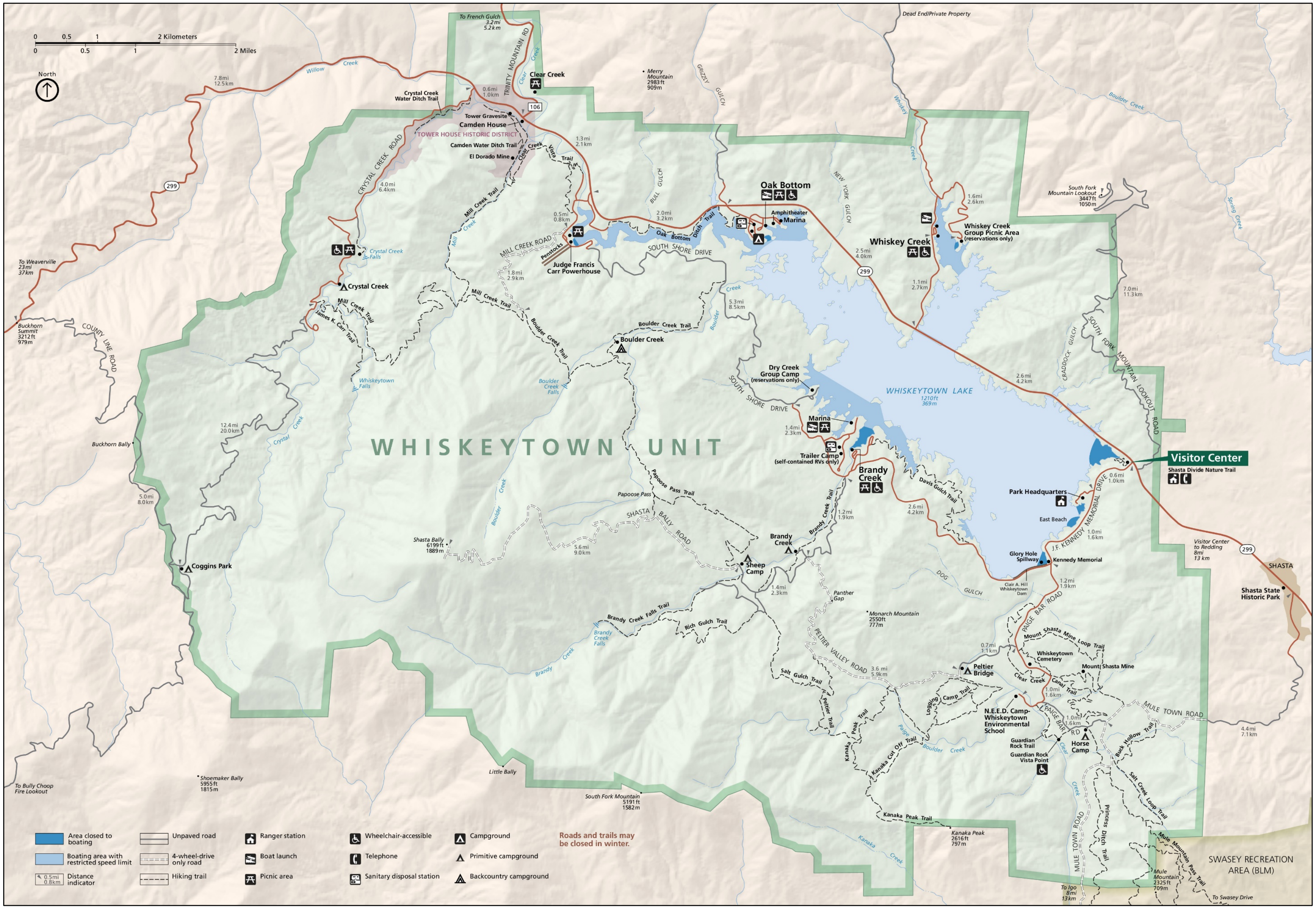


Figure 23. Park map of WHIS, California (NPS).

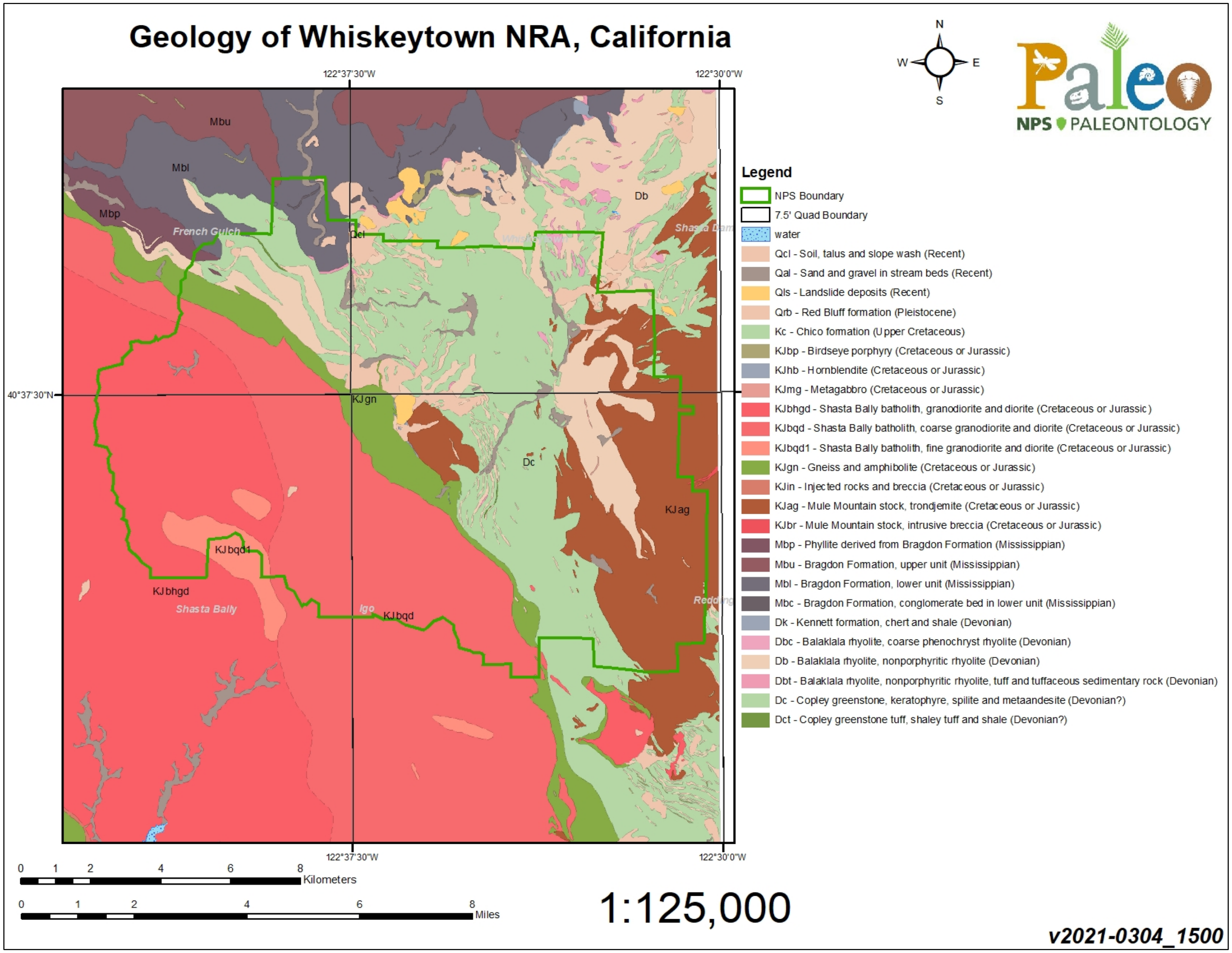


Figure 24. Geologic map of WHIS, California.

Recommendations

1. The NPS Geologic Resources Division should work with park and network staff to increase their awareness and understanding about the scientific, historic and geologic heritage significance of geologic stratotypes (type sections/localities/areas, reference sections, lithodemes). 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 KLMN Geologic Type Section Inventory report is finalized, the NPS Geologic Resources Division should schedule a briefing for the staff of the KLMN and respective network parks.
3. Numerous geologic units exist within CRLA that are geographically and geologically unique but lack designated stratotypes. Many of these units are named after iconic features of the park, such as: andesite of Wizard Island, dacite of the Watchman, andesite of Roundtop, dacite of Sentinel Rock, dacite of Mount Scott, and basaltic andesite of Red Cone. It is recommended that stratotype designations of these units be made in order to: A) provide a standard reference for scientific research; B) educate park staff and visitors about the geoheritage significance of these units; and C) help safeguard these exposures. Priority should be made to designate units that are in the closest proximity to areas where infrastructure development might negatively impact these exposures.
4. Numerous geologic units exist within LABE that are geographically and geologically unique but lack designated stratotypes. Many of these units are named after iconic features of the monument, such as: basalt of The Castles, basaltic andesite of Three Sisters, basaltic andesite of Hippo Butte, basalt of Three Sisters, andesite of Whitney Butte, basalt of Caldwell Butte, basalt of Hardin Butte, basalt of Prisoners Rock, and basaltic andesite of Juniper Butte. It is recommended that stratotype designations of these units be made in order to: A) provide a standard reference for scientific research; B) educate park staff and visitors about the geoheritage significance of these units; and C) help safeguard these exposures. Priority should be made to designate units that are in the closest proximity to areas where infrastructure development might negatively impact these exposures.
5. Numerous geologic units exist within LAVO that are geographically and geologically unique but lack designated stratotypes. Many of these units are named after iconic features of the park, such as: deposits related to the 1914–1917 eruption of Lassen Peak, deposits emplaced by the 1666 AD Cinder Cone eruption, and deposits related to the 1,110-year-old Chaos Crags eruption. It is recommended that stratotype designations of these units be made in order to: A) provide a standard reference for scientific research; B) educate park staff and visitors about the geoheritage significance of these units; and C) help safeguard these exposures. Priority should be made to designate units that are in the closest proximity to areas where infrastructure development might negatively impact these exposures.
6. 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.

7. 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.
8. From the assessment in (7), 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.
9. 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.
10. The NPS Geologic Resources Division should ensure the park-specific Geologic Type Section Inventory Reports are widely distributed and available online.
11. 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.
12. 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.
13. 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.
14. The NPS Geologic Resources Division should work with park and network staff in developing conservation protocols of significant type sections, either by appropriate fencing, walkways, and information boards or other means (e.g., phone apps).

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Appendix A: Source Information for GRI Maps of KLMN Parks

CRLA

- GMAP 75026: Bacon, C. R. 2008. Geologic map of Mount Mazama and Crater Lake Caldera, Oregon. U.S. Geological Survey, Reston, Virginia. Scientific Investigations Map 2832. Scale 1:24,000. Available at: https://pubs.usgs.gov/sim/2832/ (accessed May 6, 2021).
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LABE

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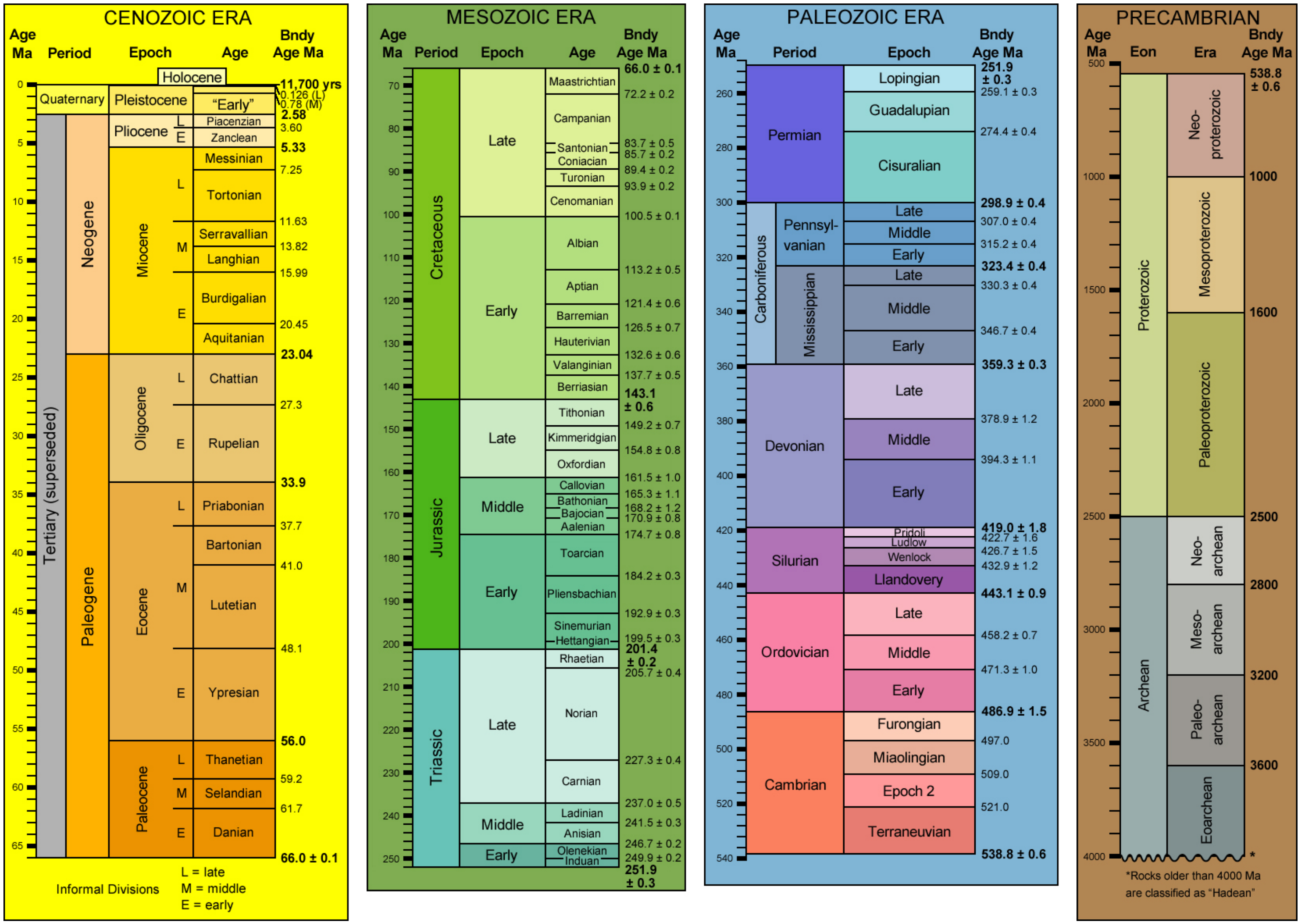
Appendix B: Geologic Time Scale



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

NPS 925/176899, July 2021

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