



National Park Service Geologic Type Section Inventory

Pacific Island Inventory & Monitoring Network

Natural Resource Report NPS/PACN/NRR—2022/2371



ON THE COVER

View facing southwest across Kaluapele (Kīlauea caldera) toward Halema'uma'u in Hawai'i Volcanoes National Park. The type sections of both the Holocene Uēkahuna Ash and Puna Basalt are located within the caldera at the base of Uēkahuna Bluff. The now abandoned Jaggar Museum located to the middle right of the photo sits atop Uēkahuna Bluff. USGS photo.

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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 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 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 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. 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 Pacific Island Inventory & Monitoring Network (PACN).

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 PACN shows there are currently no designated stratotypes for American Memorial Park (AMME), Kaloko-Honokōhau National Historical Park (KAHO), Pu‘ukoholā Heiau National Historic Site (PUHE), or Pu‘uhonua o Hōnaunau National Historical Park (PUHO).

Haleakalā National Park (HALE) has two type localities and one reference locality; Hawai‘i Volcanoes National Park (HAVO) has ten type sections, three type localities, one principal reference section, and 14 reference sections; Kalaupapa National Historical Park (KALA) has one type section and two type localities; National Park of American Samoa (NPSA) has one type locality; and War in the Pacific National Historical Park (WAPA) has one type section (Table 1)

This report ends with a recommendation section that addresses outstanding issues and future steps regarding park unit stratotypes. These recommendations will hopefully guide decision-making and help ensure that these 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 PACN stratotype units sorted by park unit and geologic age, with associated reference publications and locations.

Unit	Unit Name (GRI map symbol)	Reference	Stratotype Location	Age
HALE	Kīpahulu Member, Hāna Volcanics	Macdonald and Davis 1956	Type locality: Kīpahulu Valley [approximately latitude 20°42'03" N., longitude 156°05'25" W., Old Hawaiian Datum, Kīpahulu 7.5' Quadrangle], east end of island of Maui, HI.	Pleistocene(?)
HALE	Kula Volcanics (Qkul, Qkuls, Qkuk, Qkuv, Qkui)	Langenheim and Clague 1987	Reference locality: along Halemau'u Trail in Haleakalā Crater area, island of Maui, HI.	Pleistocene
HALE	Kumu'ūliahi Formation (Qkuk)	Macdonald 1978	Type locality: rocks in lower part of wall of Haleakalā north and northeast of Kumu'ūliahi Peak [approximately latitude 20°42'16" N., longitude 156°12' 09" W., Old Hawaiian Datum, Kaupō 7.5' Quadrangle], island of Maui, HI.	Pleistocene
HAVO	Keanakāko'i Ash Member, Puna Basalt	Langenheim and Clague 1987	Type locality: southwest of Keanakāko'i Crater, island of Hawai'i, HI.	Holocene
HAVO	Uēkahuna Ash	Stone 1926; Easton 1987; Fiske et al. 2009	Type section: at Uēkahuna Bluff, Kaluapele, Kīlauea Crater 7.5' Quadrangle, island of Hawai'i, HI. Type section (revised; mid-Bluff section): exposed in walls of hand-dug 3.12-m (10.24 ft) pit dug at top of talus apron and at base of steep caldera wall, ~30 m (98 ft) above present caldera floor [latitude 19.42247° N., longitude 155.28775° W., Old Hawaiian Datum], island of Hawai'i, HI. *DESTROYED BY ROCK FALLS IN 2018 AND NOW BURIED. Type locality: west wall of Kaluapele at base of Uēkahuna Bluff northeast of fault terraces, [Kīlauea 7.5' Quadrangle], island of Hawai'i, HI. Reference section: at Nanahu Arroyo, Hilina Pali, 0.5 km (0.3 mi) northeast of end of Hilina Pali Trail [latitude 19°18'15" N., longitude 155°18'34" W., Old Hawaiian Datum, Ka'ū Desert 7.5' Quadrangle], island of Hawai'i, HI.	Holocene
HAVO	Kulanaokuaiki Tephra Member, Uēkahuna Ash	Fiske et al. 2009	Type section: beneath the edge of the Old Kālu'e lava flow on the upper south flank of Kīlauea Volcano, ~600 m (1,970 ft) south of Kulanaokuaiki Pali, a north-facing fault scarp 7–8 km (4–5 mi) south of Kīlauea's summit, island of Hawai'i, HI.	Holocene

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

Unit	Unit Name (GRI map symbol)	Reference	Stratotype Location	Age
HAVO	Puna Basalt (Qp4o, Qp3, Qpc5)	Stearns and Macdonald 1946; Easton 1987	Type section: Uēkahuna Bluff, Kīlauea Crater [latitude 19°25'43" N., longitude 155°17'01" W., Old Hawaiian Datum, Kīlauea Crater 7.5' Quadrangle], island of Hawai'i, HI. Type locality: walls of Kīlauea caldera, island of Hawai'i, HI. Reference sections: 1. Keanabihopa (600–640 m or 1,970–2,100 ft elevation) [latitude 19°17'19" N., longitude 155°18'25" W., Old Hawaiian Datum, Ka'ū Desert 7.5' Quadrangle]; 2. Nanahu Arroyo, Hilina Pali, 0.5 km (0.3 mi) northeast of end of Hilina Pali Road [latitude 19°18'15" N., longitude 155°18'34" W., Old Hawaiian Datum, Ka'ū Desert 7.5' Quadrangle]; 3. Kīlauea Iki crater, summit lava [Volcano 7.5' Quadrangle]; 4. East Rift Zone lava, Makaopuhi crater [Makaopuhi Crater 7.5' Quadrangle]; 5. East Rift Zone lava, Nāpau crater [Volcano 7.5' Quadrangle].	Holocene
HAVO	Ka'ū Basalt (Qk5)	Stearns and Macdonald 1946	Type section: west wall of Moku'āweoweo Caldera [approximately latitude 19°28'46" N., 155°35'30" W., Old Hawaiian Datum, Mauna Loa 7.5' Quadrangle], Mauna Loa Volcano, island of Hawai'i, HI.	Pleistocene–Holocene
HAVO	Pāhala Ash (Qpha)	Easton 1987	Principal reference section: Mo'olelo, Hilina Pali [latitude 19°17'00" N., longitude 155°19'00" W., Old Hawaiian Datum, Ka'ū Desert 7.5' Quadrangle]. Reference sections: 1. Pu'ukapukapu [latitude 19°16'35" N., longitude 155°15'23" W., Old Hawaiian Datum, Ka'ū Desert 7.5' Quadrangle]; 2. Pu'ukaone [latitude 19°16'15" N., longitude 155°16'56" W., Old Hawaiian Datum, Ka'ū Desert 7.5' Quadrangle].	Pleistocene

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

Unit	Unit Name (GRI map symbol)	Reference	Stratotype Location	Age
HAVO	Hilina Basalt (Qhi)	Stearns and Macdonald 1946; Easton 1987	Type section: exposures 1.6 km (1 mi) southwest of end of Hilina Pali Road on southern slope of Kīlauea Volcano [latitude 19°17'00" W., longitude 155°18'45" W., Old Hawaiian Datum, Ka'ū Desert 7.5' Quadrangle], island of Hawai'i, HI. Type locality: at Hilina Pali on the southern slope of Kīlauea Volcano, island of Hawai'i, HI. Reference sections: 1. Keanabihopa, from base of pali (370 m or 1,210 ft elevation) to top (640 m or 2,100 ft elevation) [latitude 19°17'19" N., longitude 155°18'25" W., Old Hawaiian Datum, Ka'ū Desert 7.5' Quadrangle]. Exposure located 250 m (820 ft) south-southwest of end of Hilina Pali Road; 2. Pu'ukapukapu, from base of pali (100 m or 330 ft elevation) to top (300 m or 980 ft elevation) [latitude 19°16'45" N., longitude 155°15'35" W., Old Hawaiian Datum, Ka'ū Desert 7.5' Quadrangle].	Pleistocene
HAVO	Mo'o Ash Member, Hilina Basalt	Easton 1987	Type section: Keanabihopa, (570 m or 1,870 ft elevation) south slope of Kīlauea Volcano [latitude 19°17'19" N., longitude 155°18'25" W., Old Hawaiian Datum, Ka'ū Desert 7.5' Quadrangle], island of Hawai'i, HI. Reference section: Pu'ukapukapu, from base of pali (100 m or 330 ft elevation) to top (300 m or 980 ft elevation) [latitude 19°16'45" N., longitude 155°15'35" W., Old Hawaiian Datum, Ka'ū Desert 7.5' Quadrangle].	Pleistocene
HAVO	Pōhāka'a Ash Member, Hilina Basalt	Easton 1987	Type section: Pōhāka'a Arroyo (~425–450 m or 1,390–1,480 ft elevation) south slope of Kīlauea Volcano [latitude 19°16'40" N., longitude 155°20'00" W., Old Hawaiian Datum, Ka'ū Desert 7.5' Quadrangle], island of Hawai'i, HI. Reference section: Pu'ukapukapu, from base of pali (100 m or 330 ft elevation) to top (300 m or 980 ft elevation) [latitude 19°16'45" N., longitude 155°15'35" W., Old Hawaiian Datum, Ka'ū Desert 7.5' Quadrangle].	Pleistocene
HAVO	Kahele Ash Member, Hilina Basalt	Easton 1987	Type section: Pōhāka'a Arroyo (~470 m or 1,540 ft elevation) south slope of Kīlauea Volcano [latitude 19°16'40" N., longitude 155°20'00" W., Old Hawaiian Datum, Ka'ū Desert 7.5' Quadrangle], island of Hawai'i, HI. Reference section: Pu'ukapukapu, from base of pali (100 m or 330 ft elevation) to top (300 m or 980 ft elevation) [latitude 19°16'45" N., longitude 155°15'35" W., Old Hawaiian Datum, Ka'ū Desert 7.5' Quadrangle].	Pleistocene

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

Unit	Unit Name (GRI map symbol)	Reference	Stratotype Location	Age
HAVO	Halapē Ash Member, Hilina Basalt	Easton 1987	Type section: Keanabihopa, (395 m or 1,300 ft elevation) on south slope of Kīlauea Volcano [latitude 19°17'19" N., longitude 155°18'25" W., Old Hawaiian Datum, Ka'ū Desert 7.5' Quadrangle], island of Hawai'i, HI. Reference section: Pu'ukapukapu, from base of pali (100 m or 330 ft elevation) to top (300 m or 980 ft elevation) [latitude 19°16'45" N., longitude 155°15'35" W., Old Hawaiian Datum, Ka'ū Desert 7.5' Quadrangle].	Pleistocene
KALA	Kalaupapa Volcanics	Macdonald and Davis 1956	Type locality: Kalaupapa Peninsula [latitude 21° 11'33" N., longitude 156°59'10" W., Old Hawaiian Datum, Kaunakakai Quadrangle], island of Moloka'i, HI.	Pleistocene
KALA	East Moloka'i Volcanics	Stearns and Macdonald 1947; Beeson 1976	Type section: cliffs south of Kalaupapa Peninsula [latitude 21°11'33" N., longitude 156°59'10" W., Old Hawaiian Datum, Kaunakakai 7.5' Quadrangle], island of Moloka'i, HI. Type locality: in 500 m (1,600 ft) cliff separating Kalaupapa Peninsula from rest of island, along trail down Pali SW of Kalaupapa [Kaunakakai 7.5' Quadrangle], island of Moloka'i, HI.	Pliocene–Pleistocene
NPSA	Pago Volcanics (Ppe, Ppi, Ppt)	Stearns 1944	Type locality: at the head of Pago Pago Valley on the north side of the trail to Fagasa, Tutuila Island, American Samoa.	Pliocene–Pleistocene
WAPA	Alifan Limestone (Tal)	Tracey et al. 1964	Type section: in Alifan quarry of the Naval Ammunition Depot above Santa Rita on the north slope of Mount Alifan, island of Guam.	Miocene–Pliocene

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Many individuals were consulted in the preparation of this report on the geologic type sections for the national parks of the Pacific Island Inventory & Monitoring Network (PACN). 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 also extend our appreciation to Dr. Scott Rowland (University of Hawai‘i at Mānoa), Dr. Brett Carr and Dr. Don Swanson (USGS) for their professional assistance and support.

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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

This Pacific Island Inventory & Monitoring Network Geologic Type Section Inventory is dedicated to Thomas Casadevall, Scientist Emeritus, U.S. Geological Survey (USGS). During his career with the USGS, Tom has served in a number of important positions. From 1978 to 1996, Tom worked as a geologist with the USGS Volcano Hazards Program, stationed at the Hawaiian Volcano Observatory, the Cascades Volcano Observatory, the Alaskan Volcano Observatory, and in Denver, Colorado. Between 1996 and 2008, Tom served in the Office of the Director, USGS, with terms as Regional Director for the Western Region (1996–1997), Acting Director of the USGS (1998), Deputy Director (1999–2000), and as Regional Director of the USGS Central Region (2000–2008). Tom is a long-term friend to the National Park Service and a strong advocate and leader for the conservation of geologic heritage resources around the world. We are proud to dedicate this report to our friend and colleague Tom Casadevall.



Thomas Casadevall, Scientist Emeritus, U.S. Geological Survey.

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.

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 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 biologic evolution of our planet.

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

This geologic type section inventory for the parks of the Pacific Island Inventory & Monitoring Network (PACN) 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 has stepped up to undertake 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 which define important scientific information associated with geologic strata. Geologic formations are commonly 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). 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 prevents 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 PACN I&M Network Parks

The Pacific Island Inventory & Monitoring Network (PACN) includes nine national park units in Hawai‘i, the Northern Marianas Islands, Guam, and American Samoa. These park units include American Memorial Park (AMME), Haleakalā National Park (HALE), Hawai‘i Volcanoes National Park (HAVO), Kaloko-Honokōhau National Historical Park (KAHO), Kalaupapa National Historical Park (KALA), the National Park of American Samoa (NPSA), Pu‘ukoholā Heiau National Historic Site (PUHE), Pu‘uhonua o Hōnaunau National Historical Park (PUHO), and War in the Pacific National Historical Park (WAPA) (Figure 1). The parks that comprise the Pacific Island Network protect a combined 153,604 hectares (379,564 acres) of wilderness and vary in size from 34 hectares (86 acres) in PUHE to 130,887 hectares (323,431 acres) in HAVO.

It should be noted that the use of diacritics and non-English symbols such as the ‘okina (‘, representing a glottal stop) was uncommon in English literature until relatively recently. Most of the older reports cited in this publication render words without these features. In most cases one can “translate” the orthography used here to older usage in the literature by removing macrons and ‘okina (e.g., “Pu‘ukoholā” versus “Puukohola”).

The geology of the Pacific Island Network is dominated by Cenozoic-age igneous rocks that represent the combined processes of hot spot volcanism, subduction, magma generation, and volcanic eruption and growth. The Hawaiian Islands that include HALE, HAVO, KAHO, KALA, PUHE, and PUHO are part of the Hawaiian–Emperor seamount chain, an extensive subaerial and submarine volcanic mountain chain that extends approximately 6,000 km (3,725 mi). Over the last 70 million years, plate tectonic processes have moved the Pacific Plate over the nearly stationary Hawaiian hot spot to create a trail of more than 80 volcanoes. As the Pacific Plate continues to migrate northwestward, new volcanic islands form above the hot spot and emerge from below the sea, such as the current island of Hawai‘i. Volcanic extinction follows as a volcano moves away from the hot spot and erosion becomes the dominant force. Large landslides may occur any time in the growth or quiescence of a volcano, and subaerial erosion is on-going whenever the volcano is emergent (Sherrod et al. 2007). The extinct volcano also begins to subside. Similar to the Hawaiian Islands, the islands of American Samoa are part of a volcanic archipelago that overlies the Samoa hot spot. The islands of American Samoa, including the three islands of NPSA (Tutuila, Ta‘ū, and Ofu), are geologically young and formed within the last two million years (Thornberry-Ehrlich 2008).

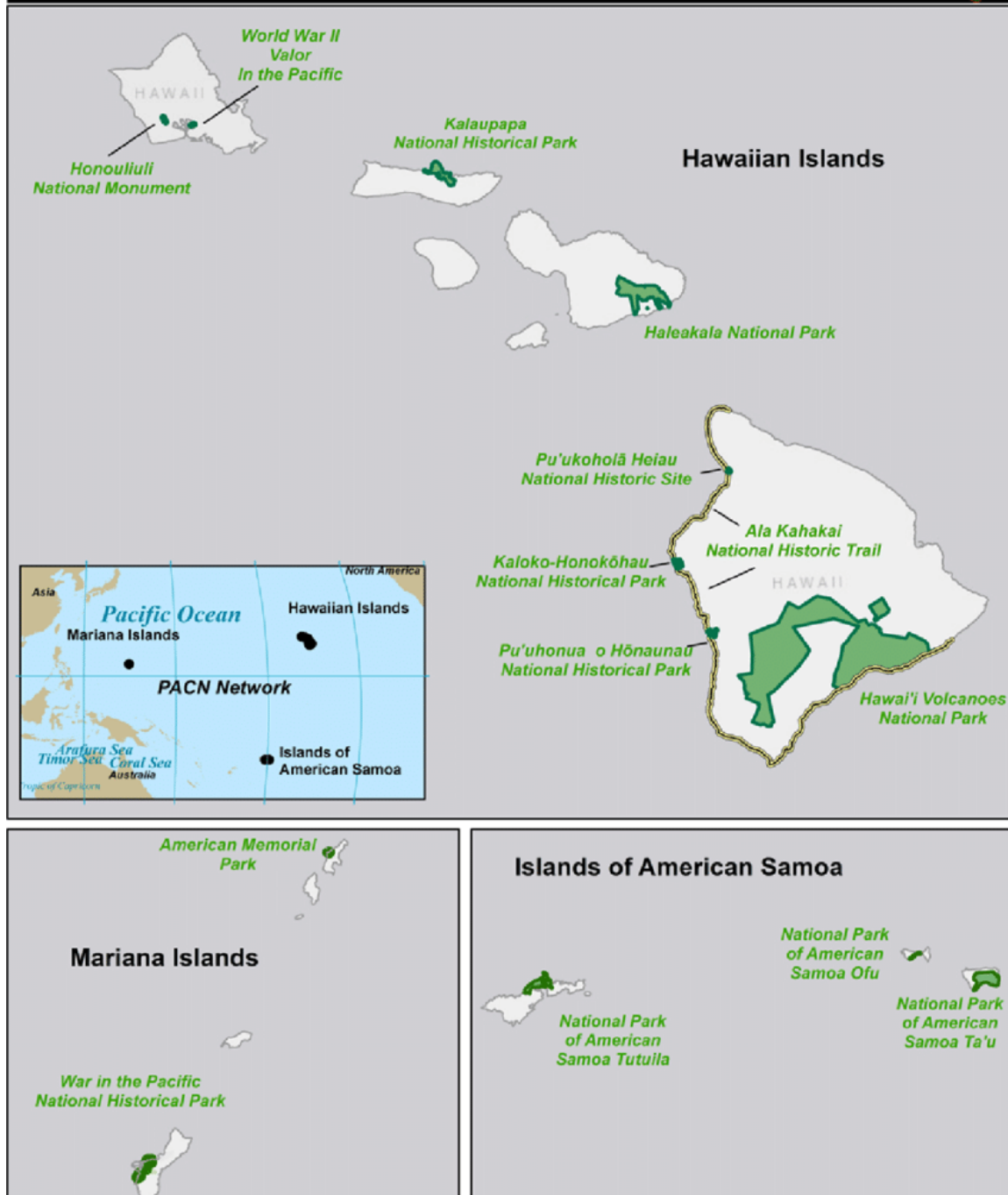


Figure 1. Map of Pacific Island I&M Network parks including American Memorial Park (AMME), Haleakalā National Park (HALE), Hawai'i Volcanoes National Park (HAVO), Kaloko-Honokōhau National Historical Park (KAHO), Kalaupapa National Historical Park (KALA), the National Park of American Samoa (NPSA), Pu'ukoholā Heiau National Historic Site (PUHE), Pu'uhonua o Hōnaunau National Historical Park (PUHO), and War in the Pacific National Historical Park (WAPA) (NPS).

The geologic setting of Guam and Saipan in the Northern Marianas Islands is part of a feature commonly called the “Ring of Fire”, an active, dynamic boundary where oceanic crust of the Pacific Plate is subducting beneath neighboring tectonic plates to be recycled deep within the Earth (Thornberry-Ehrlich 2012). The Mariana Trench—east of Guam—is the deepest point on the surface of Earth’s crust, extending more than 11 km (7 mi) below the ocean’s surface. Here, the Pacific Plate subducts northwestward beneath the Mariana and Philippine plates, facilitating the earthquakes and volcanoes associated with the region. As the Pacific Plate subducts deeper into the earth, rocks of the oceanic plate experience elevated temperature and pressure conditions. As these rocks heat up and lose moisture, the overlying rocks of the Mariana and Philippine plates begin to partially melt due to the moisture that has been driven off the down-going plate and generate magma. Molten rock generated by partial melting migrates upward where it erupts at the surface to blanket older rocks with lava and pyroclastic flows, while large masses of magma remain underground and cool to form coarsely crystalline basement rocks. The islands of Guam (AMME) and Saipan (WAPA) are a classic example of a volcanic island arc, a curved line of volcanoes rising above the ocean floor that are fueled by magma generation associated with subduction (Thornberry-Ehrlich 2012). Much of the surface of both Guam and Saipan is limestone that formed in shallow seas and was uplifted due to up-warping of the overlying plate (Schlanger et al. 1964; Behrens 1976).

Precambrian

Precambrian rocks are not exposed in any of the parks in PACN (see Appendix B for a geologic time scale).

Paleozoic

Paleozoic rocks are not exposed in any of the parks in PACN (see Appendix B for a geologic time scale).

Mesozoic

Mesozoic rocks are not exposed in any of the parks in PACN (see Appendix B for a geologic time scale).

Cenozoic

The geology of the park units of the PACN are entirely composed of Cenozoic-age rocks, primarily volcanic igneous rocks associated with the formation of the islands of Hawai‘i, Guam, and Saipan. Some of the oldest bedrock units occur in WAPA and consist of the Miocene Umatac Formation, Miocene–Pliocene Alifan Limestone, and Eocene–Oligocene Alutom Formation. The oldest rocks underlying NPSA date to the Pliocene and represent the Asaga Formation on Ofu Island. Rocks of Pliocene–Pleistocene age are found in several park units and include the Mariana Limestone (WAPA), East Moloka‘i Volcanics (KALA), and Pago Volcanics (NPSA).

Numerous Pleistocene and Holocene-age units occur in each of the park units of the PACN. On the island of Hawai‘i, numerous lava flows and pyroclastic deposits are mapped in association with the volcanoes Mauna Loa in HAVO (Ka‘ū Basalt, Pāhala Ash) and PUHO (Ka‘ū Basalt), Kīlauea in HAVO (Puna Basalt, Pāhala Ash, Hilina Basalt), Hualālai in KAHO (Hualālai Volcanics), Mauna Kea in PUHE (Hāmākua Volcanics), and Kohala in PUHE (Hāwī Volcanics, Pololū Volcanics). On

the island of Maui, the geology of HALE consists of the Pleistocene Kula Volcanics and Pleistocene–Holocene Hāna Volcanics. The Pleistocene Kalaupapa Volcanics are mapped in KALA and compose the entire northern peninsula of the island of Moloka‘i. On the islands of NPSA, the Pleistocene Lata Formation, Luatele Formation, and Holocene Fiti‘uta Formation occur on Ta‘ū Island; Pleistocene–Holocene non-calcareous sediments are mapped on Ofu Island; and Holocene-age calcareous sand deposits are found on Tutuila Island. The geology of AMME on the island of Guam consists entirely of Holocene marsh deposits, emerged carbonate sands, and artificial fill. Holocene-age surficial beach deposits and alluvium are found in WAPA.

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 for all park units of the PACN were held on March 20–21, 2003.

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 2021, GRI reports have been completed for HALE, HAVO, KAHU, KALA, NPSA, PUHE, PUHO, and WAPA; the AMME report is slated for an FY-2022 publication date. 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 PACN parks follow the selected source maps and include 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. GRI has produced various maps for the PACN parks.

Source Maps

The GRI team does not conduct original geologic mapping. The team digitizes paper maps and compiles and converts digital data to conform to the GRI GIS data model. The GRI GIS data set includes essential elements of the source maps such as map unit descriptions, a correlation chart of units, a map legend, map notes, cross sections, figures, and references. These items are typically included in a master geology document (PDF) for a specific park. The GRI team uses a unique "GMAP ID" value for each geologic source map, and all sources to produce the GRI GIS data sets for the PACN 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 NPSA was compiled using data model version 2.3, which is available at <https://www.nps.gov/articles/gri-geodatabase-model.htm>; the AMME, HALE, HAVO, KAHU, KALA, PUHE, PUHO, and WAPA 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 AMME, HALE, HAVO, KAHO, KALA, NPSA, PUHE, PUHO, or WAPA 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. 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

Described here are the methods employed and definitions adopted during this inventory of geologic type sections located within the administrative boundaries of the parks in the PACN. This report is part of an 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 PACN, 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 which transcend state boundaries. Geologic formations and other units which cross state boundaries may be referenced with different names in each of the states the units are mapped. An example would be the Triassic Chugwater Formation in Wyoming, which is equivalent to the Spearfish Formation in the Black Hills of South Dakota and Wyoming.

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

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

Methodology

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

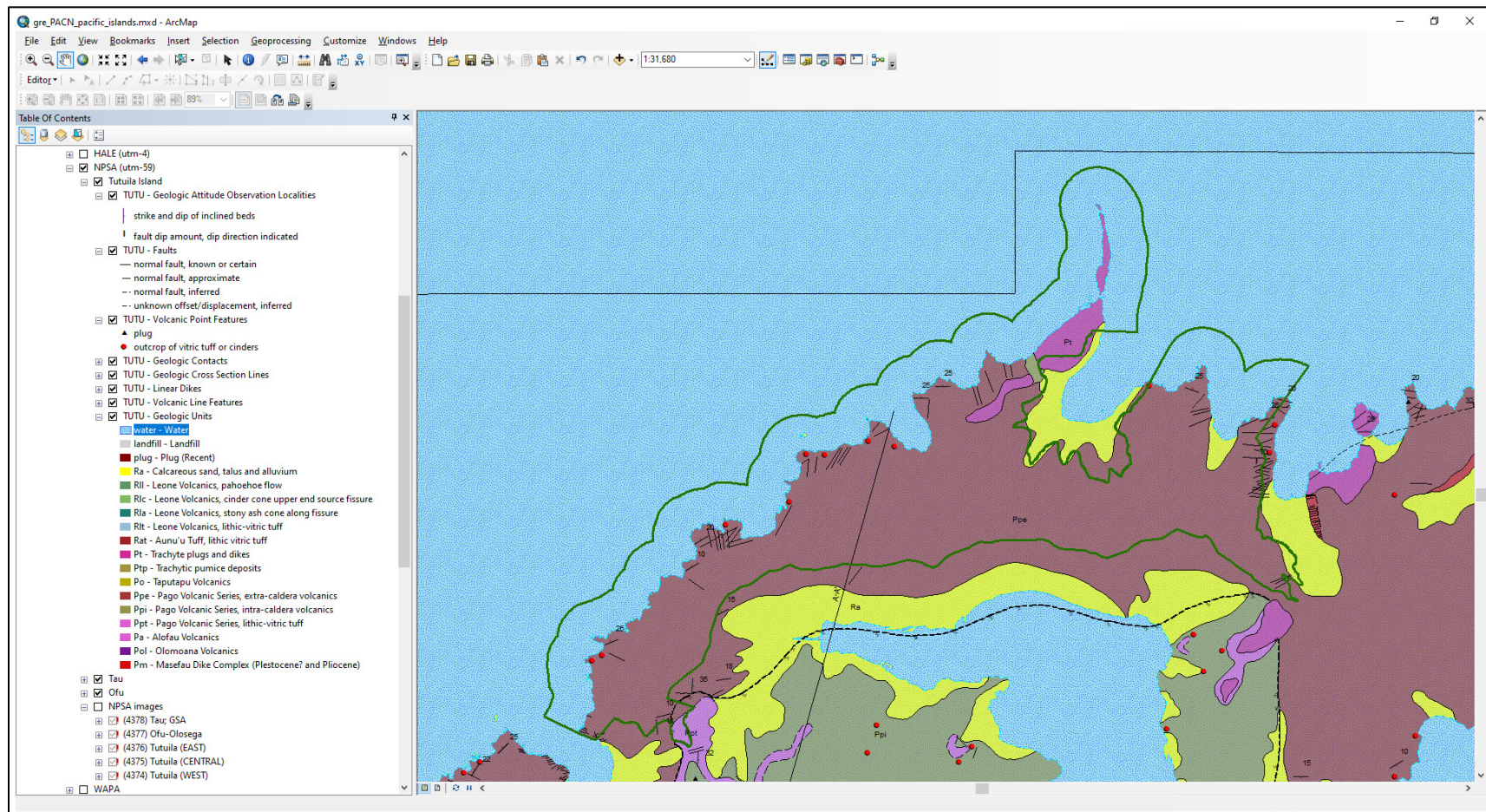


Figure 2. Screenshot of digital geologic map of the National Park of American Samoa (Tutuila Island unit) showing mapped units.

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). Figure 3 below is taken from a search on the East Moloka’i Volcanics.

USGS **AASG**
science for a changing world Association of American State Geologists

USGS HOME CONTACT USGS SEARCH USGS

Home Catalog Lexicon MapView New Mapping Standards Comments

National Geologic Map Database

Geolex — Unit Summary

Geologic Unit: East Molokai

Usage:

East Molokai Volcanics (HI*)
/East Molokai volcanic series [Informal] (HI)

[When referring to the East Molokai volcanic series of Stearns (1946), please use informally. The practice of employing "Series" for lithostratigraphic or lithodemic nomenclature is now regarded as improper (ACSN, 1961, 1970; NACSN, 1983, 2005). The term "Series" is applied formally only to chronostratigraphic units.]

Geologic age:

Tertiary
Pliocene*
Quaternary
Pleistocene*

Type section, locality, area and/or origin of name:

Type section: cliffs south of Kalaupapa Peninsula [Lat. 21 deg. 11 min. 33 sec. N., Long. 156 deg. 59 min. 10 sec. W., Kaunakakai 7.5-min quadrangle] Island of Molokai, HI (Beeson, 1976).
[Spelling of island changed to Moloka'i (Board on Geographic Names, 2003).]

AAPG geologic province:

Molokai

Significant Publications

- Correlation charts
- GNC Archives
- N.A. Stratigraphic Code
- More Resources

For more information, please contact [Nancy Stamm](#), Geologic Names Committee Secretary.
Asterisk (*) indicates published by U.S. Geological Survey authors.
"No current usage" (†) implies that a name has been abandoned or has fallen into disuse. Former usage and, if known, replacement name given in parentheses ().
Slash (/) indicates name does not conform with nomenclatural guidelines (CSN, 1933; ACSN, 1961, 1970; NACSN, 1983, 2005). This may be explained within brackets ([]).

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Figure 3. GEOLEX search result for East Moloka’i 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 km² (36 mi²) township into 36 individual 2.59 km² (1 mi²) sections, and were converted into Google Earth (.kmz file) locations using Earth Point (<https://www.earthpoint.us/TownshipsSearchByDescription.aspx>). They 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 km² (0.0625 mi²). 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.

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 was listed in GEOLEX; and (10) a generic notes field (Figure 4).

AutoSave Off PACN Type Section Inventory Timothy Henderson

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Clipboard Font Alignment Number Styles Cells Editing Analysis

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	A	B	C	D	E	F	G	H	I	J	K	L	M	N
	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
1														
2	alluvium	X										NO	Qa	
3	Hāna Volcanics; lava flows		NO		Type locality: at village of Hana	Stearns and Macdonald 1942			Cenozoic	Pleistocene(?) - Holocene	Haleakala	YES	Qhn6	
4	Hāna Volcanics; Kipahulu Member		YES - HALE	YES		Stearns and Macdonald 1942; Macdonald	Type locality: Kipahulu Valley		Cenozoic	Pleistocene(?)	Haleakala	YES		
5	Hana Volcanics; vent deposits	X							Cenozoic	Quaternary	Haleakala	NO	Qhnv6	
6	Hana Volcanics; lava flows	X							Cenozoic	Quaternary	Haleakala	NO	Qhn5	
7	Hana Volcanics; vent deposits	X							Cenozoic	Quaternary	Haleakala	NO	Qhnv5	
8	Hana Volcanics; lava flows	X							Cenozoic	Quaternary	Haleakala	NO	Qhn4	
9	Hana Volcanics; vent deposits	X							Cenozoic	Quaternary	Haleakala	NO	Qhnv4	
10	Hana Volcanics; lava flows	X							Cenozoic	Quaternary	Haleakala	NO	Qhn3	
11	Hana Volcanics; vent deposits	X							Cenozoic	Quaternary	Haleakala	NO	Qhnv3	
12	Hana Volcanics; lava flows	X							Cenozoic	Quaternary	Haleakala	NO	Qhn2	
13	Hana Volcanics; vent deposits	X							Cenozoic	Quaternary	Haleakala	NO	Qhnv2	
14	Hana Volcanics; lava flows	X							Cenozoic	Quaternary	Haleakala	NO	Qhn1	
15	Hana Volcanics; basanite of 5635-ft cone	X							Cenozoic	Quaternary	Haleakala	NO	Qhnv1	
16	Hana Volcanics; lava flows	X							Cenozoic	Quaternary	Haleakala	NO	Qhn0	
17	Hana Volcanics; vent deposits	X							Cenozoic	Quaternary	Haleakala	NO	Qhnv0	
18	Hana Volcanics; tephra deposits	X							Cenozoic	Quaternary	Haleakala	NO	Qhnt	
19	Hana Volcanics; intrusion	X							Cenozoic	Quaternary	Haleakala	NO	Qhni	
20	Hana Volcanics; explosion crater deposit	X							Cenozoic	Quaternary	Haleakala	NO	Qhne	
21	Kaupō Mud Flow; debris-avalanche deposits		NO		Type locality: mouth of Kaupo Vi	Stearns and Macdonald 1942; Macdonald and Davis 1956			Cenozoic	Pleistocene	Haleakala	YES	Qkamd	
22	Kaupō Mud Flow; conglomerate and sand	X							Cenozoic	Quaternary	Haleakala	NO	Qkamc	
23	Kula Volcanics; lava flows		YES - HALE	YES	Type locality: along Highway 37	Macdonald and Davis 1956; Langenheim	Reference locality: 2) along Highway 37		Cenozoic	Pleistocene	Haleakala	YES	Qkul	
24	Kula Volcanics; ankaramite of Summit Hill	X							Cenozoic	Quaternary	Haleakala	YES	Qkuls	
25	Kula Volcanics; Kumūliahi member [name]		YES - HALE	YES		Macdonald 1978	Type locality: rocks in lower part of		Cenozoic	Pleistocene	Haleakala	YES	Qkuk	now Kur
26	Kula Volcanics; vent deposits	X							Cenozoic	Quaternary	Haleakala	NO	Qkuv	
27	Kula Volcanics; intrusive plugs	X							Cenozoic	Quaternary	Haleakala	NO	Qkui	
28	Honomanū Basalt; lava flows		NO		Type locality: northeast slope of	Stearns and Macdonald 1942			Cenozoic	Pleistocene	Haleakala	YES	Qmnl	
29	Lahaina Volcanics; lava flows		NO		Principal reference locality: Puu	Langenheim and Clague 1987			Cenozoic	Pleistocene	West Maui	YES	Qjhl	
30	Lahaina Volcanics; vent deposits	X							Cenozoic	Quaternary	West Maui	NO	Qjhw	
31	Honolua Volcanics; lava flows		NO		Type locality: village of Honolua	Macdonald and Davis 1956; Langenheim and Clague 1987			Cenozoic	Pleistocene	West Maui	YES	Qul	
32	Honolua Volcanics; bulbous dome of Maunaloa	X							Cenozoic	Quaternary	West Maui	NO	Qoud	

DATA MODEL & URL SOURCE MAPS AMME HALE KALA HAVO-KAHO-PUHE-PUHO NPSA WAPA

Ready 90%

Figure 4. Stratotype inventory spreadsheet of the PACN displaying attributes appropriate for geolocation assessment. The purple highlighted cell represents a geologic unit supplemented to the existing GRI stratigraphic list for HALE.

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 that 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.

American Memorial Park (AMME)

American Memorial Park (AMME) is located on the island of Saipan in the Northern Mariana Islands, approximately 193 km (120 mi) north of Guam (Figure 5). It is owned by the Government of the Commonwealth of the Northern Mariana Islands and managed in conjunction with the NPS as an affiliated area. Established on August 18, 1978, AMME encompasses about 54 hectares (133 acres) and honors those who died during the Marianas Campaign of the Pacific Theater of World War II. The park serves as a living memorial for future generations to better understand the Marianas Campaign, the sacrifices made by American service men and women, and how the taking of the islands (Saipan, Tinian, and Guam) shaped the outcome of World War II. AMME contains recreational facilities, World War II era structures (Japanese pillboxes, fuel storage tanks, bunkers, and a carbide plant storage building), a World War II museum, and a flag monument dedicated to the more than 4,000 U.S. military personnel and local islanders who died in June 1944.

The geology of AMME consists of young, Quaternary-age marsh deposits, emerged carbonate sand deposits, and artificial fill surrounded by sedimentary rocks of the Miocene Tagpochau Limestone (Figure 6). Within AMME is a 12 hectare (30 acre) wetland that contains mudflats, marshes, and mangroves; this remnant habitat is now quite scarce in the Northern Marianas Islands. The wetland area of the park is home to endangered flora and fauna species such as the Nightingale Reed-warbler and is considered an important migratory bird site. Within the western park boundary of AMME is Micro Beach, one of the best white sandy beaches on Saipan that is composed predominantly of carbonate sands. Micro Beach is a significant site to the Carolinian people as it is the place where early settlers landed when they migrated to Saipan and where elders taught traditional navigational skills and burial rituals to their young (National Park Service 2017a).

There are no designated stratotypes identified within the boundaries of AMME. There are 15 identified stratotypes located within 48 km (30 mi) of AMME boundaries, for the Eocene Sankakuyama Formation (type section), Matansa Limestone (type section and type locality), Densinyama Formation (type section and type locality), and Hagman Formation (type section and type locality); Miocene Fina-sisu Formation (type section), Tagpochau Formation (type section and type locality), Machegit Conglomerate Member of the Tagpochau Formation (type section), and Donni Member of the Tagpochau Formation (type section and type locality); Pliocene–Pleistocene Mariana Limestone (reference section); and the Pleistocene Tanapag Limestone (type locality).



Figure 5. Park map of AMME, Saipan (NPS).

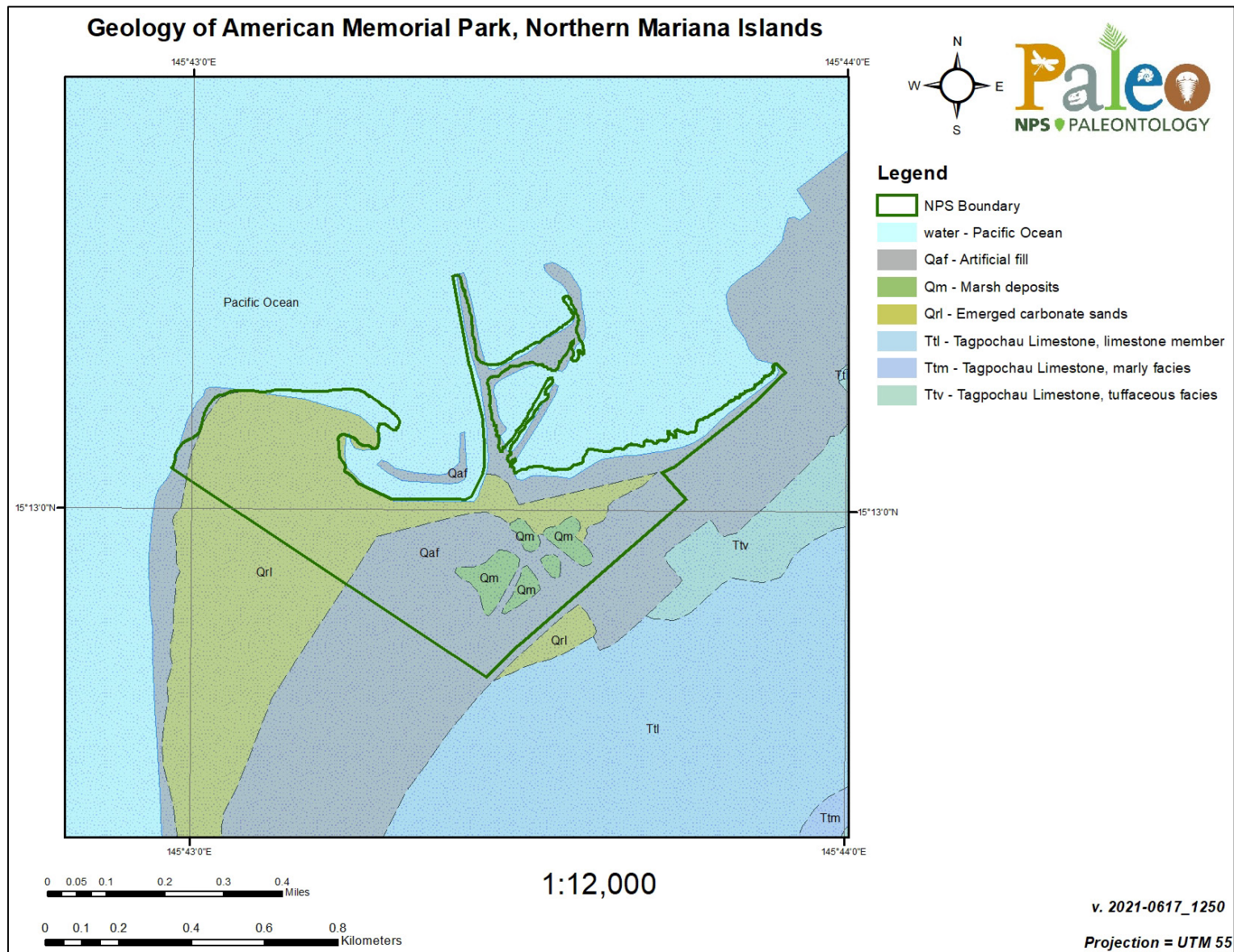


Figure 6. Geologic map of AMME, Saipan.

Haleakalā National Park (HALE)

Haleakalā National Park (HALE) is located on the southeastern side of Maui, the second-largest island in the Hawaiian Island chain (Figure 7). Originally established as a part of Hawai‘i National Park on August 1, 1916, the park was renamed on September 13, 1960, and designated a Biosphere Reserve in 1980 (National Park Service 2016). HALE protects approximately 13,461 hectares (33,265 acres) of wild volcanic landscape with a wide array of fragile and diverse native ecosystems, including rare and endangered plant and animal species found nowhere else on Earth. The park is characterized by starkly contrasting mountain and coastal environments, with a landscape that consists of a relatively stark and rugged crater, summit, gently sloping shield flank areas, and basalt flows that form broad, sloping benches or terraces (Thornberry-Ehrlich 2011a). Within a few kilometers or miles from the coast, the topography within HALE rises dramatically in elevation to 3,055 m (10,023 ft) at the summit of the shield volcano Haleakalā. The northern and eastern slopes of Haleakalā and the rain forests of the upper Kīpahulu Valley are among the richest botanical regions in Hawai‘i and home to some of the world’s rarest birds, plants, and invertebrates.

The geology of HALE predominantly consists of Pleistocene and younger igneous rock units that can be subdivided into lava flows, vent deposits, and tephras of the Kula Volcanics and Hāna Volcanics (Figure 8). Older deposits of the Kula Volcanics can be found throughout the park but are buried by younger volcanic rocks of the Hāna Volcanics in areas such as Kaupō Gap, Ko‘olau Gap, and Kīpahulu Valley. The volcanic landscape of HALE is dominated by Haleakalā, a large shield volcano that measures about 32 km (20 mi) in circumference and makes up three-quarters of Maui. In several places the rim of Haleakalā Crater rises more than 762 m (2,500 ft) above the crater floor. East of the volcano rim, the rain forest valley of Kīpahulu drops thousands of meters or feet towards the coast (Thornberry-Ehrlich 2011a).

HALE contains three identified stratotypes that represent the Pleistocene Kumu‘iliahi Formation, Kula Volcanics, and the Kīpahulu Member of the Hāna Volcanics (Table 2; Figure 9). In addition to the designated stratotypes located within HALE, stratotypes located within 48 km (30 mi) of the park boundaries include the Pleistocene Kanapou Volcanics (type section), Kaupō Mud Flow (type locality), Kula Volcanics (type locality and reference locality), Wailuku Basalt (type locality), Honomanū Basalt (type locality), Honolulu Volcanics (type locality), Lahaina Volcanics (principal reference section), Laina flow of the Lahaina Volcanics (type locality), and Kilea flow of the Lahaina Volcanics (type locality); Pleistocene(?)–Holocene Hāna Volcanics (type locality); and the type localities of the Big Falls, Hanawi, Kapaula, Keanae, Kuhiwa, Makaino, Makapipi, Mossman, Ohia, Paakea, Pauwalu, Piinaau, Waiaaka, Wailuanui, and Waiokamilo flows of the Hāna Volcanics.

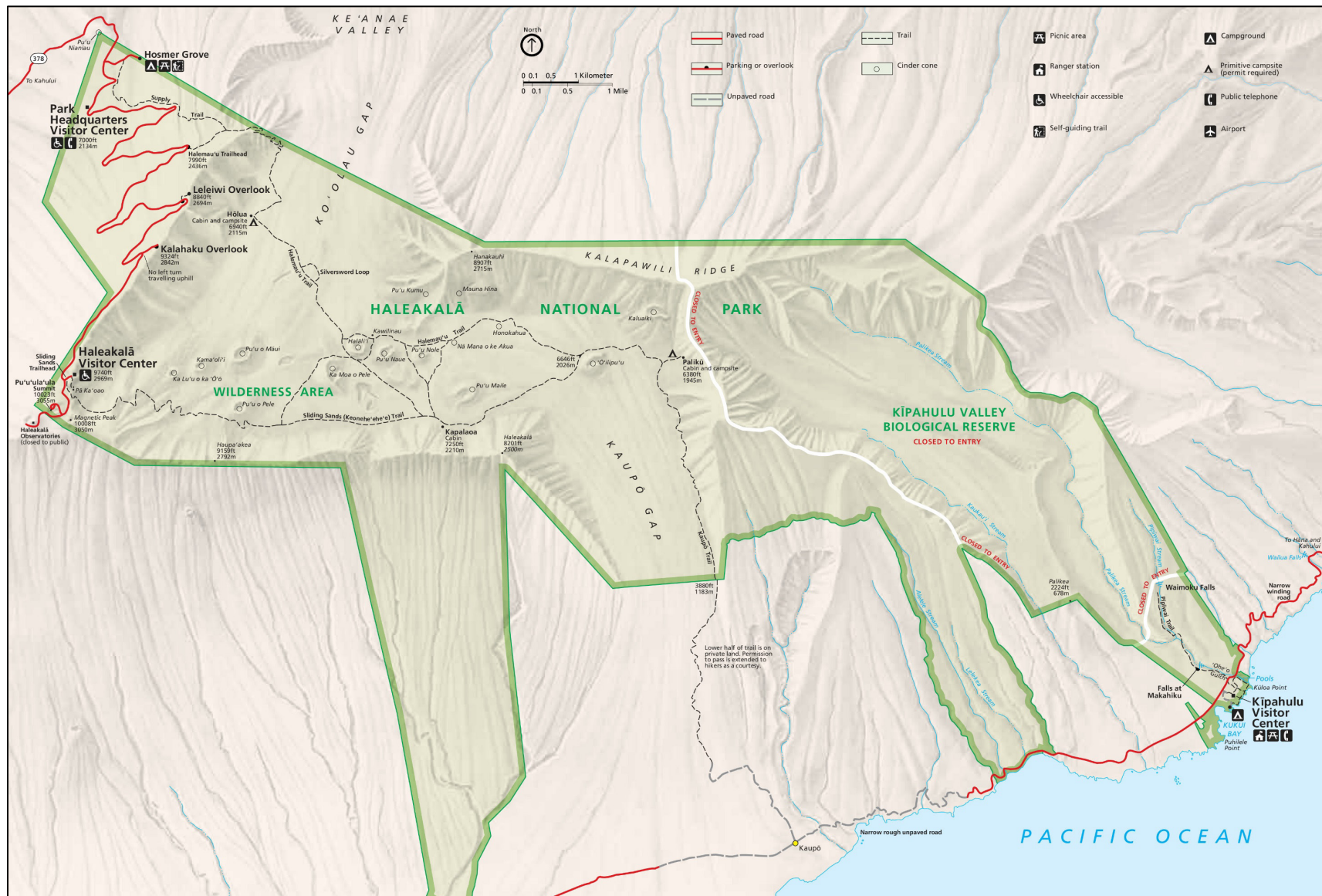


Figure 7. Park map of HALE, Hawai'i (NPS).

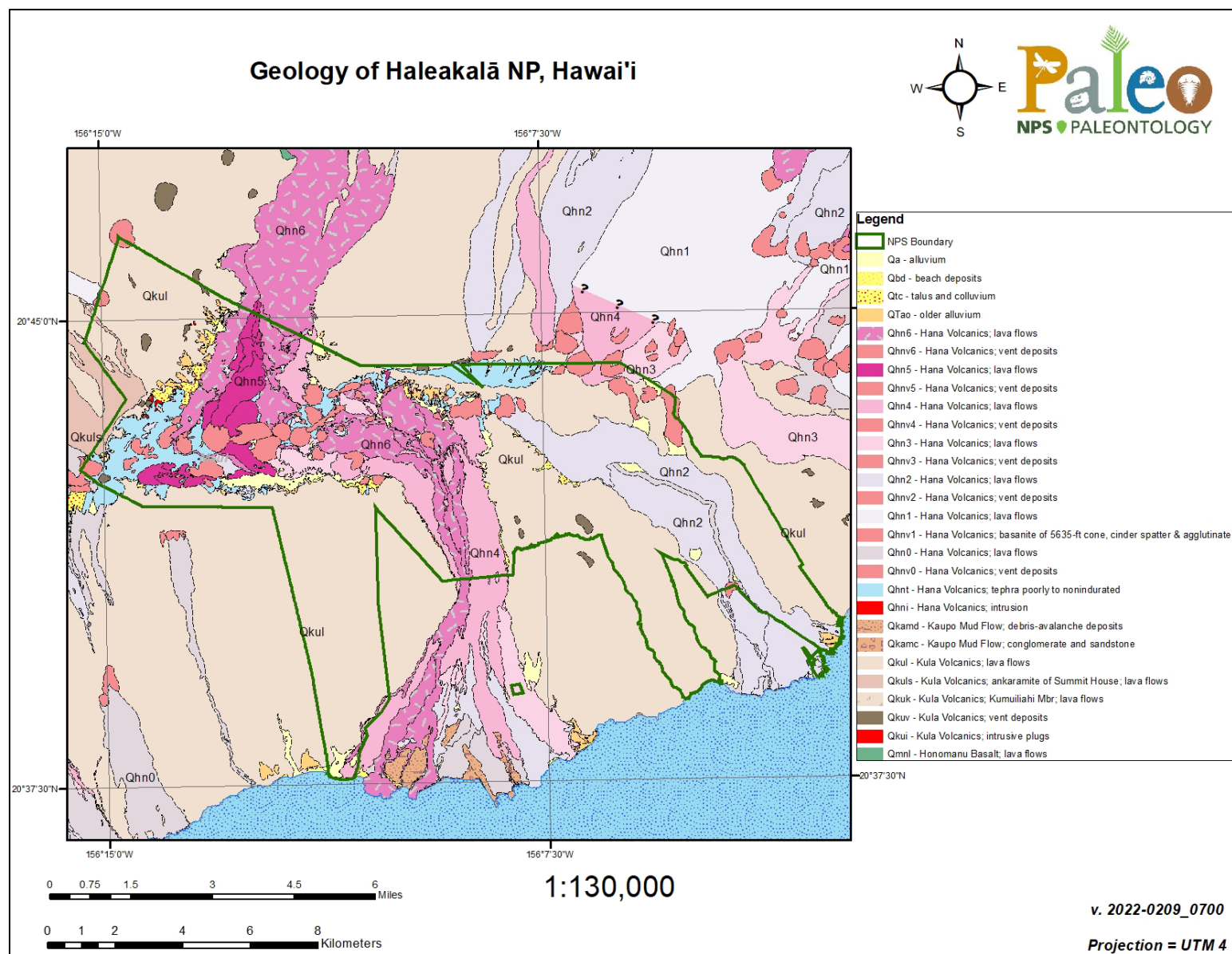


Table 2. List of HALE stratotype units sorted by age with associated reference publications and locations.

Unit Name (GRI map symbol)	Reference	Stratotype Location	Age
Kīpahulu Member, Hāna Volcanics	Macdonald and Davis 1956	Type locality: Kīpahulu Valley [approximately latitude 20°42'03" N., longitude 156°05'25" W., Old Hawaiian Datum, Kīpahulu 7.5' Quadrangle], east end of island of Maui, HI.	Pleistocene(?)
Kula Volcanics (Qkul, Qkuls, Qkuk, Qkuv, Qkui)	Langenheim and Clague 1987	Reference locality: along Halemau'u Trail in Haleakalā Crater area, island of Maui, HI.	Pleistocene
Kumu'iliahi Formation (Qkuk)	Macdonald 1978	Type locality: rocks in lower part of wall of Haleakalā north and northeast of Kumu'iliahi Peak [approximately latitude 20°42'16" N., longitude 156°12' 09" W., Old Hawaiian Datum, Kaupō 7.5' Quadrangle], island of Maui, HI.	Pleistocene

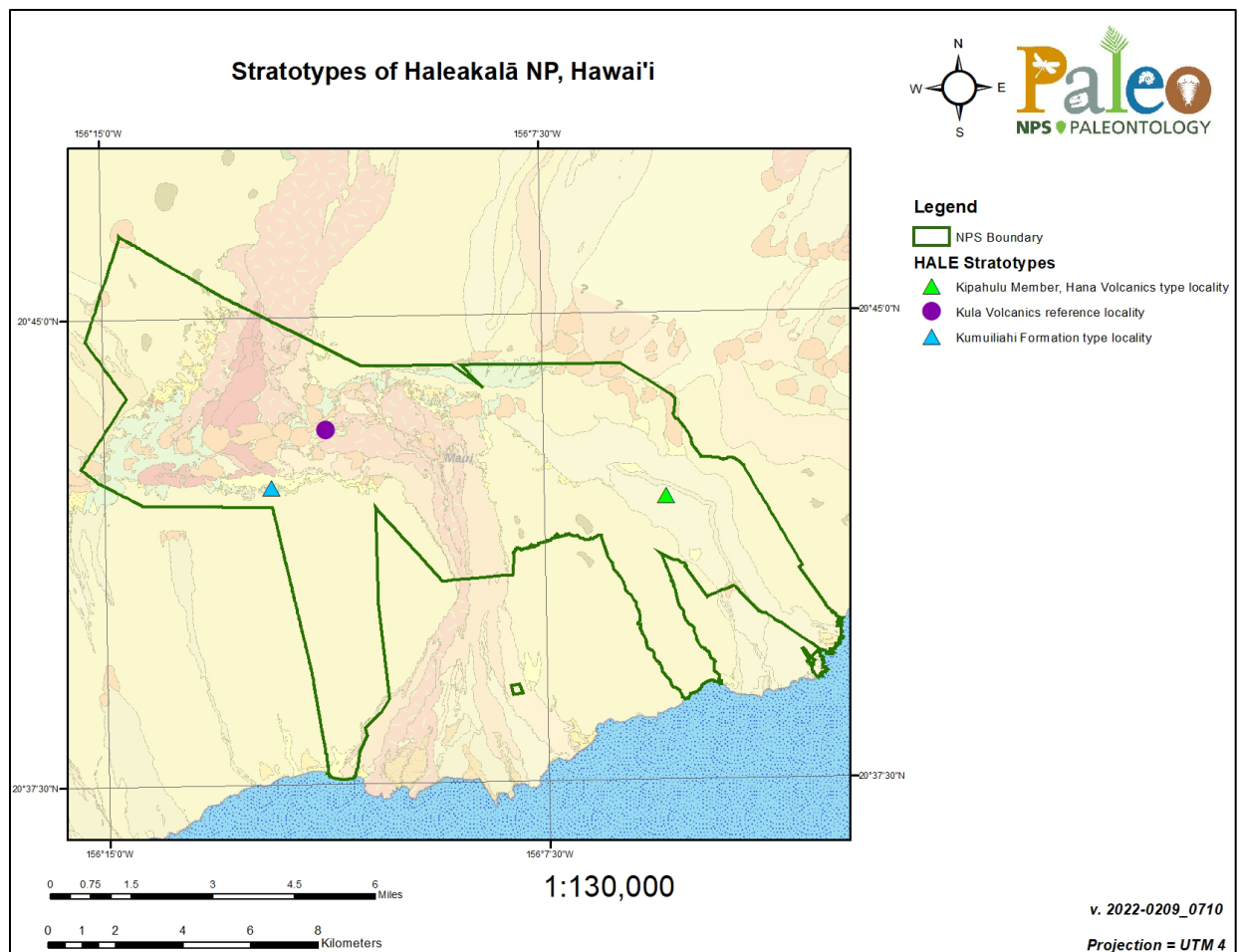


Figure 9. Modified geologic map of HALE showing stratotype locations. The transparency of the geologic units layer has been increased.

Kumu‘iliahi Formation

The Pleistocene Kumu‘iliahi Formation was named by Macdonald (1978) after its type locality exposures in the base of the south wall of Haleakalā Crater north and northeast of Kumu‘iliahi Peak (Table 2; Figure 9). Exposures of the formation are geospatially limited to the type locality and a small knob at the east edge of Ko‘olau Gap. The Kumu‘iliahi Formation consists of alkalic olivine basalt pāhoehoe and ‘a‘ā lava flows that are thin-bedded and commonly contain white phenocrysts (large mineral grains) of plagioclase feldspar up to 8 mm (0.3 in) long and basaltic hawaiiite (Macdonald 1978). Type locality exposures have an approximate maximum thickness of 73 m (240 ft). At the type locality, the formation is separated from overlying rocks of the Kula Formation by an angular unconformity and the lower contact is not exposed (Macdonald 1978).

Kula Volcanics

The Pleistocene Kula Volcanics were originally referred to as the Kula Volcanic Series by Stearns and Macdonald (1942) before Langenheim and Clague (1987) renamed the unit to better reflect its varied lithology. Rocks of the Kula Volcanics were named for the settlement of Kula (now referred to as Waiakoa) where exposures occur along the roads leading to the Kula Hospital on the west slope of the Haleakalā Crater (Stearns and Macdonald 1942). A reference locality for the Kula Volcanics is located along Halemāu‘u Trail in the Haleakalā Crater area (Table 2; Figures 9 and 10; Langenheim and Clague 1987). At the reference locality, a measured section near the head of Ke‘anae Valley is 320 m (1,050 ft) thick and consists of hawaiiite, alkali olivine basalt, and picrite basalt with phenocrysts of olivine and augite (Stearns and Macdonald 1942; Macdonald 1978). The Kula Volcanics conformably overlie the Honomanū Basalt and unconformably underlie rocks of the Hāna Volcanics.

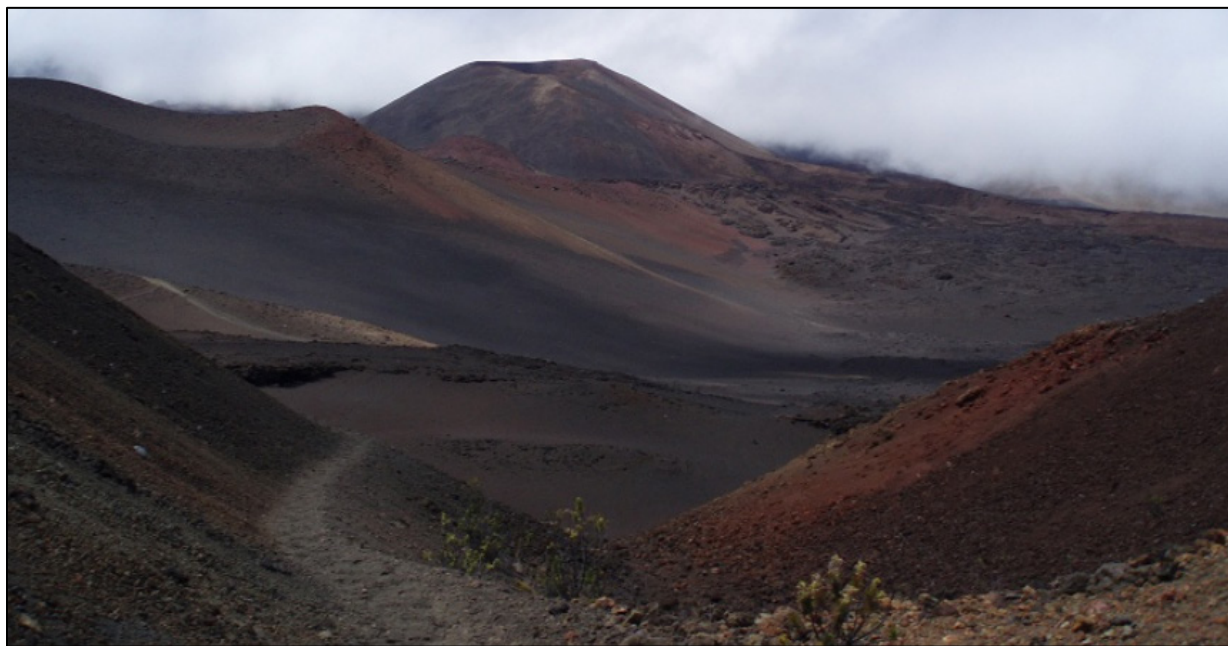


Figure 10. Cinder cones and volcanic deposits along the Halemāu‘u Trail, reference locality for the Kula Volcanics (NPS).

Kīpahulu Member, Hāna Volcanics

The Pleistocene Kīpahulu Member of the Hāna Volcanics was named by Stearns and Macdonald (1942) for a series of lava flows on the west side of Kīpahulu Valley on the eastern end of the island of Maui. Macdonald and Davis (1956) raised the unit in rank to the Kīpahulu Formation and assigned a type locality in Kīpahulu Valley [latitude 20°42'03" N., longitude 156°05'25" W., Old Hawaiian Datum, Kīpahulu 7.5' Quadrangle] (Table 2; Figures 9 and 11). A subsequent publication by Macdonald and Abbot (1970) reduced the rank of the Kīpahulu to a member of the Hāna Volcanics. Type locality exposures of the Kīpahulu Member may exceed 457 m (1,500 ft) thick and are composed of fine-grained 'a'ā flows consisting of alkalic basalt and basanite with rare occurrences of ankaramite and hawaiite (Stearns and Macdonald 1942; Langenheim and Clague 1987). Some lava flows exhibit columnar jointing and are accompanied by cinder cones and vitric ash (Stearns and Macdonald 1942). Lava flows of the Kīpahulu Member are unconformably underlain by older flows of the Hāna Volcanics and are unconformably overlain by Quaternary alluvium at the mouth of Kīpahulu Valley (Stearns and Macdonald 1942; Langenheim and Clague 1987).

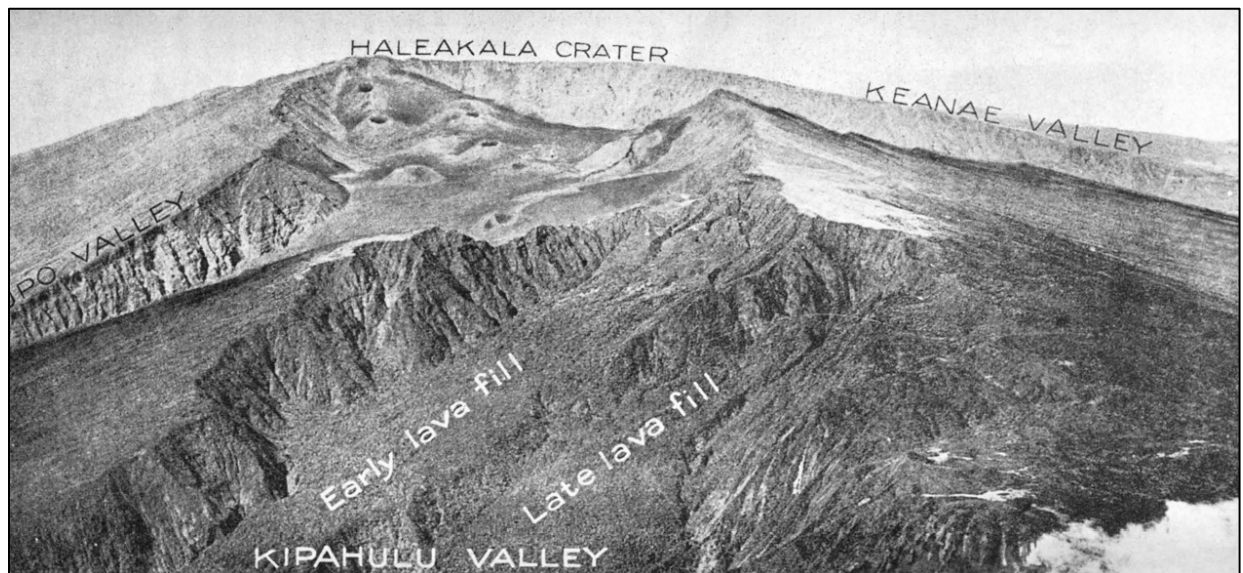


Figure 11. View looking west across Kīpahulu Valley showing type locality exposures of the Kīpahulu Member of the Hāna Volcanics. Type locality exposures consist of a terrace of early lava fills (Kīpahulu Member) bordered by valley fill of later lava flows of the Hāna Volcanics. The summit depression of Haleakalā is in the background. Plate 13 in Stearns (1946).

Hawai‘i Volcanoes National Park (HAVO)

Hawai‘i Volcanoes National Park (HAVO) is located on the southern end of the island of Hawai‘i, the southernmost and largest island of the Hawaiian Archipelago (Figure 12). Originally established as part of Hawai‘i National Park on August 1, 1916, the park was renamed on September 22, 1961, and designated a Biosphere Reserve in 1980 as well as a World Heritage Site in 1987 (National Park Service 2016). HAVO encompasses approximately 130,887 hectares (323,431 acres) of public land that includes unique geologic, biologic, and cultural landscapes. The park was established to protect, study, and provide access to Kīlauea and Mauna Loa, two of the world’s most active volcanoes, and preserve native Hawaiian ecosystems and the traditional Hawaiian culture connected to these landscapes (National Park Service 2017b). The summit of Mauna Loa, active volcanism, rare and endangered biological communities, and prehistoric sites are among some of the special features within HAVO.

The geology of HAVO is dominated by young (<2,000 years old) igneous rock units that include lava flows and vent deposits that originated from the active volcanic centers of Kīlauea and Mauna Loa (Figures 13 and 14). Dynamic geologic processes such as volcanism, mass wasting (landslide or slope movement), and seismicity are constantly reshaping the terrain of HAVO over a relatively short time scale. The park landscape consists of relatively barren, fresh lava flow areas, Kīlauea, the gentle slopes of Mauna Loa, and coastal areas where basalt flows form broad slopes and terraces separating sheltered coves along the shore (Thornberry-Ehrlich 2009). Beach areas within HAVO contain intertidal- to supratidal accumulations of black basaltic sand, green olivine sand, and coralline sediments derived from storms and marine highstands, as well as eolian (wind-driven) sand deposits. Natural features at HAVO include stark volcanic flow fields, ephemeral streams cutting narrow gorges, fresh volcanic deposits, cinder cones, numerous small craters, broad vegetated slopes, and a variety of unique and native Hawaiian ecosystems (Thornberry-Ehrlich 2009).

HAVO contains 28 identified stratotypes that are subdivided into ten type sections, three type localities, one principal reference section, and 14 reference sections (Table 3; Figures 15–18). In addition to the designated stratotypes located within HAVO, stratotypes located within 48 km (30 mi) of the park boundaries include the Pleistocene Kahuku Basalt (type locality), Nīnole Basalt (type section), Waihū Glacial Member of the Hāmākua Volcanics (type locality), Pōhakuloa Glacial Member of the Hāmākua Volcanics (type locality and reference section), Hopukani Springs Volcanic Member of the Hāmākua Volcanics (type section), Liloe Spring Volcanic Member of the Hāmākua Volcanics (type section), and Mākanaka Glacial Member of the Laupāhoehoe Volcanics (type locality); and the Pleistocene–Holocene Hualālai Volcanics (type locality), Wa‘awa‘a Trachyte Member of the Hualālai Volcanics (type locality), Kona Ash beds of the Hualālai Volcanics (type locality), and the Waikahalulu Volcanic Member of the Laupāhoehoe Volcanics (type section).

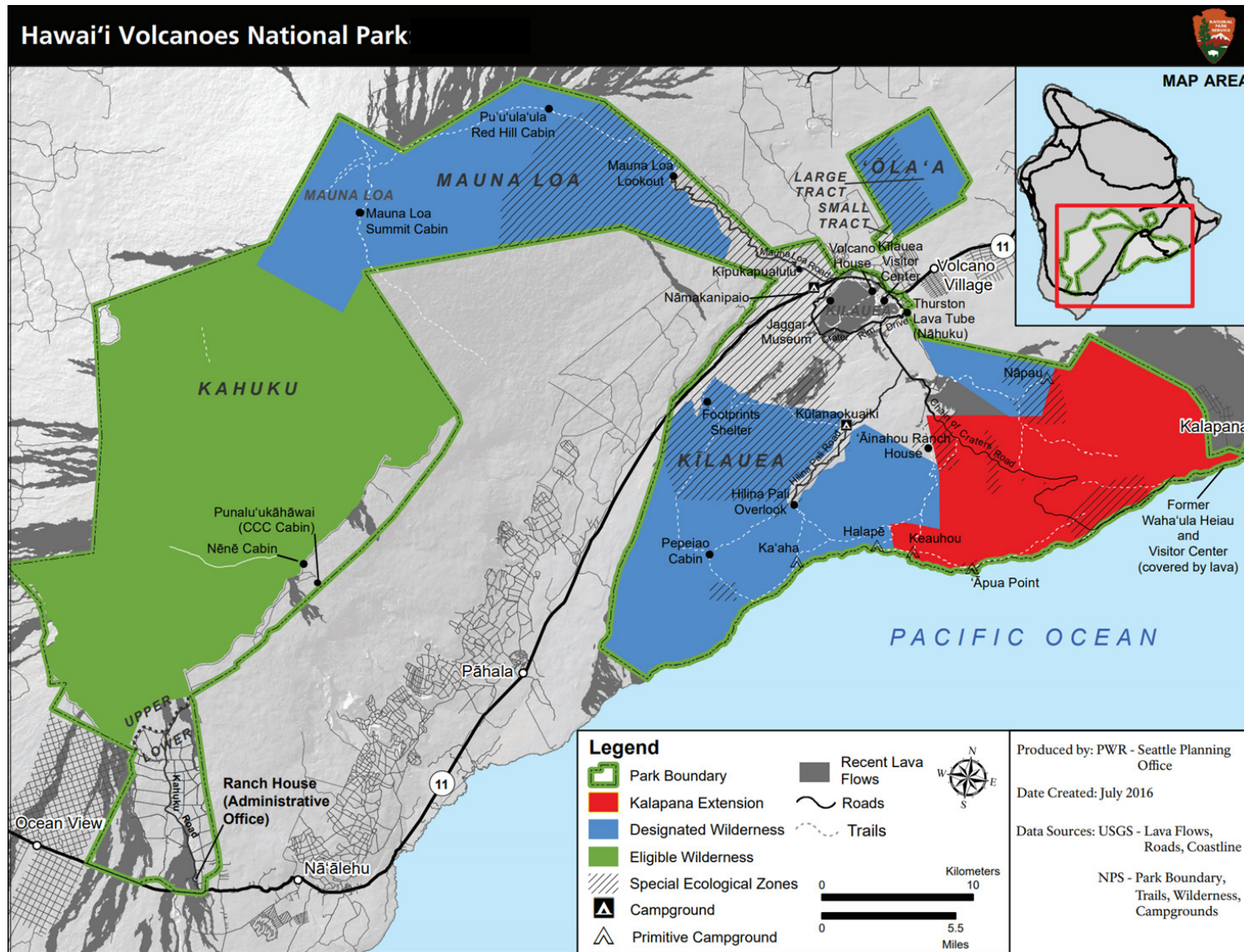


Figure 12. Park map of HAVO, Hawai'i (NPS).

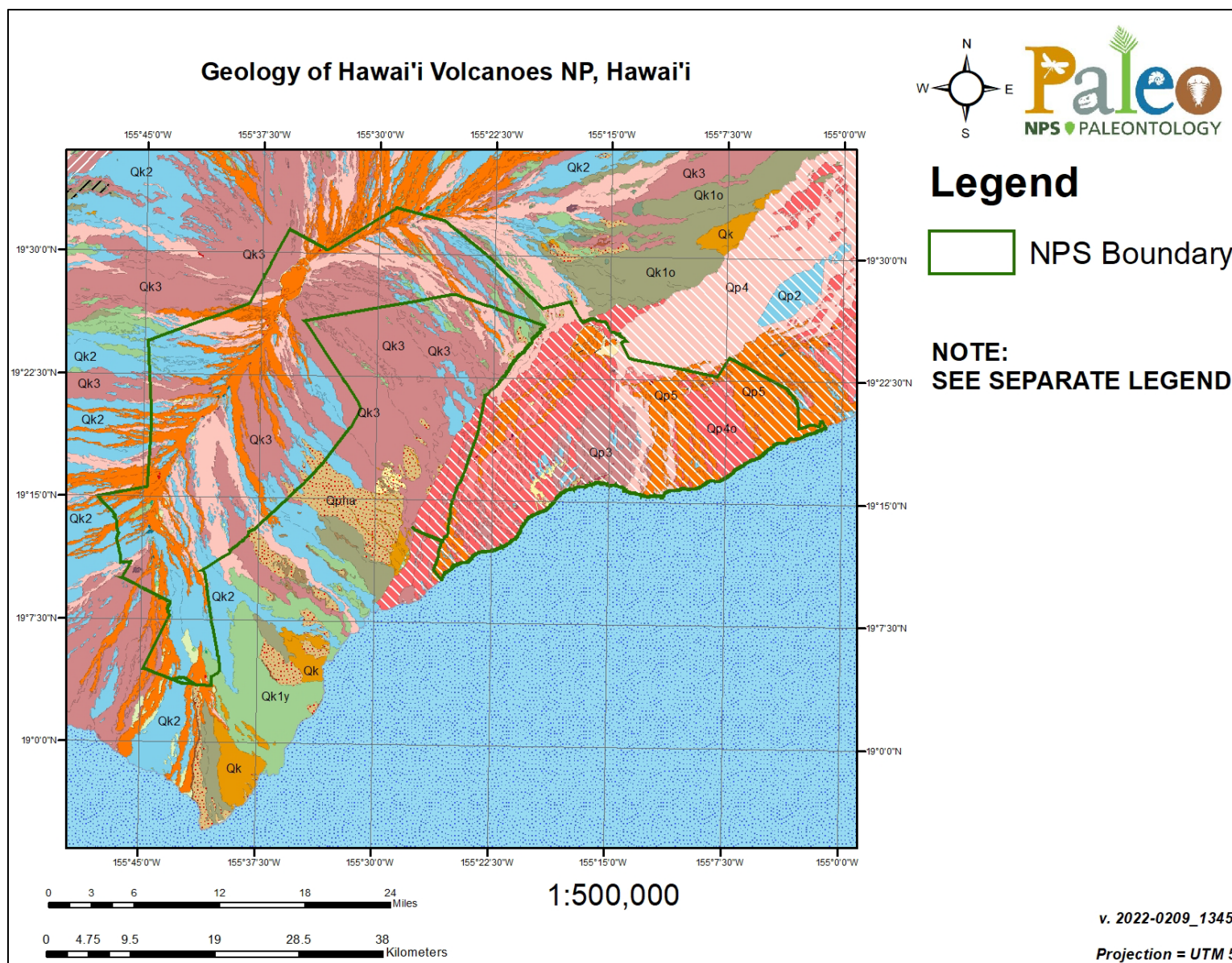


Figure 13. Geologic map of HAVO, Hawai'i; see Figure 14 for legend.

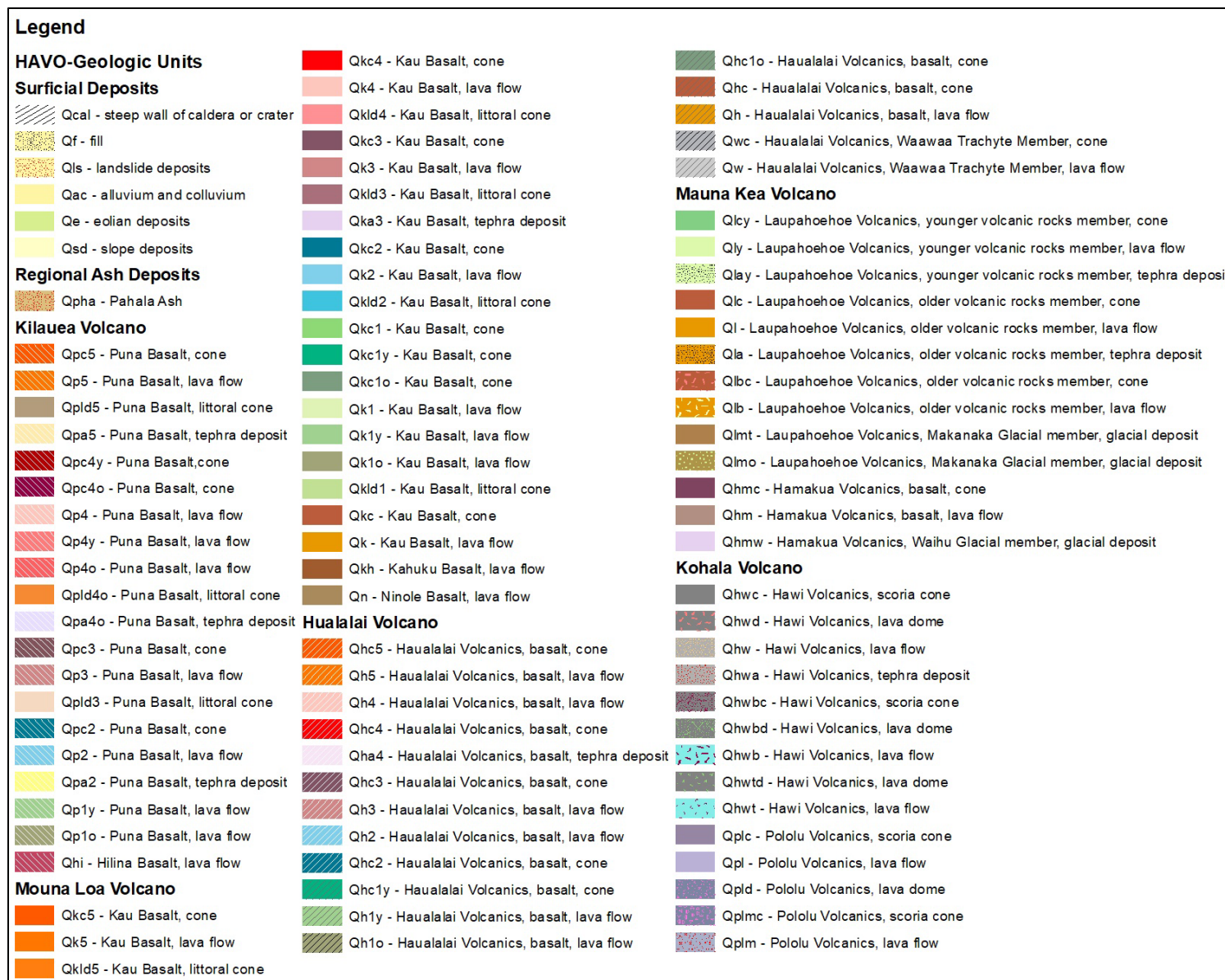


Figure 14. Geologic map legend of HAVO, Hawai'i.

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

Unit Name (GRI map symbol)	Reference	Stratotype Location	Age
Keanakāko'i Ash Member, Puna Basalt	Langenheim and Clague 1987	Type locality: southwest of Keanakāko'i Crater, island of Hawai'i, HI.	Holocene
Uēkahuna Ash	Stone 1926; Easton 1987; Fiske et al. 2009	Type section: at Uēkahuna Bluff, Kaluapele, Kīlauea Crater 7.5' Quadrangle, island of Hawai'i, HI. Type section (revised; mid-Bluff section): exposed in walls of hand-dug 3.12-m (10.24 ft) pit dug at top of talus apron and at base of steep caldera wall, ~30 m (98 ft) above present caldera floor [latitude 19.42247° N., longitude 155.28775° W.], island of Hawai'i, HI. *DESTROYED BY ROCK FALLS IN 2018 AND NOW BURIED. Type locality: west wall of Kaluapele at base of Uēkahuna Bluff northeast of fault terraces, [Kīlauea 7.5' Quadrangle], island of Hawai'i, HI. Reference section: at Nanahu Arroyo, Hilina Pali, 0.5 km (0.3 mi) northeast of end of Hilina Pali Trail [latitude 19°18'15" N., longitude 155°18'34" W., Old Hawaiian Datum, Ka'ū Desert 7.5' Quadrangle], island of Hawai'i, HI.	Holocene
Kulanaokuaiki Tephra Member, Uēkahuna Ash	Fiske et al. 2009	Type section: beneath the edge of the Old Kālu'e lava flow on the upper south flank of Kīlauea Volcano, ~600 m (1,970 ft) south of Kulanaokuaiki Pali, a north-facing fault scarp 7–8 km (4–5 mi) south of Kīlauea's summit, island of Hawai'i, HI.	Holocene
Puna Basalt (Qp4o, Qp3, Qpc5)	Stearns and Macdonald 1946; Easton 1987	Type section: Uēkahuna Bluff, Kīlauea Crater [latitude 19°25'43" N., longitude 155°17'01" W., Old Hawaiian Datum, Kīlauea Crater 7.5' Quadrangle], island of Hawai'i, HI. Type locality: walls of Kīlauea caldera, island of Hawai'i, HI. Reference sections: 1. Keanabihopa (600–640 m or 1,970–2,100 ft elevation) [latitude 19°17'19" N., longitude 155°18'25" W., Old Hawaiian Datum, Ka'ū Desert 7.5' Quadrangle]; 2. Nanahu Arroyo, Hilina Pali, 0.5 km (0.3 mi) northeast of end of Hilina Pali Road [latitude 19°18'15" N., longitude 155°18'34" W., Old Hawaiian Datum, Ka'ū Desert 7.5' Quadrangle]; 3. Kīlauea Iki crater, summit lava [Volcano 7.5' Quadrangle]; 4. East Rift Zone lava, Makaopuhi crater [Makaopuhi Crater 7.5' Quadrangle]; 5. East Rift Zone lava, Nāpau crater [Volcano 7.5' Quadrangle].	Holocene
Ka'ū Basalt (Qk5)	Stearns and Macdonald 1946	Type section: west wall of Moku'āweoweo Caldera [approximately latitude 19°28'46" N., 155°35'30" W., Old Hawaiian Datum, Mauna Loa 7.5' Quadrangle], Mauna Loa Volcano, island of Hawai'i, HI.	Pleistocene –Holocene

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

Unit Name (GRI map symbol)	Reference	Stratotype Location	Age
Pāhala Ash (Qpha)	Easton 1987	Principal reference section: Mo'olelo, Hilina Pali [latitude 19°17'00" N., longitude 155°19'00" W., Old Hawaiian Datum, Ka'ū Desert 7.5' Quadrangle]. Reference sections: 1. Pu'ukapukapu [latitude 19°16'35" N., longitude 155°15'23" W., Old Hawaiian Datum, Ka'ū Desert 7.5' Quadrangle]; 2. Pu'ukaone [latitude 19°16'15" N., longitude 155°16'56" W., Old Hawaiian Datum, Ka'ū Desert 7.5' Quadrangle].	Pleistocene
Hilina Basalt (Qhi)	Stearns and Macdonald 1946; Easton 1987	Type section: exposures 1.6 km (1 mi) southwest of end of Hilina Pali Road on southern slope of Kīlauea Volcano [latitude 19°17'00" W., longitude 155°18'45" W., Old Hawaiian Datum, Ka'ū Desert 7.5' Quadrangle], island of Hawai'i, HI. Type locality: at Hilina Pali on the southern slope of Kīlauea Volcano, island of Hawai'i, HI. Reference sections: 1. Keanabihopa, from base of pali (370 m or 1,210 ft elevation) to top (640 m or 2,100 ft elevation) [latitude 19°17'19" N., longitude 155°18'25" W., Old Hawaiian Datum, Ka'ū Desert 7.5' Quadrangle]. Exposure located 250 m (820 ft) south-southwest of end of Hilina Pali Road; 2. Pu'ukapukapu, from base of pali (100 m or 330 ft elevation) to top (300 m or 980 ft elevation) [latitude 19°16'45" N., longitude 155°15'35" W., Old Hawaiian Datum, Ka'ū Desert 7.5' Quadrangle].	Pleistocene
Mo'o Ash Member, Hilina Basalt	Easton 1987	Type section: Keanabihopa, (570 m or 1,870 ft elevation) south slope of Kīlauea Volcano [latitude 19°17'19" N., longitude 155°18'25" W., Old Hawaiian Datum, Ka'ū Desert 7.5' Quadrangle], island of Hawai'i, HI. Reference section: Pu'ukapukapu, from base of pali (100 m or 330 ft elevation) to top (300 m or 980 ft elevation) [latitude 19°16'45" N., longitude 155°15'35" W., Old Hawaiian Datum, Ka'ū Desert 7.5' Quadrangle].	Pleistocene
Pōhāka'a Ash Member, Hilina Basalt	Easton 1987	Type section: Pōhāka'a Arroyo (~425–450 m or 1,390–1,480 ft elevation) south slope of Kīlauea Volcano [latitude 19°16'40" N., longitude 155°20'00" W., Old Hawaiian Datum, Ka'ū Desert 7.5' Quadrangle], island of Hawai'i, HI. Reference section: Pu'ukapukapu, from base of pali (100 m or 330 ft elevation) to top (300 m or 980 ft elevation) [latitude 19°16'45" N., longitude 155°15'35" W., Old Hawaiian Datum, Ka'ū Desert 7.5' Quadrangle].	Pleistocene

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

Unit Name (GRI map symbol)	Reference	Stratotype Location	Age
Kahele Ash Member, Hilina Basalt	Easton 1987	Type section: Pōhāka'a Arroyo (~470 m or 1,540 ft elevation) south slope of Kīlauea Volcano [latitude 19°16'40" N., longitude 155°20'00" W., Old Hawaiian Datum, Ka'ū Desert 7.5' Quadrangle], island of Hawai'i, HI. Reference section: Pu'ukapukapu, from base of pali (100 m or 330 ft elevation) to top (300 m or 980 ft elevation) [latitude 19°16'45" N., longitude 155°15'35" W., Old Hawaiian Datum, Ka'ū Desert 7.5' Quadrangle].	Pleistocene
Halapē Ash Member, Hilina Basalt	Easton 1987	Type section: Keanabihopa, (395 m or 1,300 ft elevation) on south slope of Kīlauea Volcano [latitude 19°17'19" N., longitude 155°18'25" W., Old Hawaiian Datum, Ka'ū Desert 7.5' Quadrangle], island of Hawai'i, HI. Reference section: Pu'ukapukapu, from base of pali (100 m or 330 ft elevation) to top (300 m or 980 ft elevation) [latitude 19°16'45" N., longitude 155°15'35" W., Old Hawaiian Datum, Ka'ū Desert 7.5' Quadrangle].	Pleistocene

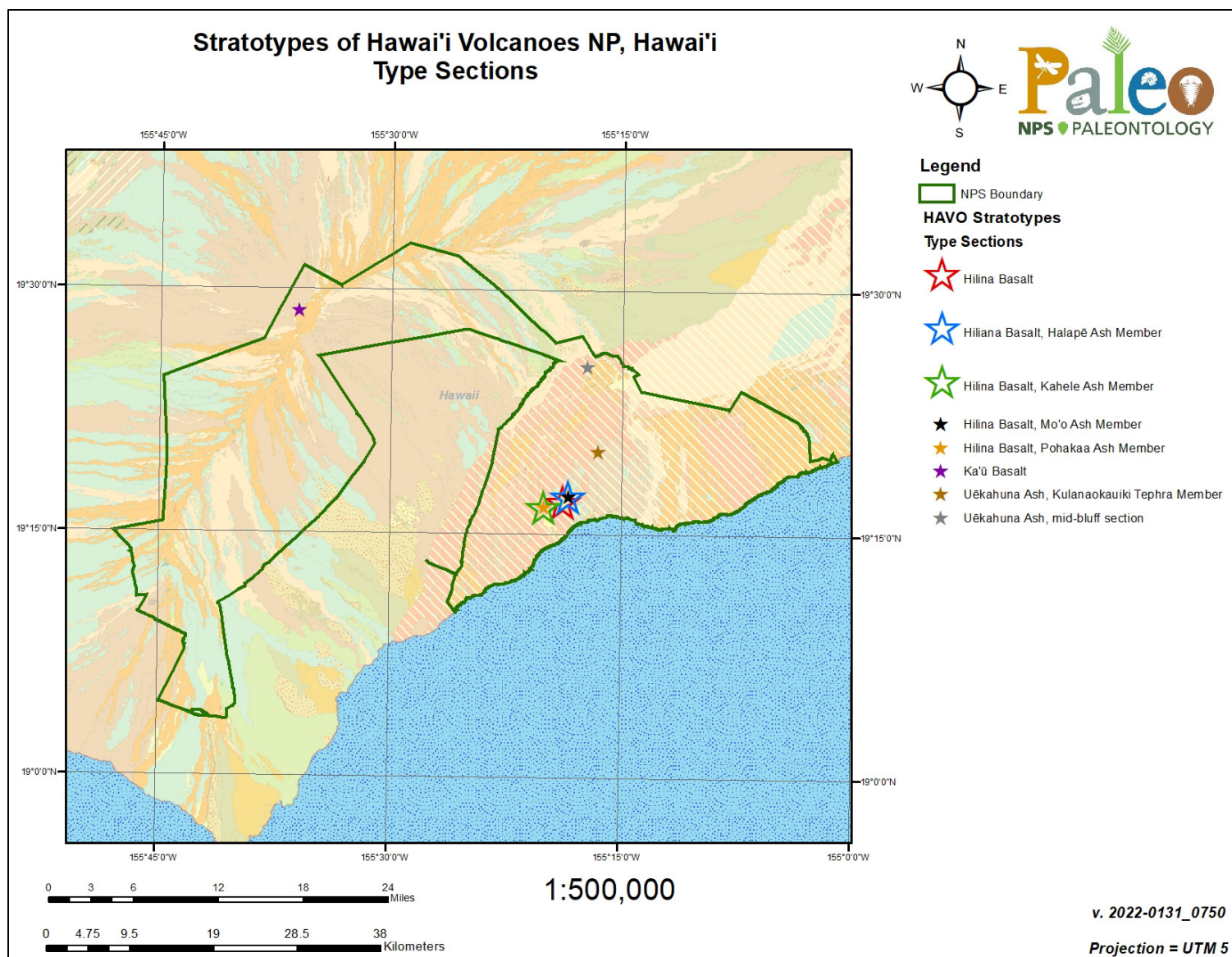


Figure 15. Modified geologic map of HAVO showing type section locations. The transparency of the geologic units layer has been increased.

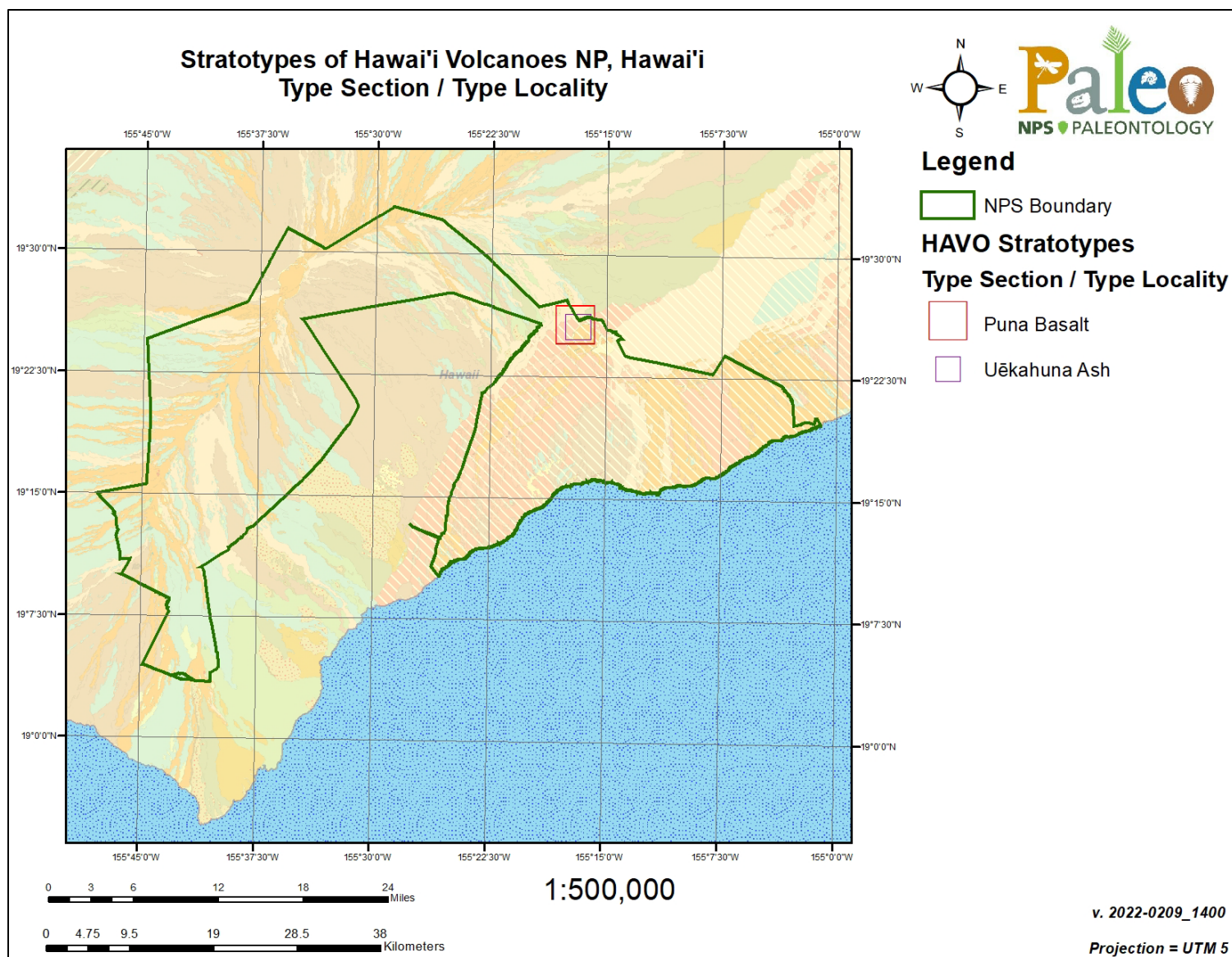


Figure 16. Modified geologic map of HAVO showing type section and type locality locations. The transparency of the geologic units layer has been increased.

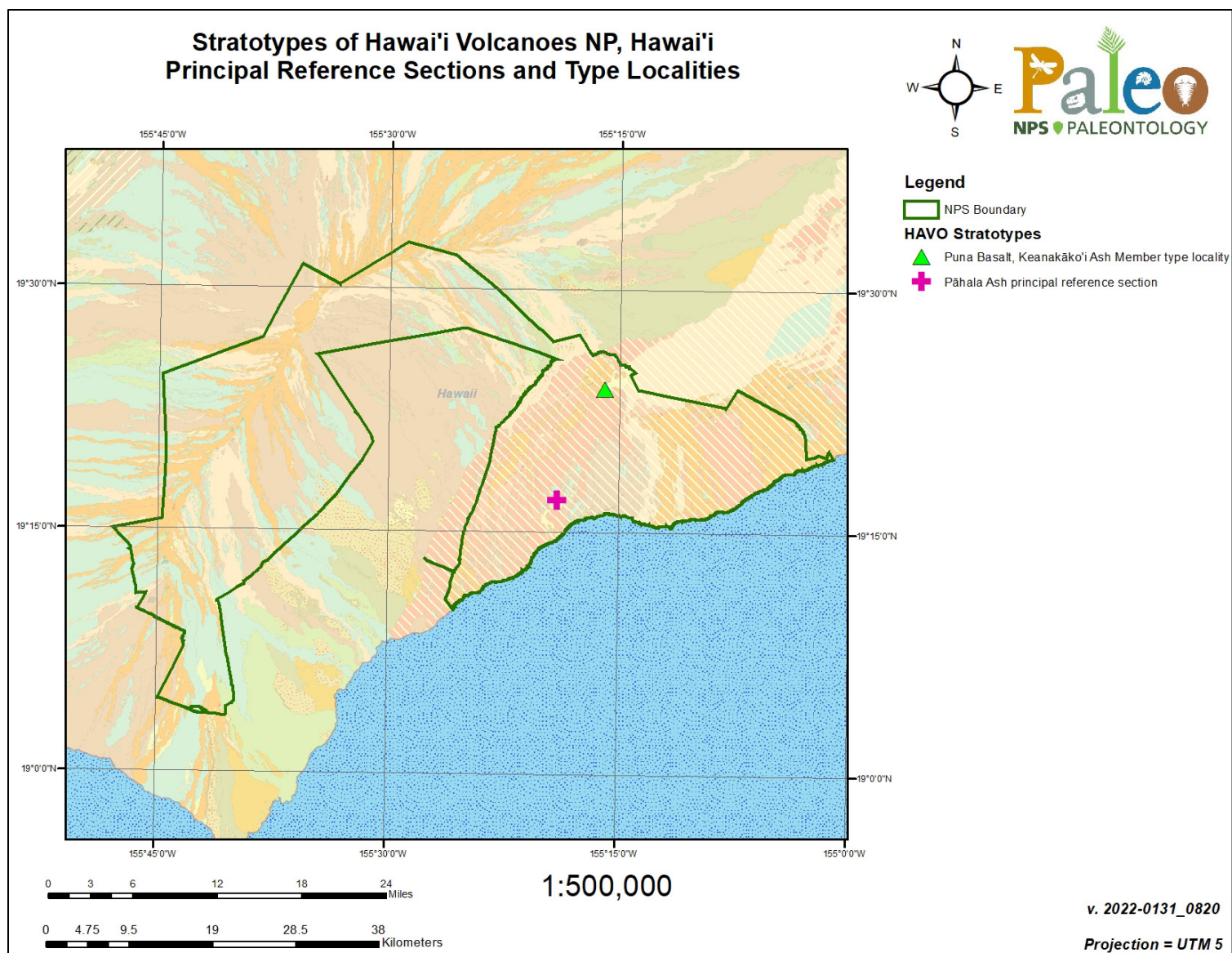


Figure 17. Modified geologic map of HAVO showing principal reference section and type locality locations. The transparency of the geologic units layer has been increased.

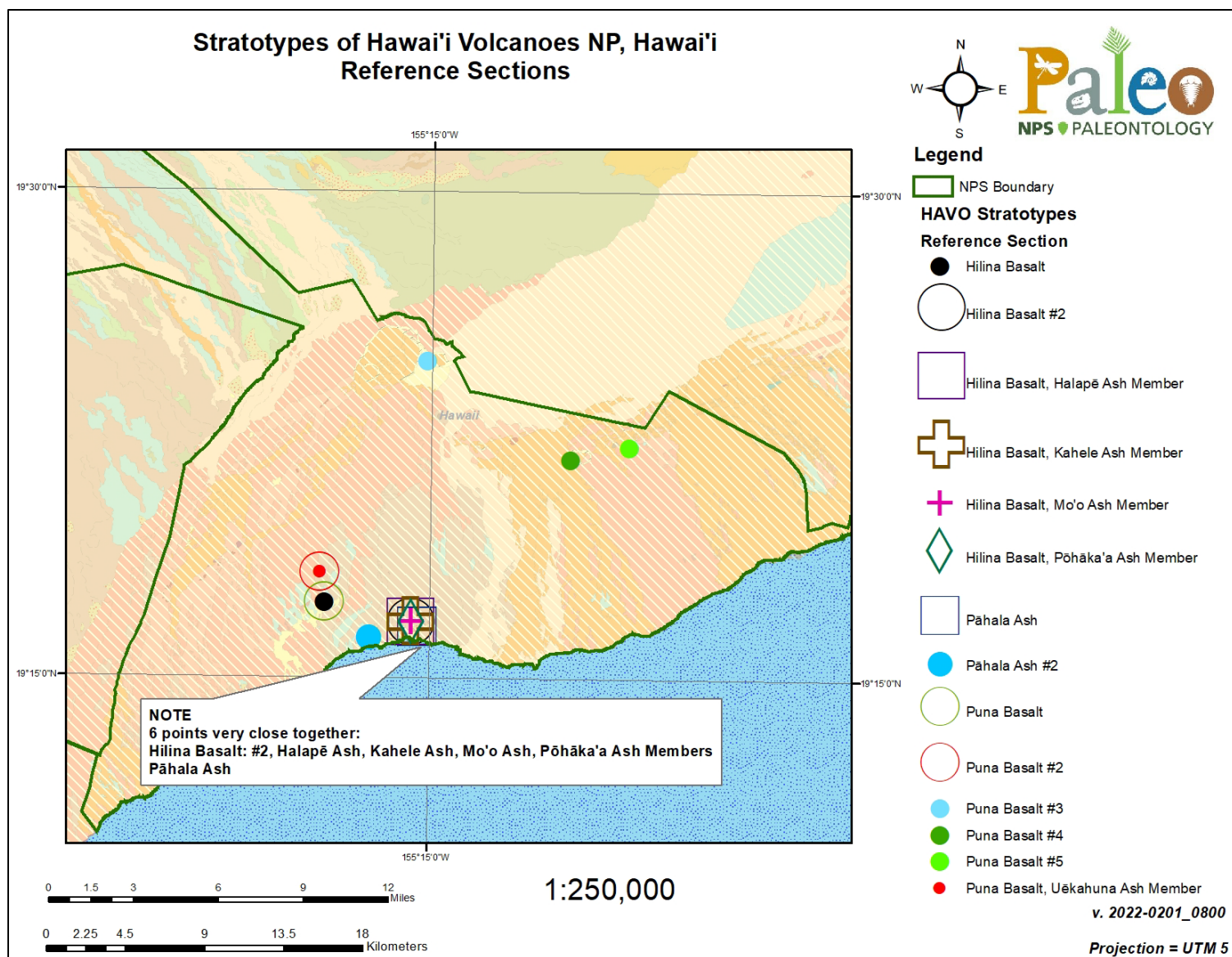


Figure 18. Modified geologic map of HAVO showing reference section locations. The transparency of the geologic units layer has been increased.

Hilina Basalt

The Pleistocene Hilina Basalt was originally referred to as the Hilina Volcanic Series by Stearns and Macdonald (1946) before it was revised by Easton (1987) and Langenheim and Clague (1987) to denote lithology and volcanic origin. The unit is named after its type locality exposures along the Hilina fault system on the southern slope of Kīlauea (Table 3; Figures 15, 19, and 20; Stearns and Macdonald 1946). Type locality exposures measure approximately 300 m (1,000 ft) thick and consist of thin-bedded olivine basalt ‘a‘ā and pāhoehoe lava flows and vitric tuff beds capped by about 9 m (30 ft) of Pāhala Ash (Figure 19; Stearns and Macdonald 1946). Easton (1987) provides a detailed description of the type section location about 1.6 km (1 mi) southwest of the end of Hilina Pali Road on the southern slope of Kīlauea (Table 3; Figure 14). Additional reference sections of the Hilina Basalt are located at the following: 1) Keanabihopa, from the base of the pali to the top (370–640 m or 1,210–2,100 ft elevation) located 250 m (820 ft) south-southwest of the end of Hilina Pali Road [latitude 19°17'19" N., longitude 155°18'25" W., Old Hawaiian Datum, Ka‘ū Desert 7.5' Quadrangle]; and 2) Pu'ukapukapu, from the base of the pali to the top (100–300 m elevation or 330–980 ft elevation) [latitude 19°16'45" N., longitude 155°15'35" W., Old Hawaiian Datum, Ka‘ū Desert 7.5' Quadrangle] (Table 3; Figure 17; Easton 1987). The Hilina Basalt underlies the Pāhala Ash, and its base is not exposed.



Figure 19. Type locality exposures of the Hilina Basalt in the Kapukapu fault escarpment on the southern slope of Kīlauea Volcano at Halapē (photo courtesy of Jacob W. Frank). Exposures along the escarpment measure approximately 300 m (1,000 ft) thick and consist of lava flows and vitric tuff beds (thin light-colored layers) that are capped by Pāhala Ash.



Figure 20. Pāhoehoe and 'a'ā lava flows of Hilina Pali on the southern slope of Kīlauea, type locality exposures of the Hilina Basalt (NPS/MICHAEL SZOENYI).

Halapē Ash Member, Hilina Basalt

The Pleistocene Halapē Ash Member of the Hilina Basalt was proposed by Easton and Garcia (1980) and named after the Halapē area at the base of Pu'ukapukapu. The type section is designated at Keanabihopa (395 m or 1,300 ft elevation) on the south slope of Kīlauea [latitude 19°17'19" N., longitude 155°18'25" W., Old Hawaiian Datum, Ka'ū Desert 7.5' Quadrangle] (Table 3; Figure 15; Easton 1987). An additional reference section is located at Pu'ukapukapu, from the base of the pali to the top (100–300 m or 330–980 ft elevation) [latitude 19°16'45" N., longitude 155°15'35" W., Old Hawaiian Datum, Ka'ū Desert 7.5' Quadrangle] (Table 3; Figure 18; Easton 1987). The Halapē Ash Member is a thin unit measuring about 10–20 cm (4–8 in) thick that consists of red-weathering, poorly-bedded, clayey soil and brown beds of palagonite (hydrated basaltic glass) that underlie the Kahele Member of the Hilina Basalt (Easton 1987).

Kahele Ash Member, Hilina Basalt

The Pleistocene Kahele Ash Member of the Hilina Basalt was named by Easton and Garcia (1980) after Kahele Arroyo. Easton (1987) designated the type section at Pōhāka'a Arroyo (~470 m or 1,542 ft elevation) on the south slope of Kīlauea [latitude 19°16'40" N., longitude 155°20'00" W., Old Hawaiian Datum, Ka'ū Desert 7.5' Quadrangle] (Table 3; Figure 15). The type section measures approximately 100 cm (39 in) thick and consists of yellowish-red to reddish-brown palagonite, reddish-brown to black scoria and pumice, as well as rippled, coarse-bedded, pink- to gray pebble

gravel (Figure 21; Easton 1987). An additional reference section is located at Pu'ukapukapu, from the base of the pali to the top (100–300 m or 330–980 ft elevation) [latitude 19°16'45" N., longitude 155°15'35" W., Old Hawaiian Datum, Ka'ū Desert 7.5' Quadrangle] (Table 3; Figure 18; Easton 1987). The Kahele Ash Member overlies the Halapē Ash Member and underlies the Pōhāka'a Ash Member of the Hilina Basalt.



Figure 21. Type section exposure of the Kahele Ash Member of the Hilina Basalt at Pōhāka'a Arroyo, Hilina Pali. Entire thickness of the member is shown (100 cm or 40 in). Hammer for scale. Figure 11.5 from Easton (1987).

Pōhāka'a Ash Member, Hilina Basalt

The Pleistocene Pōhāka'a Ash Member of the Hilina Basalt was proposed by Easton and Garcia (1980) and named after its type section exposure at Pōhāka'a Arroyo (~425–450 m or 1,390–1,480 ft elevation) on the south slope of Kīlauea [latitude 19°16'40" N., longitude 155°20'00" W., Old Hawaiian Datum, Ka'ū Desert 7.5' Quadrangle] (Table 3; Figures 15 and 22; Easton 1987). The type section consists of six individual ash layers that have a combined measured thickness of about 6.25 m (20 ft); however, the member locally varies from 8 to 15 m (26 to 49 ft) thick at Pōhāka'a Arroyo (Easton 1987). The unit is composed of reworked sedimentary and pyroclastic material (pāhoehoe crusts, scoria), regularly layered beds of palagonite with distinct grains of pumice or accretionary lapilli, vitric ash, and soil separated by intercalated lava flows (Figure 23; Decker and Christiansen 1984; Easton 1987). Some ash layers contain abundant lithic and crystal fragments that appear to be pyroclastic-surge deposits (Decker and Christiansen 1984; Easton 1987). An additional reference section for the member is designated at Pu'ukapukapu, from the base of the pali to the top (100–300 m or 330–980 ft elevation) [latitude 19°16'45" N., longitude 155°15'35" W., Old Hawaiian Datum, Ka'ū Desert 7.5' Quadrangle] (Table 3; Figure 18; Easton 1987). The Pōhāka'a Ash Member overlies the Kahele Ash Member and underlies the Mo'o Ash Member of the Hilina Basalt.



Figure 22. Type section exposure of the Pōhāka'a Ash Member of the Hilina Basalt at Pōhāka'a Arroyo. Undulating beds near the hammer may represent base-surge deposits. Figure 11.8 from Easton (1987).

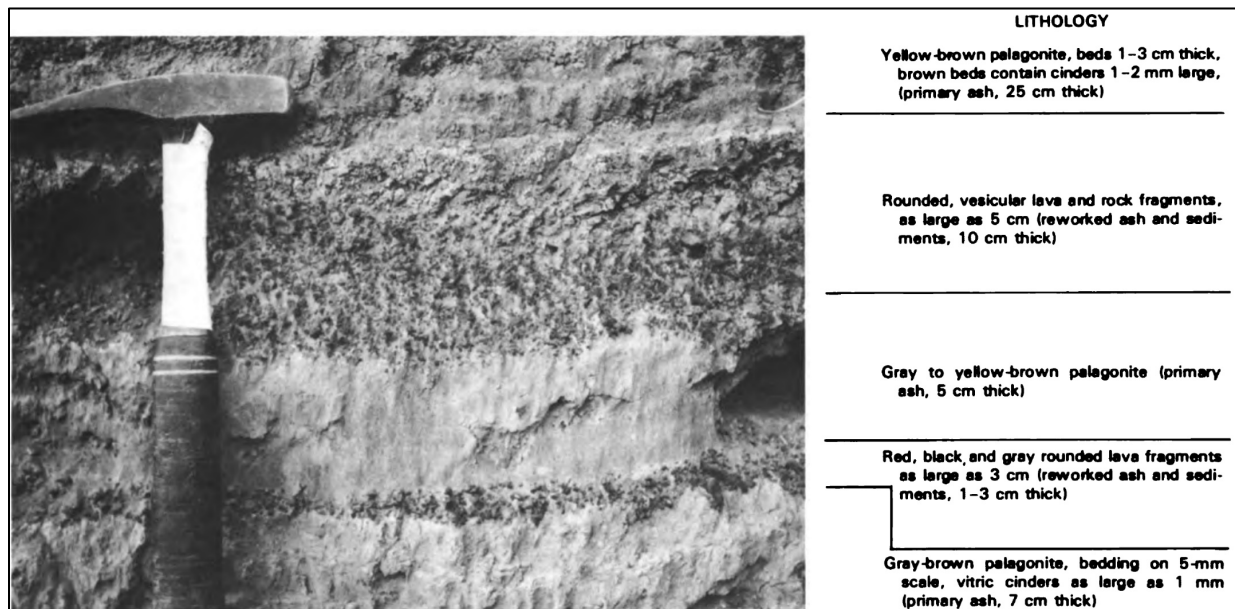


Figure 23. Closeup view of the lower beds of the Pōhāka'a Ash Member, Keanabihopa, showing typical bedding and lithology. Figure 11.6 from Easton (1987).

Mo'o Ash Member, Hilina Basalt

The Pleistocene Mo'o Ash Member of the Hilina Basalt was named by Easton and Garcia (1980) after Mo'o Arroyo where the unit is exposed. The type section is located at Keanabihopa (570 m or 1,870 ft elevation) on the south slope of Kīlauea [latitude 19°17'19" N., longitude 155°18'25" W., Old Hawaiian Datum, Ka'ū Desert 7.5' Quadrangle] (Table 3; Figure 15; Easton 1987). At the type section the Mo'o Ash Member measures approximately 2.5 m (8 ft) thick and consists of yellowish-

brown vitric ash, palagonite, and soil with several beds of brown accretionary lapilli (Decker and Christiansen 1984; Easton 1987). An additional reference section of the member is located at Pu'ukapukapu, from the base of the pali to the top (100–300 m or 330–980 ft elevation) [latitude 19°16'45" N., longitude 155°15'35" W., Old Hawaiian Datum, Ka'ū Desert 7.5' Quadrangle] (Table 3; Figure 18; Easton 1987). The Mo'ō Ash Member overlies the Pōhāka'a Ash Member of the Hilina Basalt and underlies the Pāhala Ash.

Pāhala Ash

The Pleistocene Pāhala Ash was originally referred to as the “Pahala series” by Washington (1923), who derived the name from the village of Pāhala on the southeastern slope of Mauna Loa. Easton (1987) designated a principal reference section for the unit at Mo'ōlelo, Hilina Pali, about 20 km (12 mi) south of Kaluapele (Kīlauea caldera) [latitude 19°17'00" N., longitude 155°19'00" W., Old Hawaiian Datum, Ka'ū Desert 7.5' Quadrangle] (Table 3; Figure 17; Easton 1987). The principal reference section measures 14 m (47 ft) thick and consists of a mixture of yellowish-brown palagonite and beds of reworked ash, sand, and gravel (Easton 1987). Two supplemental reference sections of the Pāhala Ash are located at the following: 1) Pu'ukapukapu [latitude 19°16'35" N., longitude 155°15'23" W., Old Hawaiian Datum, Ka'ū Desert 7.5' Quadrangle]; and 2) Pu'ukaone [latitude 19°16'15" N., longitude 155°16'56" W., Old Hawaiian Datum, Ka'ū Desert 7.5' Quadrangle] (Table 3; Figure 18; Easton 1987). Pāhala Ash beds at Pu'ukapukapu are approximately 1–2 m (3–6 ft) thick and measure about 1.8–3 m (6–10 ft) thick at Pu'ukaone (Easton 1987). Where stratotypes are assigned in the region of Kīlauea, the Pāhala Ash overlies the Hilina Basalt and underlies, or is interbedded with the Puna Basalt.

Ka'ū Basalt

The Pleistocene–Holocene Ka'ū Basalt was originally referred to as the Kau Volcanic Series by Stearns and Macdonald (1946), who derived the name after the Ka'ū District where the unit is well exposed. Stearns and Macdonald (1946) designated the type section in the west wall of Moku'āweoweo Caldera [approximately latitude 19°28'46" N., longitude 155°35'30" W., Old Hawaiian Datum, Mauna Loa 7.5' Quadrangle], Mauna Loa (Table 3; Figures 15 and 24). The type section measures 125 m (410 ft) thick and predominantly consists of olivine basalt pāhoehoe and 'a'ā lava flows with a few thin interbedded ash layers (Stearns and Macdonald 1946). In the type section region of Mauna Loa, the Ka'ū Basalt overlies the Pāhala Ash.



Figure 24. Northeast-facing view of the summit of Mauna Loa showing Moku'āweoweo Caldera and smaller pit craters on the southwest rift zone after a flurry of snow. The type section of the Ka'ū Basalt is located in the western wall of Moku'āweoweo Caldera. Mauna Kea is in the background. Plate 8 from Stearns (1946).

Puna Basalt

The Holocene Puna Basalt was originally named the Puna Volcanic Series by Stearns and Macdonald (1946) who derived the name from the Puna District on the island of Hawai'i. The type locality of the basalt is located in the walls of Kaluapele, where the type section was measured at Uēkahuna Bluff [latitude 19°25'43" N., longitude 155°17'01" W., Old Hawaiian Datum, Kīlauea Crater 7.5' Quadrangle] (Table 3; Figure 15; Stearns and Macdonald 1946; Easton 1987). The type section of the unit measures about 136 m (446 ft) thick and predominantly consists of olivine basalt pāhoehoe lava flows that have been subdivided into 63 individual flows with two thick tephra deposits (Figures 25 and 26; Stearns and Macdonald 1946; Casadevall and Dzurisin 1987). Pāhoehoe flows range from highly vesicular flows on the carapace of the volcano, to massive columnar-jointed basalts ponded in Kaluapele, pit craters, and rift-zone grabens (Stearns and Macdonald 1946). Interbedded within the Puna basalt flows are a few vitric ash and tuff beds that form a small part of the unit and measure about 0.3 m (1 ft) thick (Stearns and Macdonald 1946). Numerous lava tubes are present in the pāhoehoe flows, and the unit also comprises more than 100 cinder and spatter cones along the east and southwest rift zones of Kīlauea (Figure 27; Stearns and Macdonald 1946). In addition to the type section, five reference sections for the Puna Basalt were designated by Easton (1987) in the following locations: 1) Keanabihopa (600–640 m or 1,970–2,100 ft elevation) [latitude 19°17'19" N., longitude 155°18'25" W., Old Hawaiian Datum, Ka'ū Desert 7.5' Quadrangle]; 2) Nanahu Arroyo, Hilina Pali, approximately 0.5 km (0.3 mi) northeast of end of Hilina Pali Road [latitude 19°18'15"

N., longitude 155°18'34" W., Old Hawaiian Datum, Ka'ū Desert 7.5' Quadrangle]; 3) Kīlauea Iki Crater, summit lava [Volcano 7.5' Quadrangle]; 4) Makaopuhi Crater, East Rift Zone lava [Makaopuhi Crater 7.5' Quadrangle]; and 5) Nāpau Crater, East Rift Zone lava [Volcano 7.5' Quadrangle] (Table 3; Figure 18).

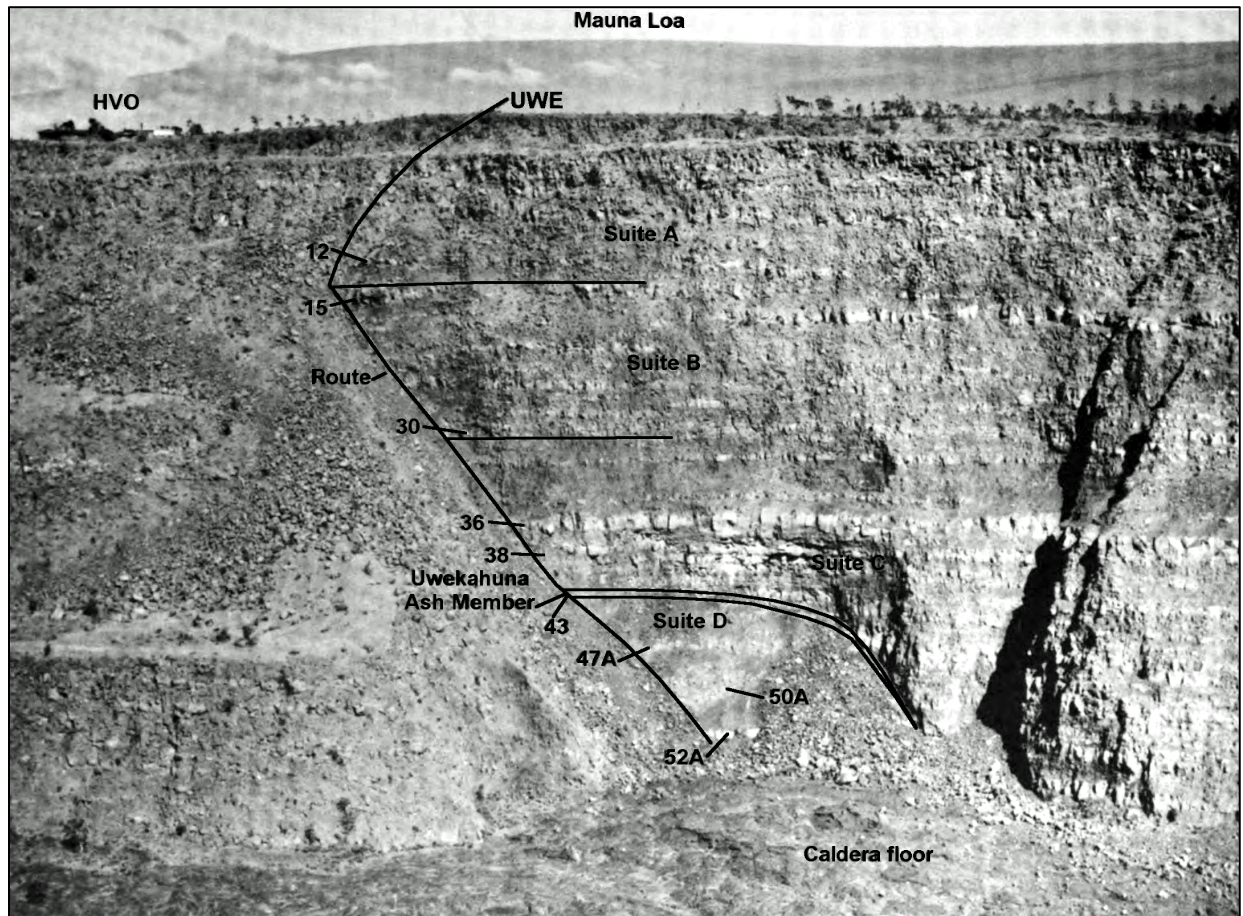


Figure 25. Type section exposure of the Puna Basalt at Uēkahuna Bluff. Sampling route, selected units, and lava suites of Casadevall and Dzurisin (1987) are labeled, including the Uēkahuna Ash [unit 43]. HVO, former USGS Hawaiian Volcano Observatory and Jaggar Museum. UWE, Uēkahuna triangulation tower. Height of the cliff from unit 52A to the rim is 135 m (445 ft). Summit of Mauna Loa is in the distant background. Figure 13.3 from Casadevall and Dzurisin (1987) (annotations enhanced for readability).



Figure 26. Looking toward Uēkahuna Bluff from across the summit caldera of Kīlauea after the summit collapse of 2018. The former USGS Hawaiian Volcano Observatory and Jaggar Museum are shown at the top of the bluff (NPS/J. WEI).



Figure 27. Three of the main volcanic cones (center and right) that make up the Kamakai'a Hills on Kīlauea Volcano's Southwest Rift Zone. Numerous (>100) cinder cones and spatter cones consisting of Puna Basalt exist along the rift zone (USGS).

Uēkahuna Ash

The Holocene Uēkahuna Ash was first proposed by Stone (1926) and previously regarded as a member of the Puna Basalt before Fiske et al. (2009) raised the unit to formation rank. The type locality and type section are designated in the west wall of Kaluapele at the base of Uēkahuna Bluff, northeast of nearby fault terraces [Kīlauea 7.5' Quadrangle], island of Hawai'i (Table 3; Figure 16; Stone 1926; Easton 1987). A revised “mid-Bluff” type section was designated by Fiske et al. (2009) in the exposed walls of a 3.12-m (10.24 ft) pit hand-dug at the top of a talus apron and at the base of the steep caldera wall, approximately 30 m (98 ft) above the present caldera floor [latitude 19.42247° N., longitude 155.28775° W.] (Table 3; Figures 16, 28, and 29). However, this section was buried by several meters of talus in 2018 and must be considered destroyed (D. Swanson, USGS, pers. comm., 2022). The Uēkahuna Ash is composed of a mix of very fine to coarse vitric and lithic ash, lapilli, and pumice, mostly of fall origin but including one or two pyroclastic surge deposits (Figure 30; Langenheim and Clague 1987; Fiske et al. 2009). An additional reference section is located at Nanahu Arroyo, Hilina Pali, about 0.5 km (0.3 mi) northeast of the end of Hilina Pali Trail [latitude 19°18'15" N., longitude 155°18'34" W., Old Hawaiian Datum, Ka'ū Desert 7.5' Quadrangle] (Table 3; Figure 18; Easton 1987). At the type locality, the Uēkahuna Ash overlies the Hornet and Kīpuka Nēnē lava flows and underlies the Old Kālu'e lava flow (Fiske et al. 2009).

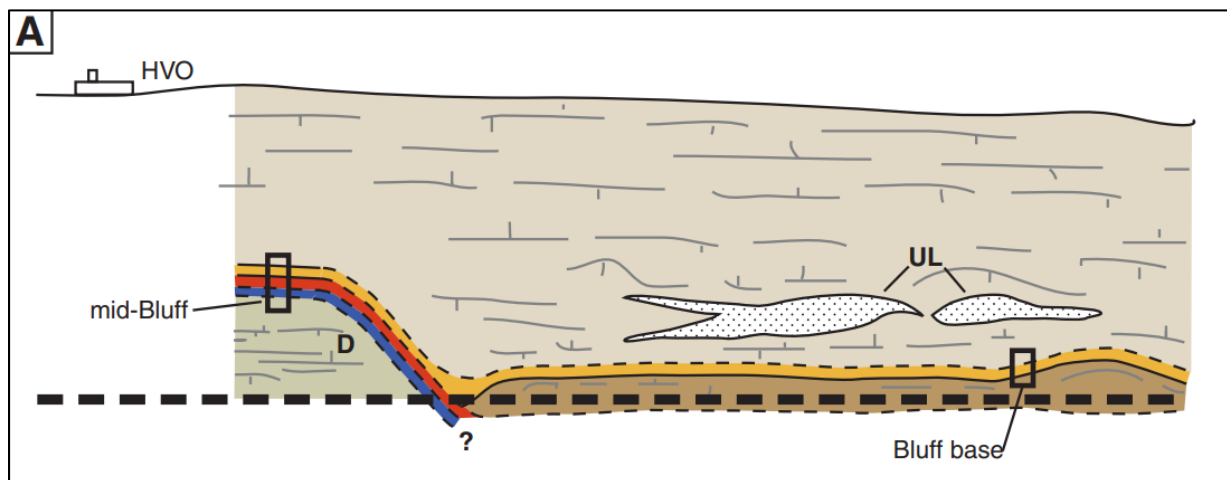


Figure 28. Sketch of 120-m (394 ft) Uēkahuna Bluff showing location of Bluff-base and mid-Bluff type sections of the Uēkahuna Ash (bold rectangles). Thick dashed line marks the present day caldera floor. UL, Uēkahuna laccolith; HVO, Hawaiian Volcano Observatory; D, Suite D lava flows of Casadevall and Dzurisin (1987). Figure 10A from Fiske et al. (2009).



Figure 29. Photograph of the 3.12-m (10.24 ft) mid-Bluff type section of the Uēkahuna Ash, consisting of vitric and lithic ash, lapilli, and pumice. Figure 10C from Fiske et al. (2009).



Figure 30. Photograph of Bluff-base type section of the Uēkahuna Ash. Shovel handle rests on thin bedded to laminated vitric ash (letter A). Brush rests against lithic ash and lapilli (letters C and D). The middle of the section consists of lithic coarse ash containing blocks and rip-up clasts (letter B). Modified figure 10E from Fiske et al. (2009).

Kulanaokuaiki Tephra Member, Uēkahuna Ash

The Holocene Kulanaokuaiki Tephra Member of the Uēkahuna Ash was named by Fiske et al. (2009) after Kulanaokuaiki Pali, a north-facing fault scarp 7–8 km (4–5 mi) south of Kīlauea’s summit. The type section is designated beneath the edge of the Old Kālu‘e lava flow on the upper south flank of Kīlauea, approximately 600 m (1,950 ft) south of the Kulanaokuaiki Pali, island of Hawai‘i (Table 3; Figures 15 and 31; Fiske et al. 2009). The member is divided into five pyroclastic units that are chiefly composed of low-density pumice lapilli, scattered lithic fragments, scattered vitric clasts (including Pele’s hair and tears), and frothy pumice (Fiske et al. 2009). The lower two units of the member are separated from the upper three units by a widespread erosional disconformity. At the type section, the Kulanaokuaiki Tephra Member underlies the Old Kālu‘e lava flow and younger reworked material and overlies pre-Kulanaokuaiki deposits of the Uēkahuna Ash and the Kīpuka Nēnē lava flow (Fiske et al. 2009).



Figure 31. Type section of the Kulanaokuaiki Tephra Member on the upper south flank of Kīlauea Volcano (USGS/DON SWANSON).

Keanakāko‘i Ash Member (Keanakāko‘i Tephra), Puna Basalt

The Holocene Keanakāko‘i Ash Member of the Puna Basalt was originally named the Keanakāko‘i Formation by Wentworth (1938) for exposures located near Keanakāko‘i Crater on the island of Hawai‘i. Modern workers more accurately refer to the unit as the Keanakāko‘i Tephra following the detailed stratigraphy developed by Swanson and Houghton (2018). The type locality of the member is located southwest of Keanakāko‘i Crater and predominantly consists of thin- and thick-bedded, vitric to lithic pyroclastic deposits that range in grain size from ash to blocks (Swanson and Houghton 2018). Type locality exposures predominantly consist of thin-bedded ash, interlayered thin beds of accretionary lapilli and lapilli ash, and pyroclastic density currents measuring approximately 11 m (36 ft) thick (Table 3; Figures 17 and 32; Swanson and Houghton 2018). Several sections of the Keanakāko‘i Tephra are described around Kaluapele in Swanson and Houghton (2018) that include informal type localities and emphasize the heterogeneity of the unit. The Keanakāko‘i Ash Member is the youngest member of the Puna Basalt and overlies older lava flows of the formation. Younger flows overlie the Keanakāko‘i in places.

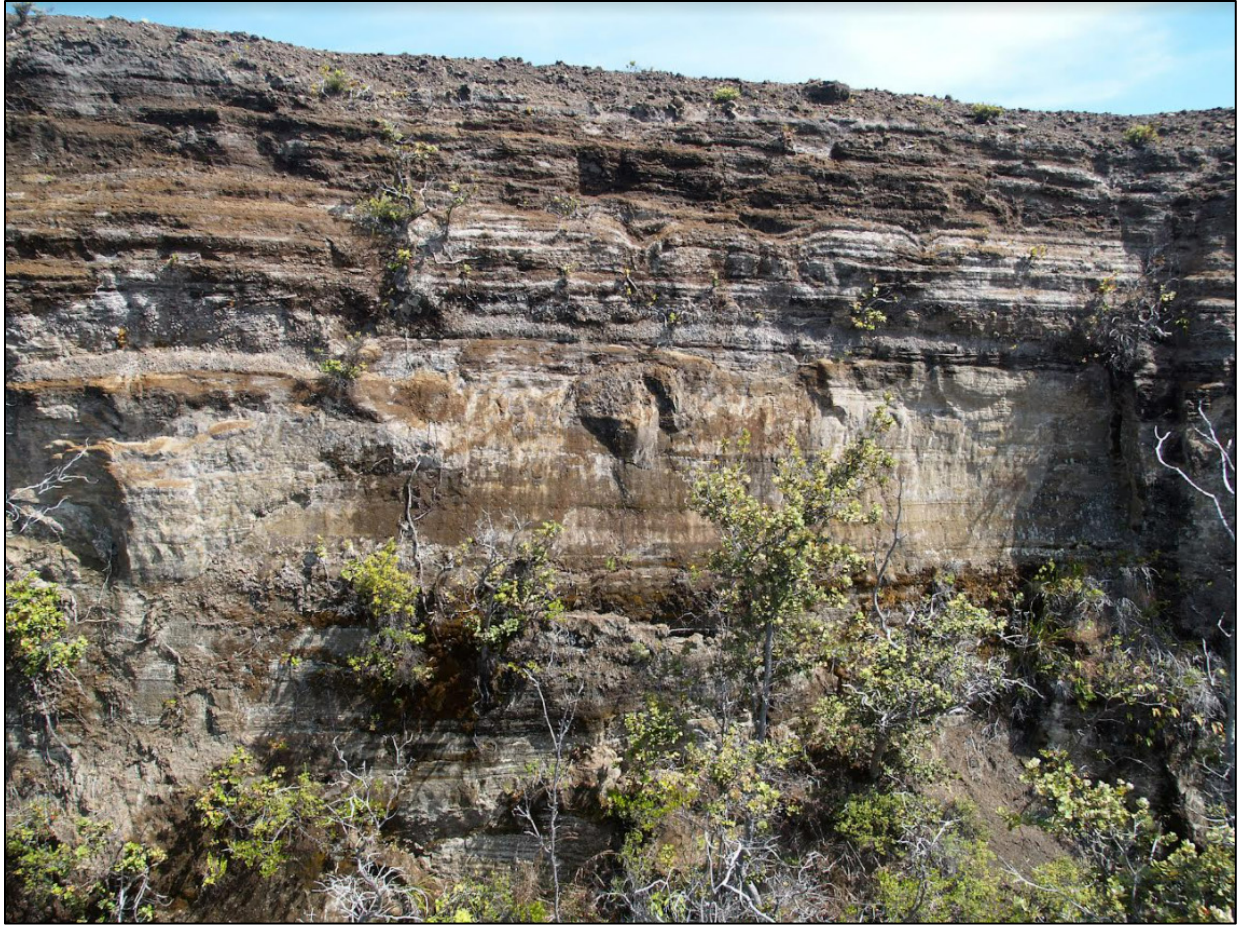


Figure 32. Type locality exposures of the Keanakāko'i Ash Member located southwest of Keanakāko'i Crater (USGS/DON SWANSON). Exposures measure approximately 11 m (36 ft) thick.

Kaloko-Honokōhau National Historical Park (KAHO)

Kaloko-Honokōhau National Historical Park (KAHO) is located on the west coast of the island of Hawai‘i, approximately 4.8 km (3 mi) south of the Keahole International Airport and 4.8 km (3 mi) north of the town of Kailua-Kona (Figure 33). Established on November 10, 1978, KAHO encompasses about 470 hectares (1,163 acres) and once sustained early Hawaiian settlements prior to the arrival of Europeans. The historical park was established for the preservation, interpretation, and practice of traditional Native Hawaiian activities and culture. KAHO contains coastal areas, archaeological remnants, and three fishponds that illustrate ingenious engineering, aquaculture techniques, and practices of the past that offer opportunities for Hawaiian aquaculture to thrive into the future.

Located on the western slope of Hualālai Volcano, the geology of KAHO is dominated by volcanic flows of the Hualālai volcanic center (Figure 34). The Holocene-age basaltic flows at KAHO can be subdivided into three distinct eruptive episodes: 1) approximately 3,000–1,500 years old; 2) 5,000–3,000 years old; and 3) 10,000–5,000 years old (Wolfe and Morris 1996). These lava flows generally have an undissected (free of erosion channels) surface and represent older pāhoehoe lavas characterized by a smooth, “ropey” texture that were later covered in part by ‘a‘ā lavas that have a rough, jagged texture (Wolfe and Morris 1996). The landscape of KAHO consists of stark, rugged basalt flows that form broad benches or terraces along the shore, with sparse carbonate sand and gravel beach areas that include intertidal and supratidal accumulations of perched storm sediments (Thornberry-Ehrlich 2011b).

There are no designated stratotypes identified within the boundaries of KAHO. There are three identified stratotypes located within 48 km (30 mi) of KAHO boundaries, for the Pleistocene–Holocene Hualālai Volcanics (type locality), Wa‘awa‘a Trachyte Member of the Hualālai Volcanics (type locality), and the Kona Ash beds of the Hualālai Volcanics (type locality).



Figure 33. Park map of KAHO, Hawai'i (NPS).

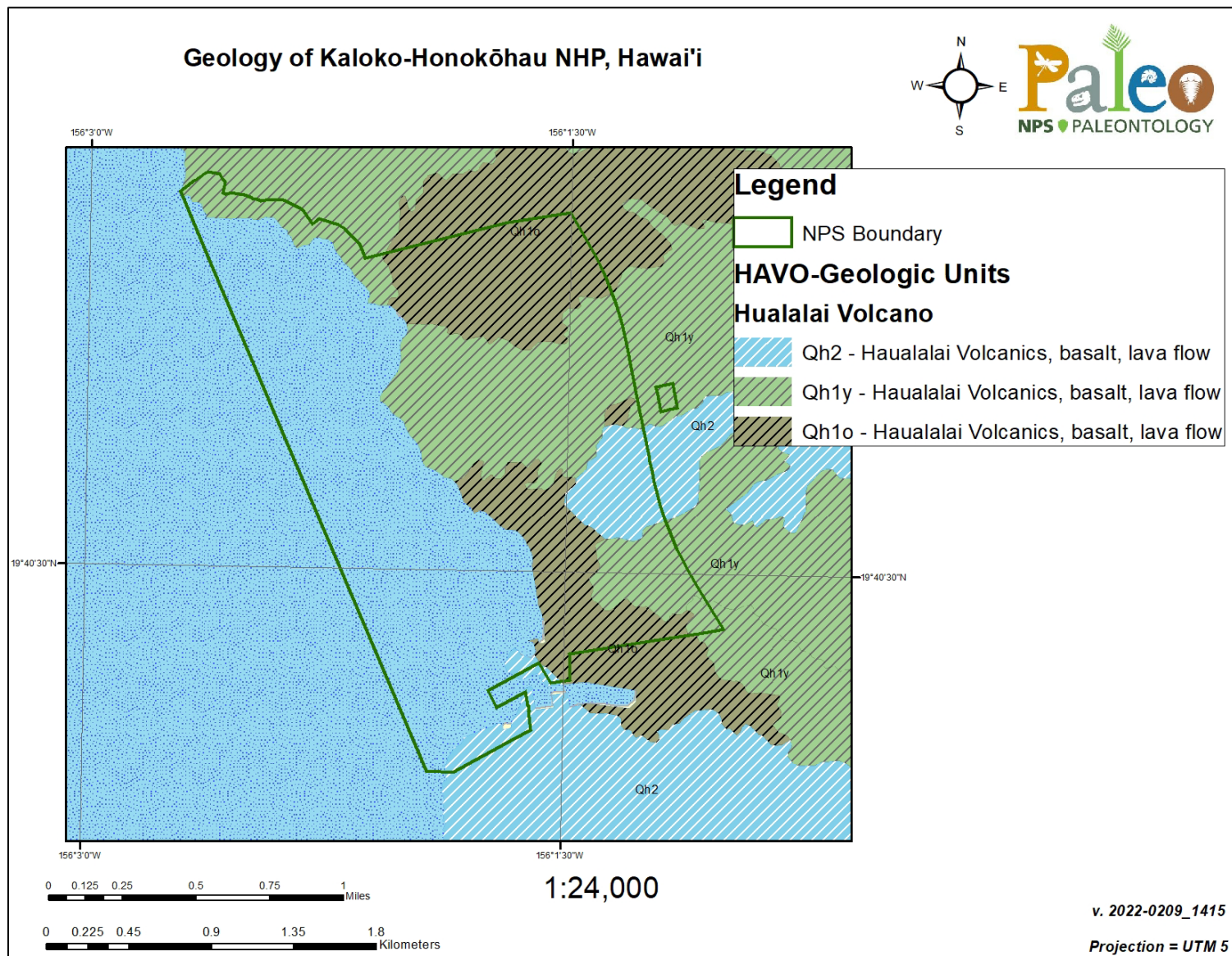


Figure 34. Geologic map of KAHO, Hawai'i.

Kalaupapa National Historical Park (KALA)

Kalaupapa National Historical Park (KALA) is located along the north-central coast of the island of Molokaʻi in Maui County, Hawaiʻi (Figure 35). Established on December 22, 1980, KALA covers approximately 4,362 hectares (10,779 acres) and contains the site of the Molokaʻi Hansen’s disease (leprosy) settlement, areas relating to early settlement, and a diverse biological community that includes rare and endangered species (National Park Service 2016). The establishment of KALA honors the story of the isolated Hansen’s disease community by preserving its site and values, in addition to telling the Hawaiian cultural history at Kalaupapa that dates back more than 900 years. The landscape of KALA includes the relatively flat Kalaupapa Peninsula (also called the Makanalua Peninsula) with gently sloping flanks of the Kauhakō Crater and three steep-sloped interior valleys whose walls rise to include the rim of some of the steepest sea cliffs in the world. The highest sea cliffs of the north shore of Molokaʻi stand 1,101 m (3,315 ft) above the Pacific Ocean and were designated a national natural landmark because of their geological significance (Thornberry-Ehrlich 2010). The offshore areas of KALA encompass 809 hectares (2,000 acres) and include the islets of Huelo and ʻŌkala.

The geology of KALA is primarily composed of Cenozoic-age igneous units that can be broken down into lava flows, vent deposits, and volcanic domes (Figure 36). The steep sea cliffs that rise above the lower Kalaupapa Peninsula are comprised of the Pliocene–Pleistocene East Molokaʻi Volcanics and represent the oldest exposures in the park. Rocks that form the low-lying tongue of land at the base of the cliffs consist of the Pleistocene Kalaupapa Volcanics. A veneer of Quaternary-age alluvium (unconsolidated sand and gravel deposits) is mapped at the base of the sea cliffs. On the island of Molokaʻi, the East Molokaʻi volcano has its highest peak (Kamakou) at 1,515 m (4,970 ft) in elevation and was once much larger than it is today. At one point in geologic time the northern half of the volcano catastrophically collapsed along a 40 km (25 mi) long scarp, effectively halving the size of the collapse caldera at its summit and forming the famous cliffs (also called pali) of Molokaʻi (Thornberry-Ehrlich 2010).

KALA contains three identified stratotypes that represent the Pliocene–Pleistocene East Molokaʻi Volcanics and the Pleistocene Kalaupapa Volcanics (Table 4; Figure 37). In addition to the designated stratotypes located within KALA, stratotypes located within 48 km (30 mi) of the park boundaries include the Pliocene–Pleistocene West Molokaʻi Volcanics (type locality); and the Pleistocene Hulopoe Gravel (type section), Wailuku Basalt (type locality), Lānaʻi Basalt (principal reference section), Honolua Volcanics (type locality), Lahaina Volcanics (principal reference section), and type localities of the Laina and Kilea flows of the Lahaina Volcanics.

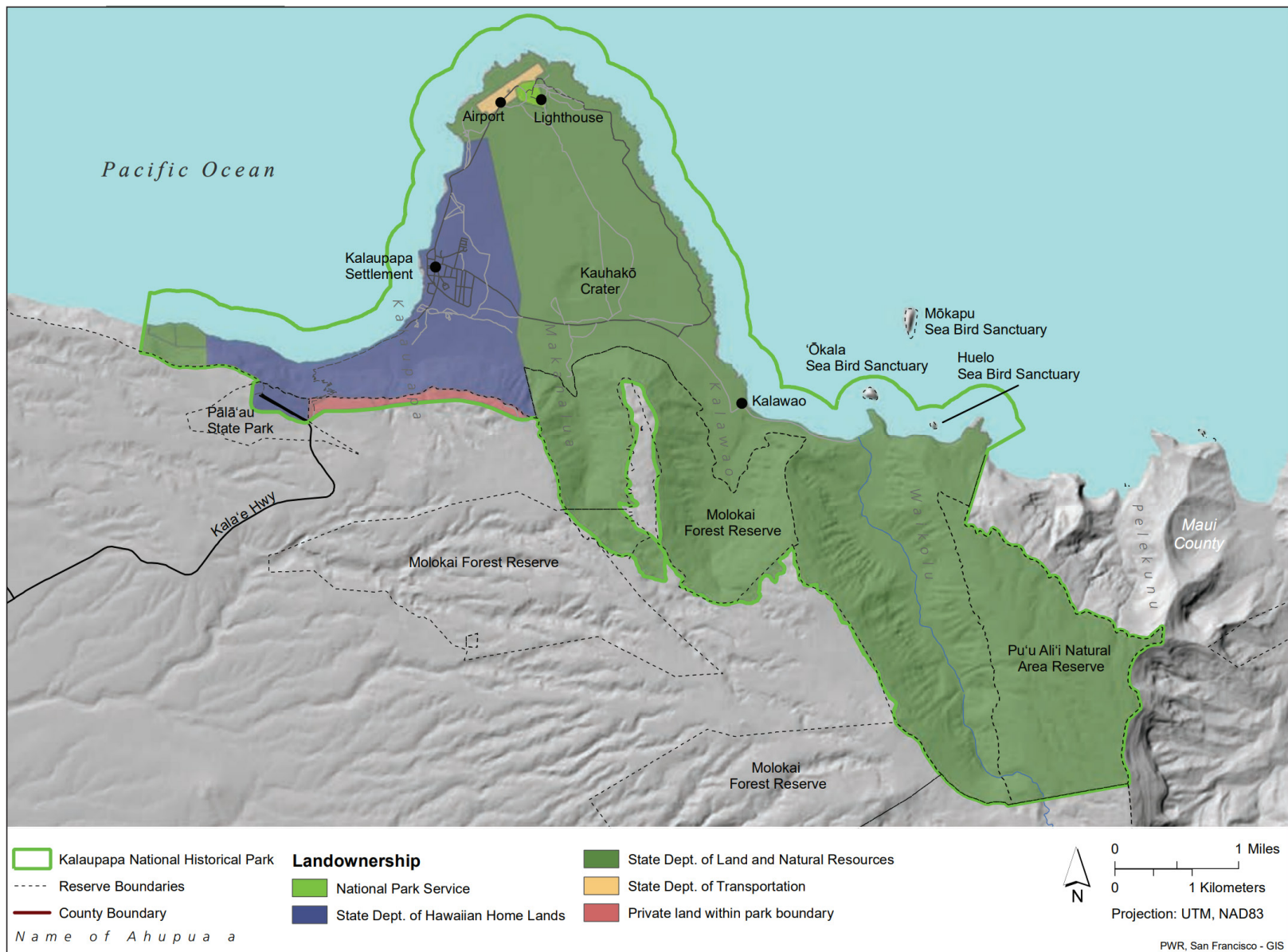


Figure 35. Park map of KALA, Hawai'i (NPS).

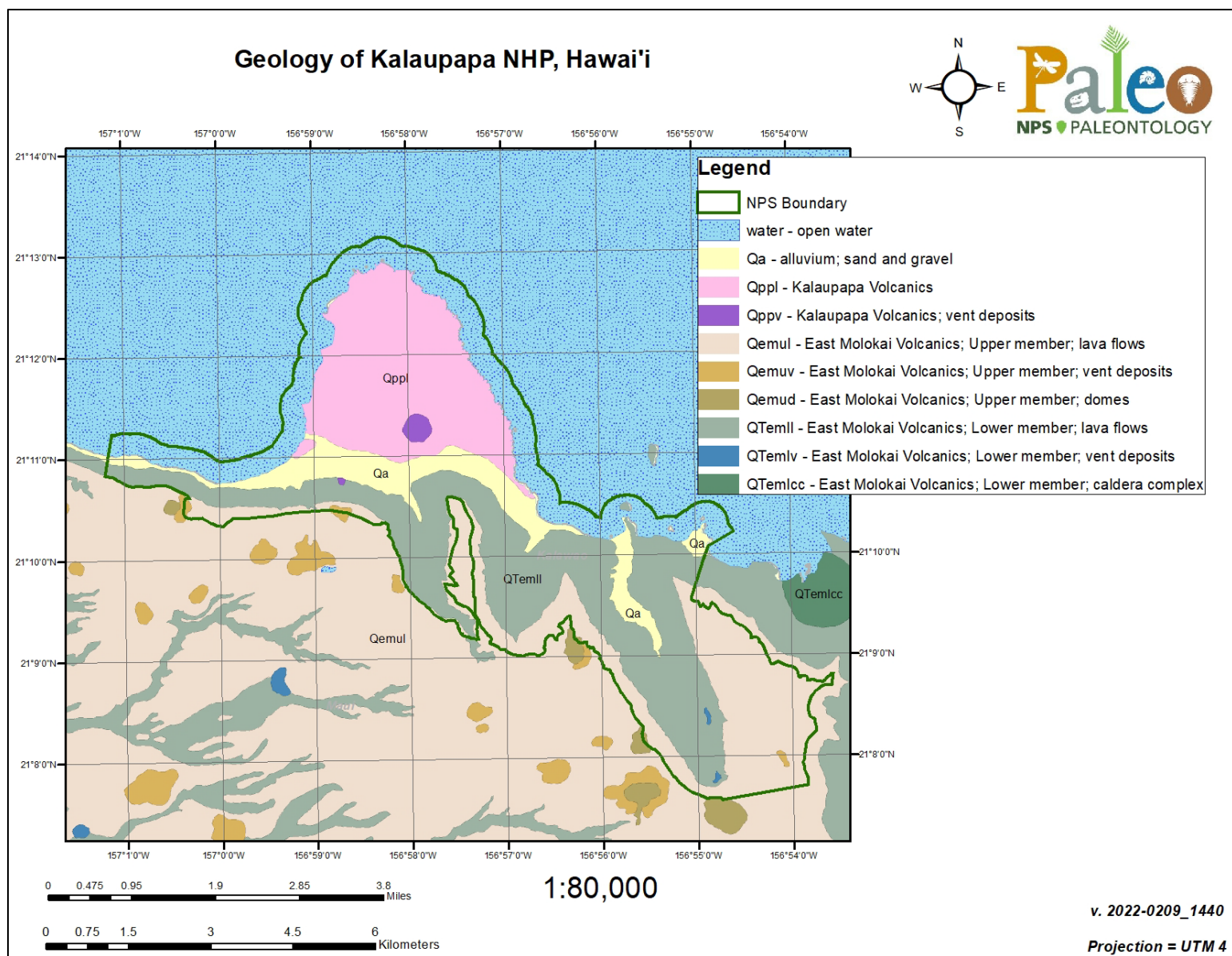


Figure 36. Geologic map of KALA, Hawai'i.

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

Unit Name (GRI map symbol)	Reference	Stratotype Location	Age
Kalaupapa Volcanics	Macdonald and Davis 1956	Type locality: Kalaupapa Peninsula [latitude 21° 11'33" N., longitude 156°59'10" W., Old Hawaiian Datum, Kaunakakai 7.5' Quadrangle], island of Moloka'i, HI.	Pleistocene
East Moloka'i Volcanics	Stearns and Macdonald 1947; Beeson 1976	Type section: cliffs south of Kalaupapa Peninsula [latitude 21°11'33" N., longitude 156°59'10" W., Old Hawaiian Datum, Kaunakakai 7.5' Quadrangle], island of Moloka'i, HI. Type locality: in 500 m (1,600 ft) cliff separating Kalaupapa Peninsula from rest of island, along trail down Pali SW of Kalaupapa [Kaunakakai 7.5' Quadrangle], island of Moloka'i, HI.	Pliocene–Pleistocene

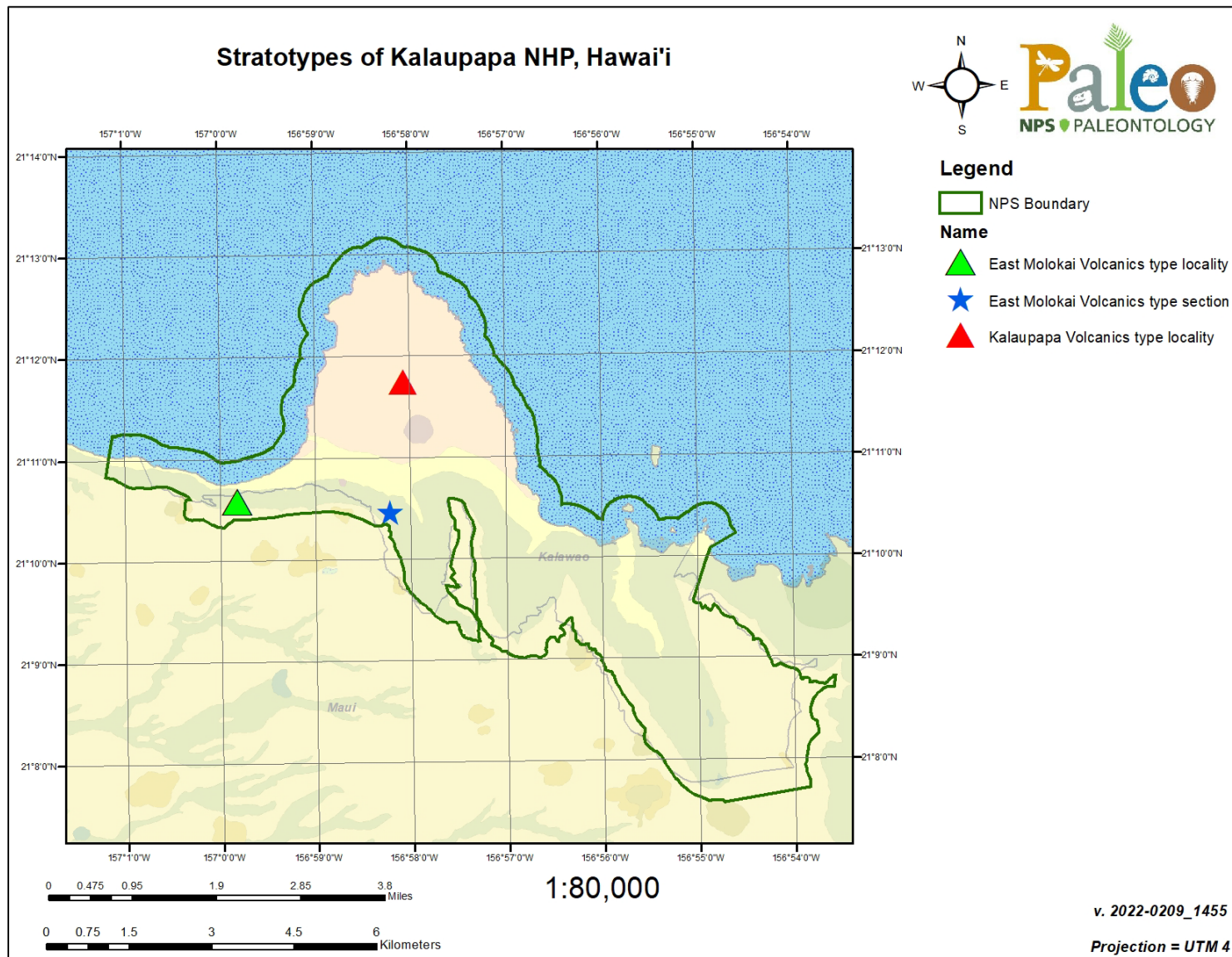


Figure 37. Modified geologic map of KALA showing stratotype locations. The transparency of the geologic units layer has been increased.

East Molokaʻi Volcanics

The Pliocene–Pleistocene East Molokaʻi Volcanics were originally referred to as the East Molokaʻi Volcanic Series by Stearns (1946) and named after East Molokaʻi Volcano on the island of Molokaʻi. Stearns and Macdonald (1947) designated the type locality in a 500 m (1,600 ft)-tall cliff separating Kalaupapa Peninsula from the rest of the island, located along the trail which leads from Kalaʻe down the northern cliff to Kalaupapa [Kaunakakai 7.5' Quadrangle, island of Molokaʻi] (Table 4; Figures 37 and 38). Beeson (1976) provided a more precise type section description in the cliffs south of Kalaupapa Peninsula [latitude 21°11'33" N., longitude 156°59'10" W., Old Hawaiian Datum, Kaunakakai 7.5' Quadrangle] (Table 4; Figure 38). Type locality exposures consist of an upper member of andesitic 'a'ā lava flows measuring about 60 m (200 ft) thick and a lower member predominantly composed of thin-bedded olivine basalt or basalt pāhoehoe and 'a'ā lava flows measuring about 272 (894 ft) thick (Stearns and Macdonald 1947). The East Molokaʻi Volcanics unconformably overlie the West Molokaʻi Volcanics and unconformably underlie the Kalaupapa Volcanics.

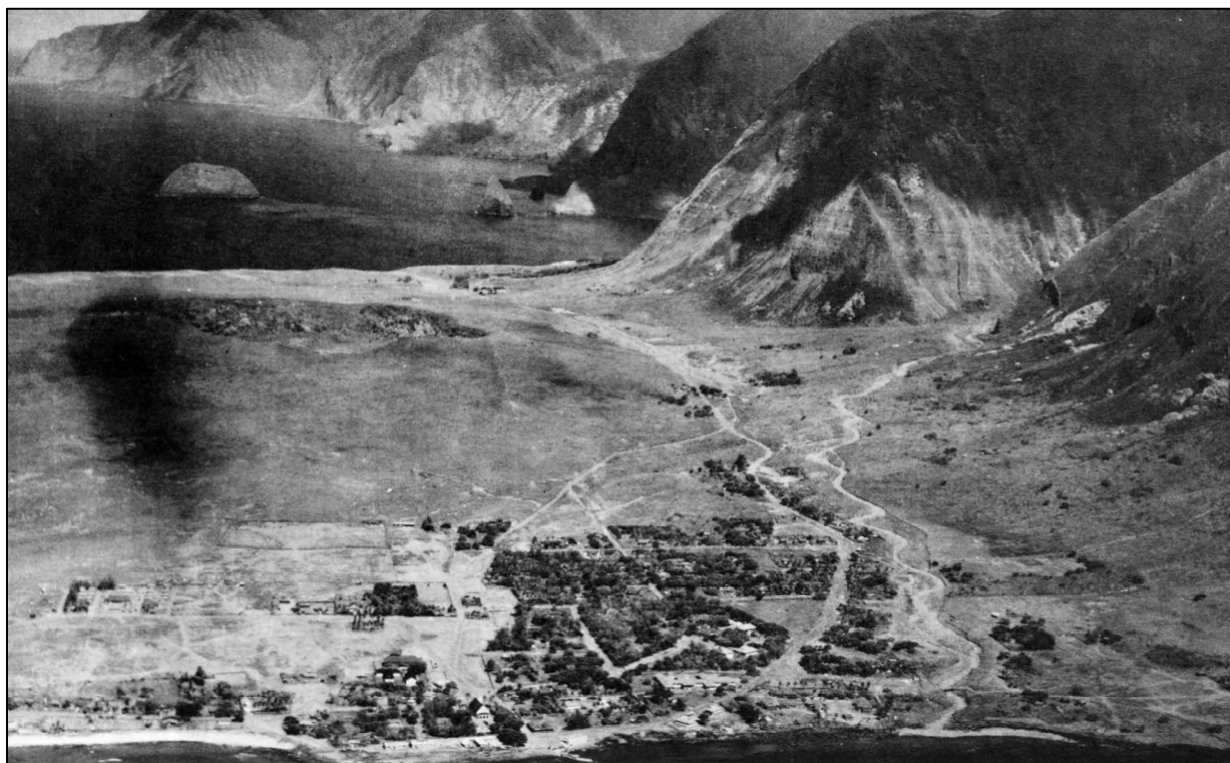


Figure 38. Kalaupapa Peninsula and the surrounding cliffs on the north side of East Molokaʻi. The cliffs south of the Peninsula consist of the type locality exposures of the East Molokaʻi Volcanics, while the peninsula represents the type locality of the Kalaupapa Volcanics. Kauhakō Crater is seen in the foreground of the peninsula to the left. Plate 23 from Stearns (1946).

Kalaupapa Volcanics

The Pleistocene Kalaupapa Volcanics were originally named the Kalaupapa Basalt by Stearns (1946) after the Kalaupapa leper settlement constructed on top of the unit. Later work by Langenheim and Clague (1987) re-described the unit as the Kalaupapa Volcanics to reflect a range of compositions that include alkalic basalt and basanite. The type locality of the unit was designated by Macdonald and Davis (1956) on Kalaupapa Peninsula [latitude 21°11'33" N., longitude 156°59'10" W., Old Hawaiian Datum, Kaunakakai 7.5' Quadrangle] on Moloka'i (Table 4; Figures 37 and 39). Lava flows of the unit erupted from a flat lava shield 123 m (405 ft) high indented by a summit crater named Kauhakō Crater that is more than 135 m (450 ft) deep (Stearns and Macdonald 1947; Clague et al. 1982). The Kalaupapa Volcanics unconformably overlie the East Moloka'i Volcanics and underlie younger Pleistocene–Holocene sedimentary deposits.



Figure 39. View from Pali Trail toward the Kalaupapa Peninsula on the northern island of Moloka'i, type locality of the Kalaupapa Volcanics (NPS). Kauhakō Crater can be seen to the upper right of the photo.

National Park of American Samoa (NPSA)

The National Park of American Samoa (NPSA) is located in the South Pacific more than 4,200 km (2,600 mi) southwest of Hawai‘i and is the only National Park Service unit in the southern Hemisphere. Authorized on October 31, 1988, the land base of NPSA was established in September 1993 when a 50-year lease agreement was signed between the American Samoa Government and the National Park Service. NPSA encompasses approximately 3,341 hectares (8,257 acres) and was established to preserve, protect, and interpret paleotropical rainforests, coral reef ecosystems, and Samoan cultural traditions and resources that date back 3,000 years. The park is distributed among three remote volcanic islands (of seven in American Samoa) that include Ta‘ū, Ofu, and Tutuila (Figure 40). These three separate islands contain lush rainforests, cloud forests, littoral forests, diverse coral communities, lagoons, wetlands, and beaches (Thornberry-Ehrlich 2008).

The islands of American Samoa are a series of broad shield volcanoes that rise thousands of meters or feet above the Pacific Ocean floor and consist of alternating lava flows and pyroclastic debris that hardened into tuff, volcanic breccia, lapilli, and cinder layers (Thornberry-Ehrlich 2008). The Ofu Island unit of NPSA contains some of the oldest exposures in the park, represented by volcanic breccias and plugs of the Pliocene Asaga Formation (Figure 41). Younger Pleistocene and Holocene sedimentary rocks consisting of calcareous sediments and alluvium are also mapped within the Ofu Island unit. The Ta‘ū Island unit of NPSA consists of volcanic units of the Pleistocene Lata Formation that are subdivided into intra-caldera flows and post-caldera volcanics. Ponded lavas and pāhoehoe flows of the Pleistocene Luatele Formation and lava flows of the Holocene Fiti‘uta Formation are located within the park boundaries on the northeastern portion of Ta‘ū Island (Figure 42). The Tutuila Island unit of NPSA is composed of volcanic rocks of the Pliocene–Pleistocene Pago Volcanics, trachyte pumice deposits, plugs, and dikes, as well as younger Holocene deposits consisting of calcareous sand, talus, and alluvium (Figure 43).

NPSA contains one identified stratotype that represents the type locality of the Pliocene–Pleistocene Pago Volcanics (Table 5; Figure 44). In addition to the designated stratotype located within NPSA, there is one stratotype located within 48 km (30 mi) of the park boundaries that represents the Pliocene Taputapu Volcanics (type locality).



Figure 40. Park maps of NPSA (above, Tutuila Island unit; below, Ofu and Ta'ū island units), American Samoa (NPS).

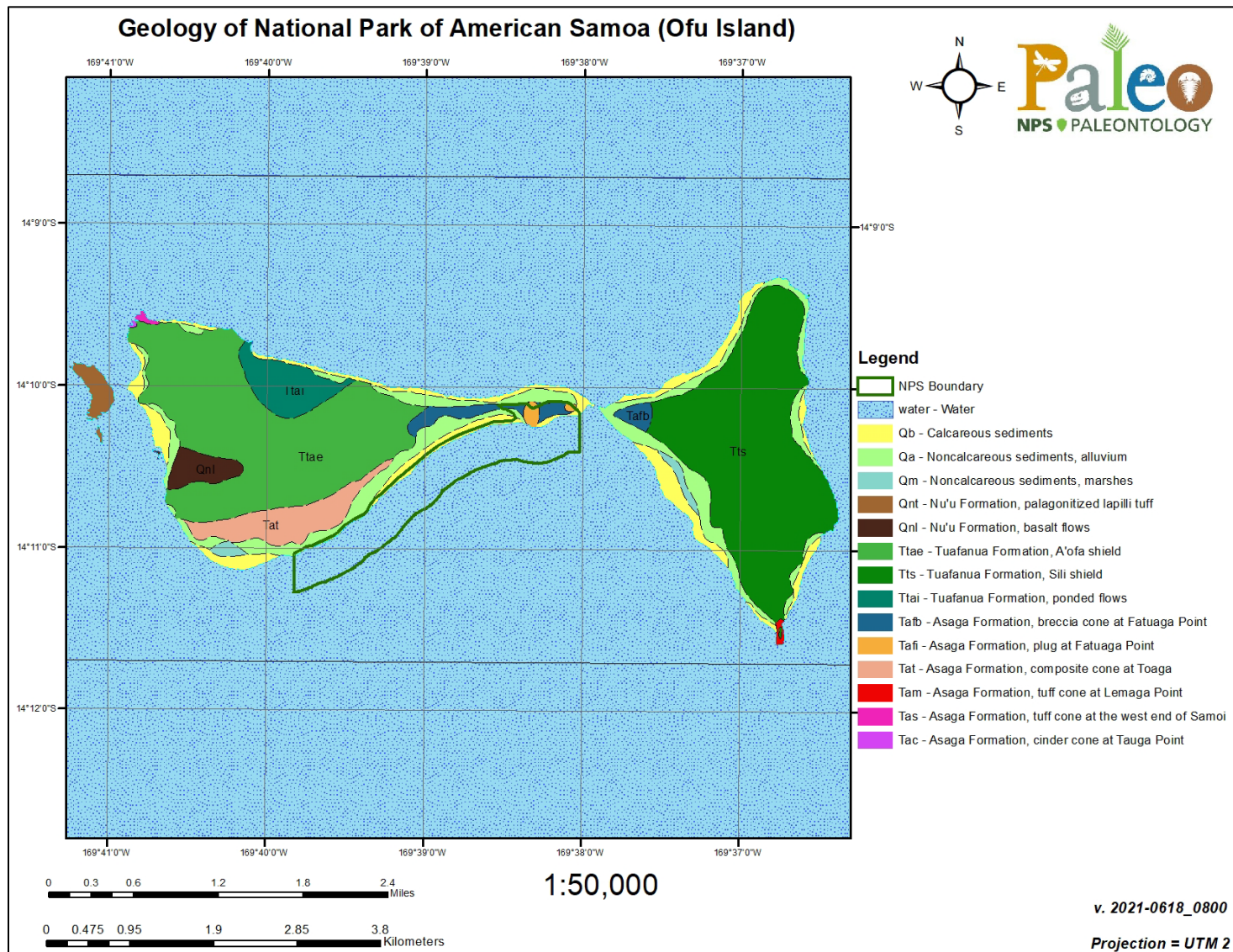


Figure 41. Geologic map of NPSA (Ofu Island unit), American Samoa.

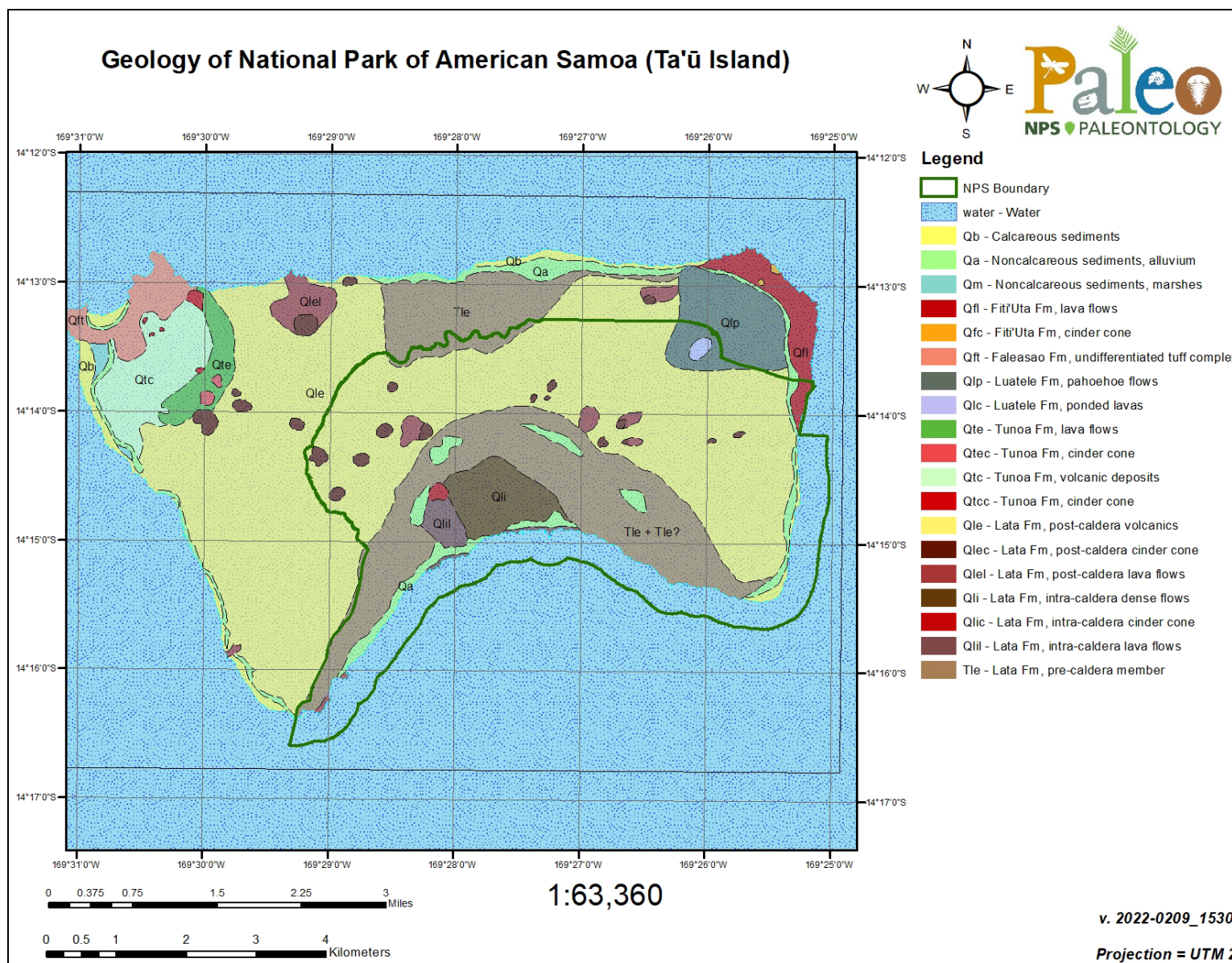


Figure 42. Geologic map of NPSA (Ta'ū Island unit), American Samoa.

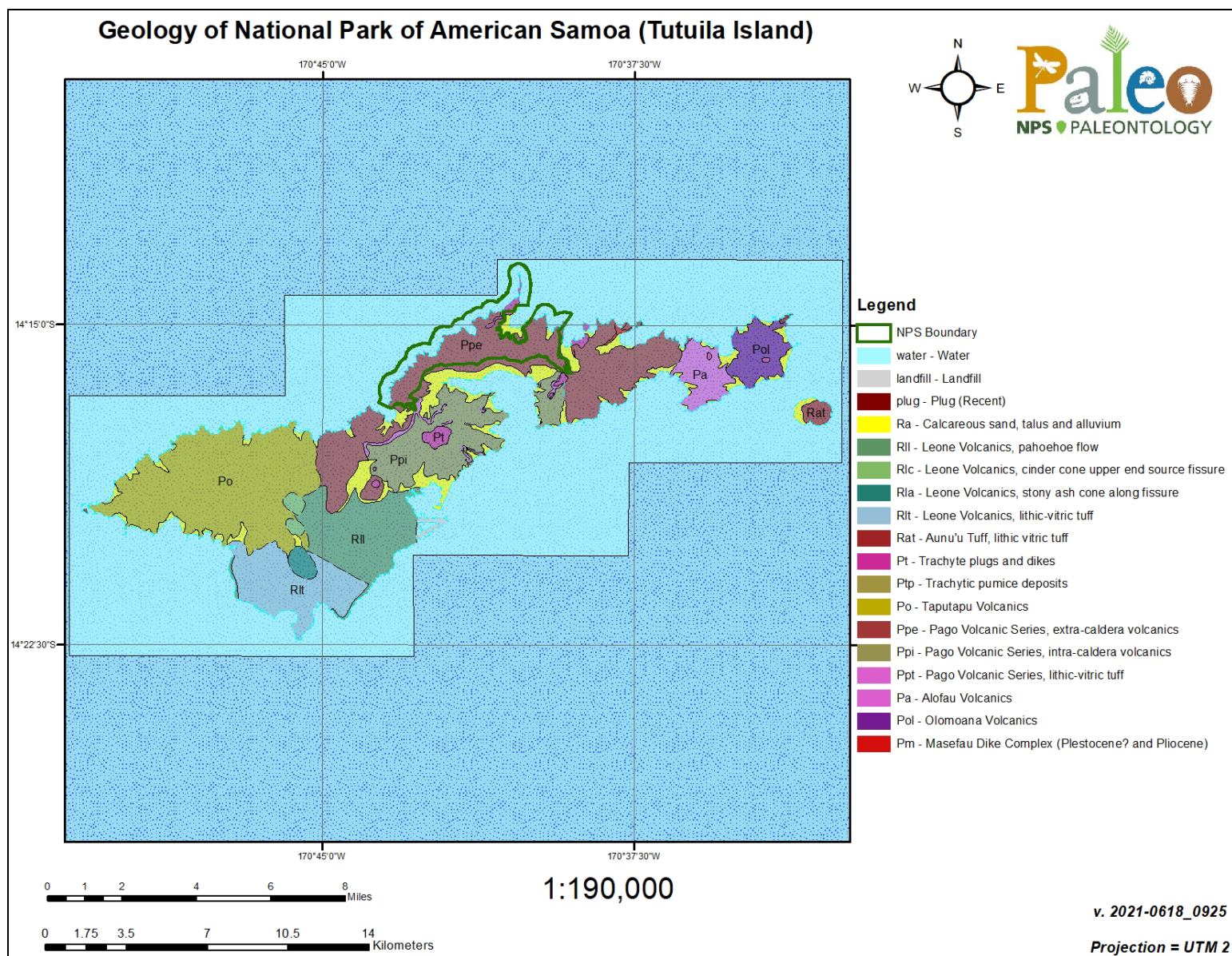


Figure 43. Geologic map of NPSA (Tutuila Island unit), American Samoa.

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

Unit Name (GRI map symbol)	Reference	Stratotype Location	Age
Pago Volcanics (Ppe, Ppi, Ppt)	Stearns 1944	Type locality: at the head of Pago Pago Valley on the north side of the trail to Fagasa, Tutuila Island, American Samoa.	Pliocene–Pleistocene

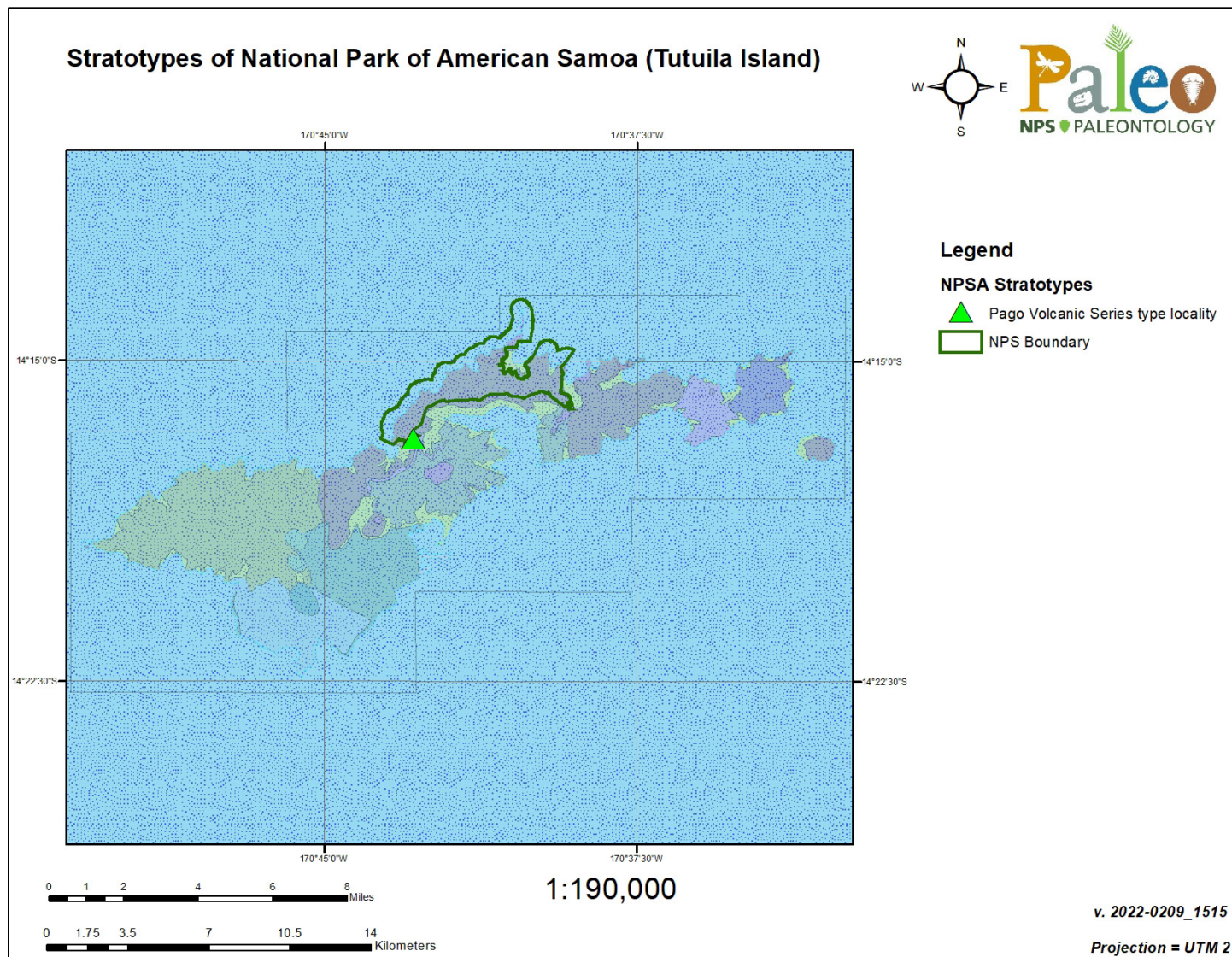


Figure 44. Modified geologic map of NPSA showing stratotype locations. The transparency of the geologic units layer has been increased.

Pago Volcanics

The Pliocene–Pleistocene Pago Volcanics was first proposed by Stearns (1944) as the Pago Volcanic Series to describe a thick sequence of lava flows, tuffs, plugs, cinder cones, and breccias that form the central part of Tutuila Island, American Samoa. The type locality of the unit is located at the head of Pago Pago Valley on the north side of the trail to Fagasa (Table 5; Figures 44 and 45; Stearns 1944). Type locality exposures measure about 150 m (500 ft) thick and consist of an informal tuff and breccia member that forms the entire head wall of the valley (Stearns 1944). Deposits at the type locality contain very fine-grained laminated silty tuffs through lapilli tuffs, coarse blocky beds of breccia, and thick accumulations of basaltic lava fountain debris overlain by lithic beds of pumice and ashy shale (Stearns 1944). The Pago Volcanics overlie rocks of the Alofau Volcanics and underlie the Taputapu Volcanics.

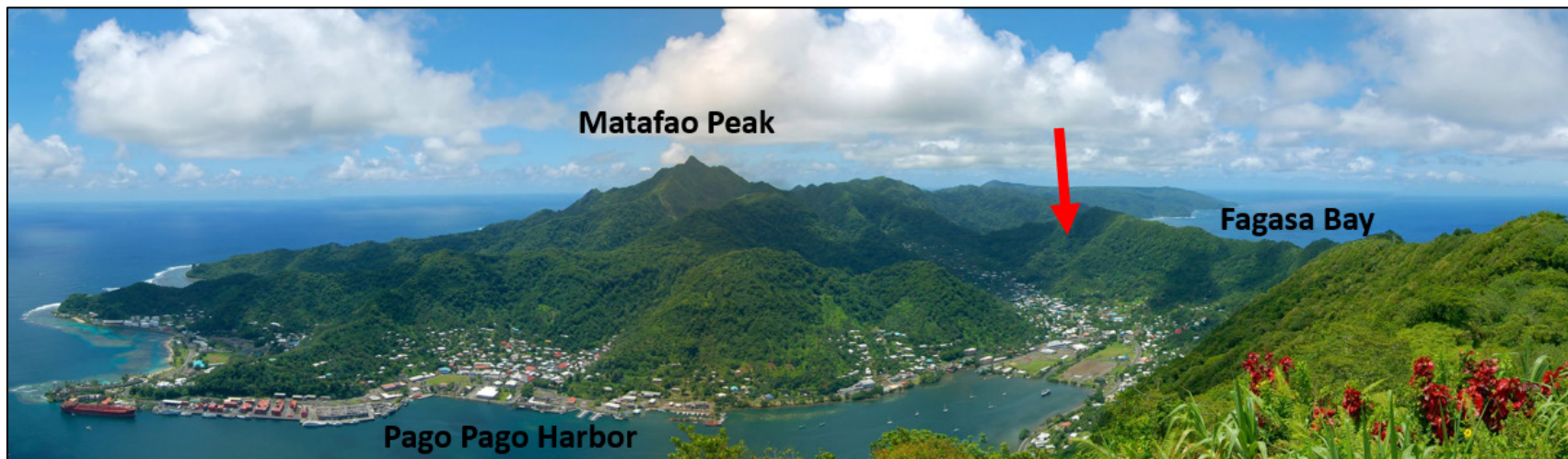


Figure 45. Western view across Pago Pago Valley (NPS). Type locality exposures of the Pago Volcanics are located at the head of the valley on the north trail to Fagasa (red arrow).

Pu‘ukoholā Heiau National Historic Site (PUHE)

Pu‘ukoholā Heiau National Historic Site (PUHE) is located on the northwestern shore of the island of Hawai‘i about 56 km (35 mi) north of Kailua-Kona in the district of south Kohala (Figure 46). Established on August 17, 1972, PUHE encompasses approximately 34 hectares (86 acres) and preserves the ruins of Pu‘ukoholā Heiau (“Temple of the Hill of the Whale”), built in 1791 by King Kamehameha the Great during his rise to power (National Park Service 2016). The park provides scenic views of Kawaihae Bay along the Kohala coast to the southwest where large concentrations of blacktip reef sharks (*Carcharhinus melanopterus*) gather. In addition to the remains of Pu‘ukoholā Heiau, PUHE protects other historically significant sites that include: 1) Mailekini Heiau, a “luakini heiau” (temple), which was eventually converted to a military fort; 2) the ruins of Hale o Kapuni Heiau, a temple dedicated to sharks, which are believed to be sacred ancestral guardians; 3) the Royal Court (or Pelekane), site of diplomatic meetings between King Kamehameha and foreign visitors; and 4) John Young’s homestead, believed to contain the remains of the first Western-style house in Hawai‘i.

PUHE is located at the junction of the slopes of Mauna Kea and Kohala Mountain, and is situated upon lava flows from both volcanoes. The landscape at PUHE inspired King Kamehameha the Great to establish a religious center there, as the geology provided an ideal setting for the construction of a great temple atop a prominent hill where the park is today (Thornberry-Ehrlich 2011c). The temple caps the highpoint of a lava dome that rises approximately 15 m (50 ft) and overlooks the shore toward Kawaihae Bay and Pelekane Beach. The geology of the historic site is predominantly composed of basaltic lava flows of the Pleistocene-age Hāmākua Volcanics that originated from the Mauna Kea volcanic center (Figure 47). The northern portion of PUHE contains lava flows of the Pleistocene-age Pololū Volcanics and Hāwī Volcanics that are associated with Kohala, the oldest volcano on the island of Hawai‘i. Kohala lava flows within PUHE are at least 120,000 years old (Thornberry-Ehrlich 2011c; Sherrod et al. 2021).

There are no designated stratotypes identified within the boundaries of PUHE. There are 12 identified stratotypes located within 48 km (30 mi) of PUHE boundaries, for the Pleistocene Waihū Glacial Member of the Hāmākua Volcanics (type locality), Pōhakuloa Glacial Member of the Hāmākua Volcanics (type locality and reference section), Hopukani Springs Volcanic Member of the Hāmākua Volcanics (type section), Liloe Spring Volcanic Member of the Hāmākua Volcanics (type section), Mākanaka Glacial Member of the Laupāhoehoe Volcanics (type locality), Pololū Volcanics (type section), and Hāwī Volcanics (type section); and the Pleistocene–Holocene Hualālai Volcanics (type locality), Wa‘wa‘a Trachyte Member of the Hualālai Volcanics (type locality), Kona Ash beds of the Hualālai Volcanics (type locality), and the Waikahalulu Volcanic Member of the Laupāhoehoe Volcanics (type section).

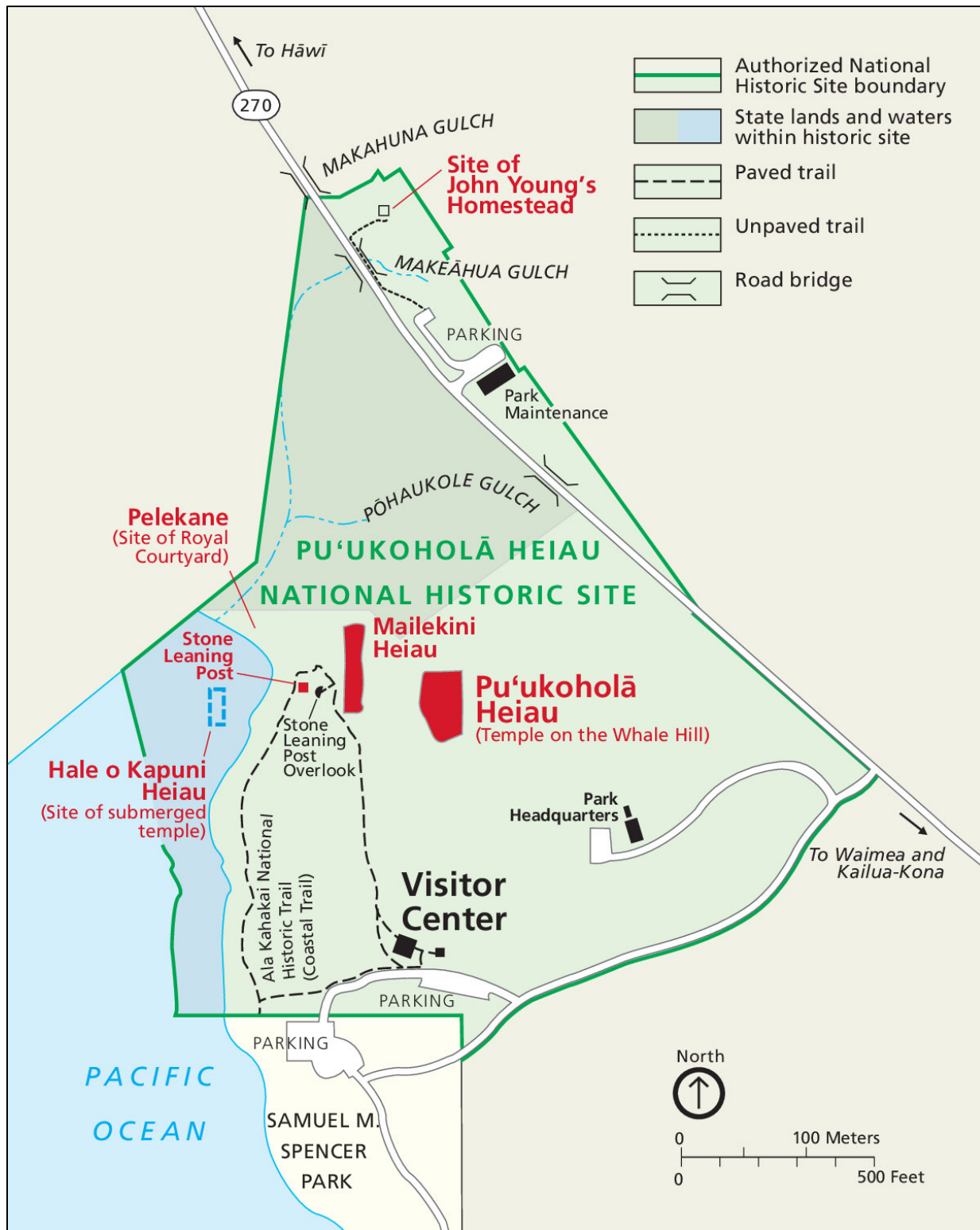


Figure 46. Park map of PUHE, Hawai'i (NPS).

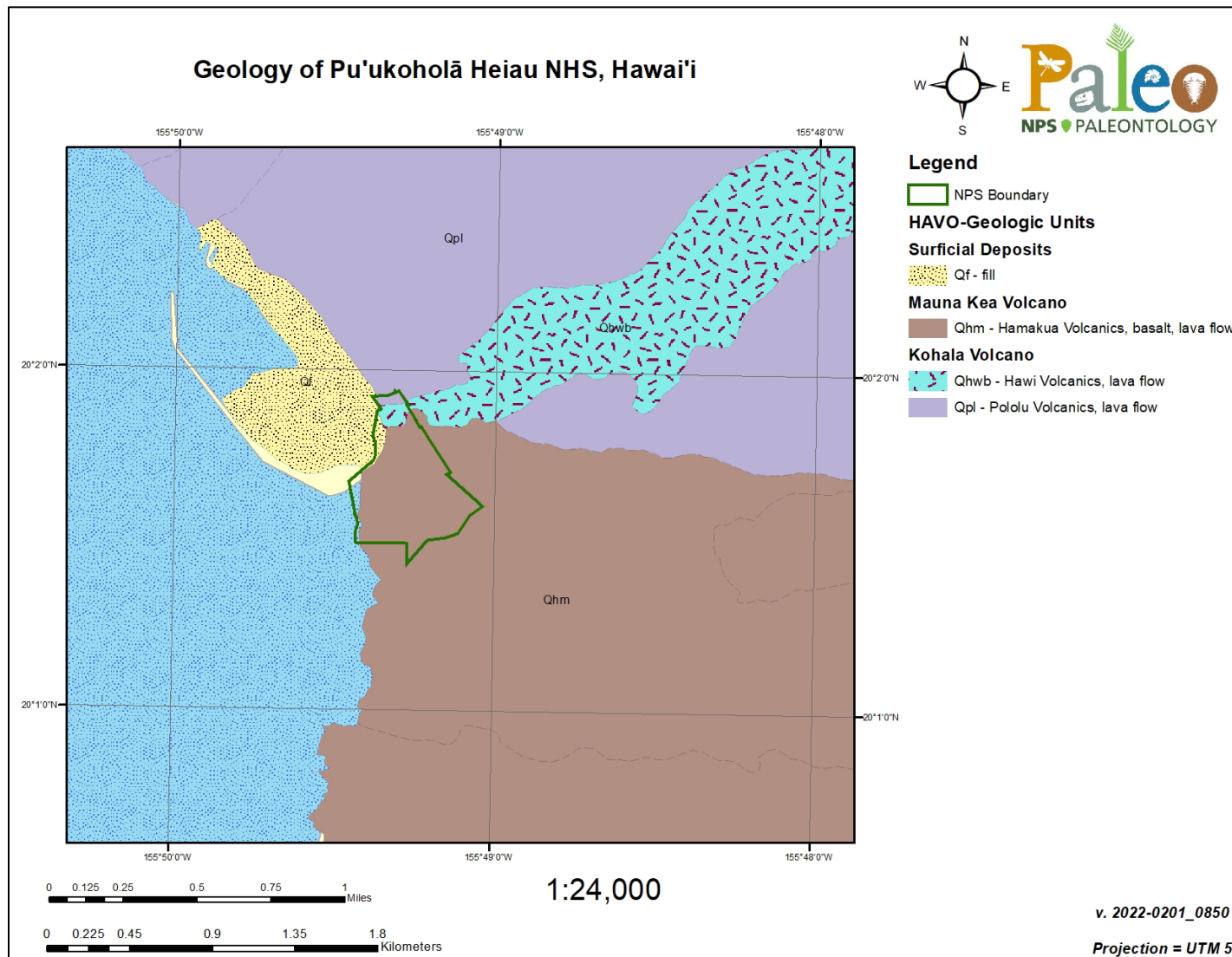


Figure 47. Geologic map of PUHE, Hawai'i.

Pu‘uhonua o Hōnaunau National Historical Park (PUHO)

Pu‘uhonua o Hōnaunau National Historical Park (PUHO) is located on the west coast of the island of Hawai‘i about 35 km (22 mi) south of Kailua-Kona (Figure 48). Originally established as City of Refuge National Historical Park on July 26, 1955, the park was renamed on November 10, 1978, and covers approximately 170 hectares (420 acres) (National Park Service 2016). The word “Pu‘uhonua” means place of refuge, and until the death of King Kamehameha the Great in 1819 the site of PUHO was considered sacred ground for vanquished Hawaiian warriors, non-combatants, and breakers of “kapu” (ancient Hawaiian laws of conduct) could escape death (Thornberry-Ehrlich 2011d). In old Hawai‘i, kapu governed all aspects of society and the punishment for violators was swift and severe—the land of Pu‘uhonua offered the only option for survival by swimming across Kealakekua Bay. Within the park boundaries of PUHO are ancient housing structures, royal fishponds, coconut groves, and scenic shores. Preserved religious relics at PUHO include abandoned temples and carved wooden images (“Ki‘i”) containing the bones of 23 chiefs of ancient Hawaiian society that are believed to infuse the area with their power.

Situated on the western flank of Mauna Loa, the seaward-sloping landscape of PUHO predominantly consists of young volcanic rocks of the Pleistocene–Holocene-age Ka‘ū Basalt (Figure 49). The Ka‘ū Basalt originated from the Mauna Loa volcanic center and forms relatively low-relief lava flows and broad benches along the shore that are mantled by pockets of sandy beaches and rocky shorelines covered by basalt boulders (Thornberry-Ehrlich 2011d). Some of these lava flows form lava tube caves within the southeastern area of PUHO. At least three different lava flows of the Ka‘ū Basalt are mapped within PUHO and include (from north to south): 1) the extensive and most recent 1,500–750 year-old flow that stretches from the northern park boundary to Keanai‘e Pali; 2) a 5,000–3,000 year-old flow that extends from Keanai‘e Pali to the southwestern edge of PUHO; and 3) a 3,000–1,500 year-old flow that covers the southeastern portion of the park (Thornberry-Ehrlich 2011d).

There are no designated stratotypes identified within the boundaries of PUHO. There are four identified stratotypes located within 48 km (30 mi) of PUHO boundaries, for the Pleistocene Nīnole Basalt (type section), Pleistocene–Holocene Hualālai Volcanics (type locality), Wa‘awa‘a Trachyte Member of the Hualālai Volcanics (type locality), and the Kona Ash beds of the Hualālai Volcanics (type locality).

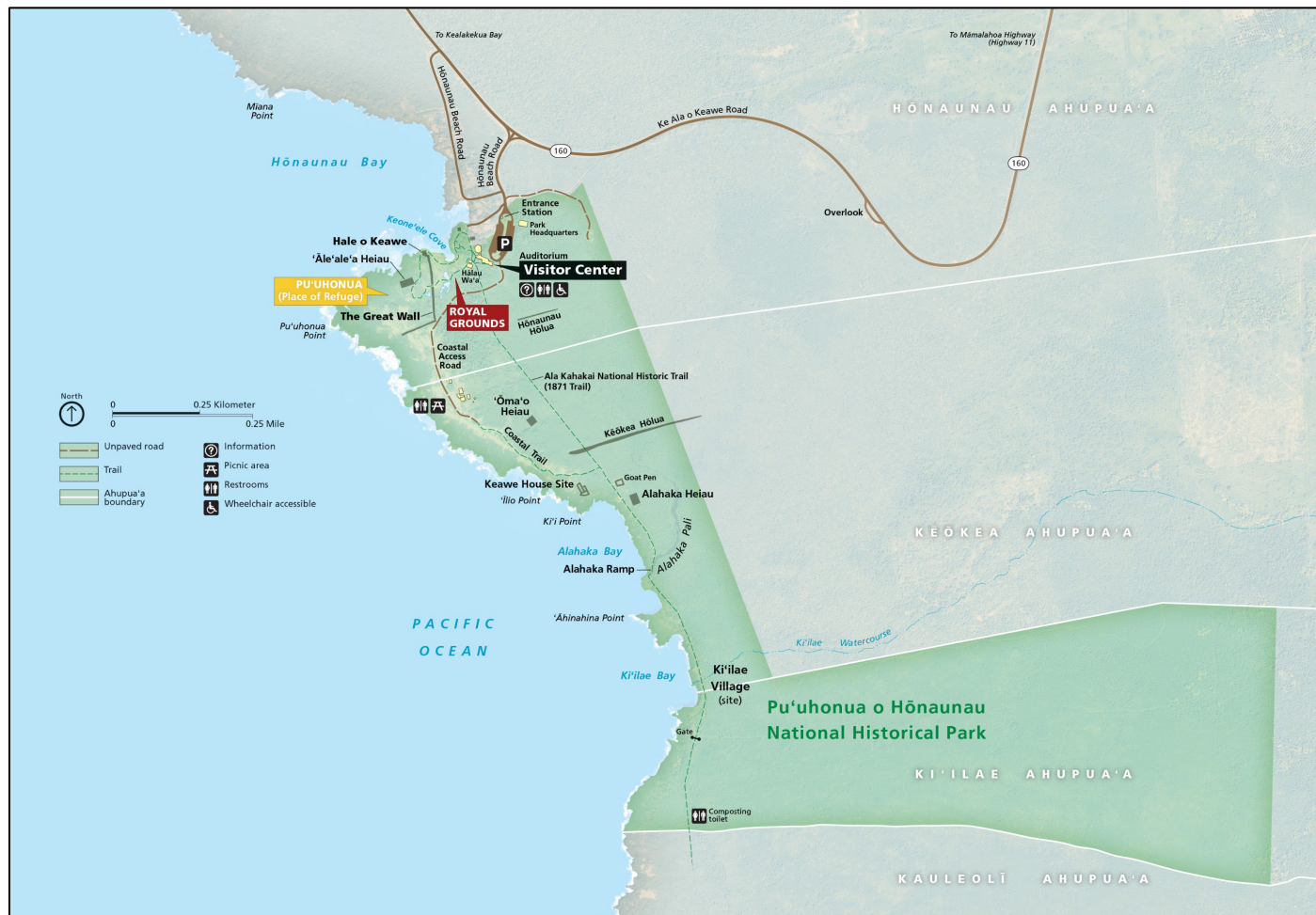


Figure 48. Park map of PUHO, Hawai'i (NPS).

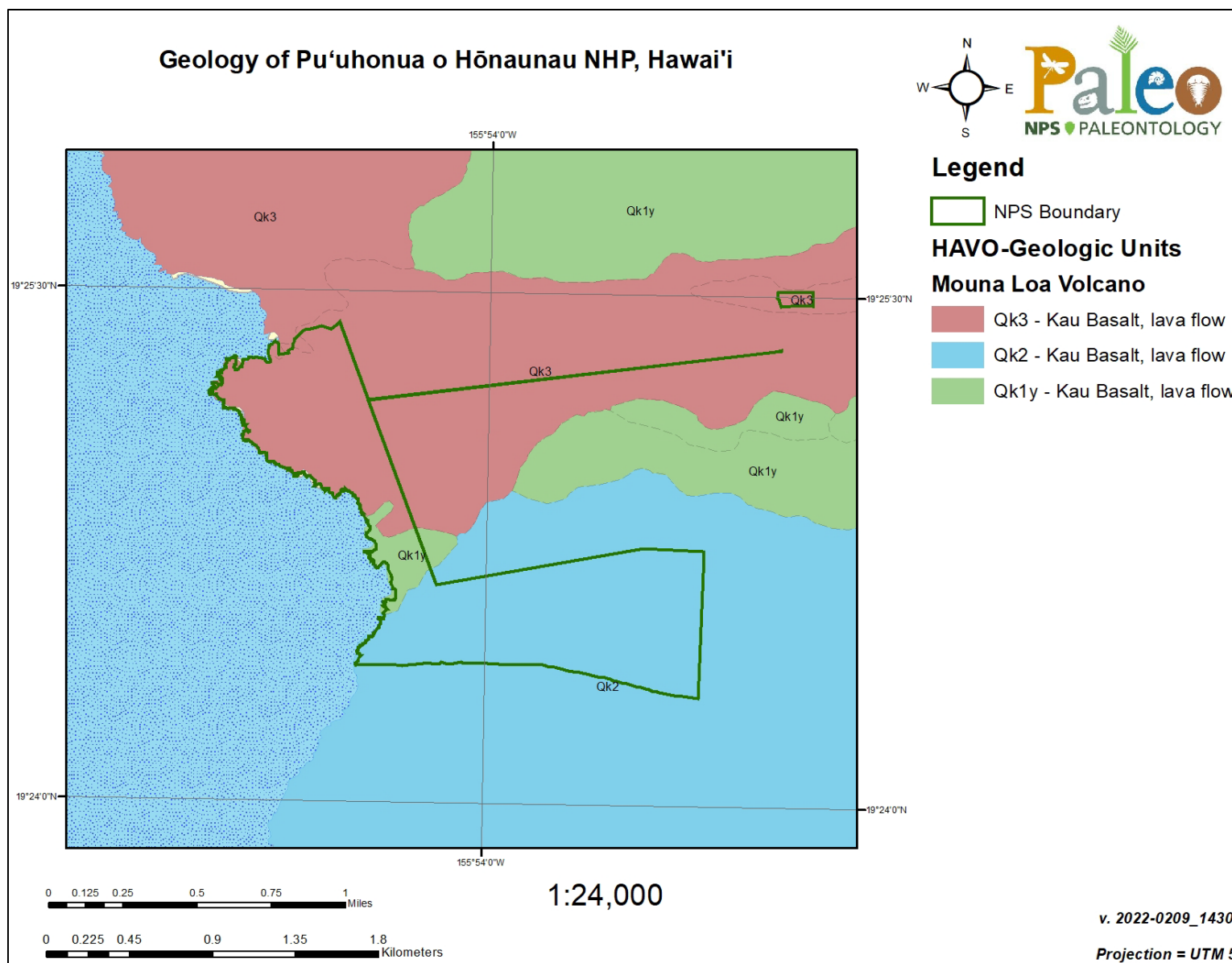


Figure 49. Geologic map of PUHO, Hawai‘i.

War in the Pacific National Historical Park (WAPA)

War in the Pacific National Historical Park (WAPA) is located on the island of Guam, an unincorporated U.S. territory in the western Pacific (Figure 50). Established on August 18, 1978, WAPA encompasses approximately 822 hectares (2,031 acres) distributed across seven units on the island from the summit of Mount Tenjo to the submerged war relics on the offshore coral reefs (National Park Service 2016). The historical park commemorates the bravery and sacrifice of all those who contributed to the campaigns of the Pacific Theater of World War II. The island of Guam was a strategic position during World War II, and the 1944 liberation of Guam by American forces proved to be a major struggle. Key features of the 1944 battles, such as the invasion landing beaches, pillboxes, caves, foxholes, gun emplacements, and historic structures, are preserved in WAPA as tangible World War II resources that help tell the story of the battle over Guam.

The geology of Guam provides the foundation for the dramatic World War II stories that WAPA commemorates. Mapped within the separate park units of WAPA are young, Cenozoic-age volcanic and sedimentary rocks that range from the Eocene–Oligocene to the Holocene. Individual formations within WAPA include (from oldest to youngest) the Eocene–Oligocene Alutom Formation, Miocene Umatac Formation, Miocene–Pliocene Alifan Limestone, Pliocene–Pleistocene Mariana Limestone, and recent beach deposits and alluvium (Figure 51). The volcanic rocks of the Alutom and Umatac Formations record the early history of Guam as part of a still-active island arc. However, the volcanoes near Guam are quiet today and active volcanism is focused on the Northern Mariana Islands (Thornberry-Ehrlich 2012). The accumulation of the younger Alifan and Mariana limestones above the volcanic rocks began before the islands emerged from the sea and are found atop the highest peaks of Guam, indicating a prolonged history of uplift associated with the convergence of the Pacific and Mariana tectonic plates. The limestones of Guam form the substrate for unique ecosystems such as limestone forests and contain classic carbonate karst features such as caves, pinnacles, and blind valleys.

War in the Pacific National Historical Park contains one identified stratotype that represents the type section of the Miocene–Pliocene Alifan Limestone (Table 6; Figure 52). In addition to the designated stratotype located within WAPA, stratotypes located within 48 km (30 mi) of the park boundaries include the Eocene–Oligocene Alutom Formation (type locality); Oligocene Mahlac Member of the Alutom Formation (type locality); Miocene Umatac Formation (type section), Bonya Limestone (type locality), and Talisay Member of the Alifan Limestone (type locality); Miocene–Pliocene Barrigada Limestone (type section and type locality) and Janum Formation (type section); and the Pliocene–Pleistocene Agana Argillaceous Member of the Mariana Limestone (type locality).

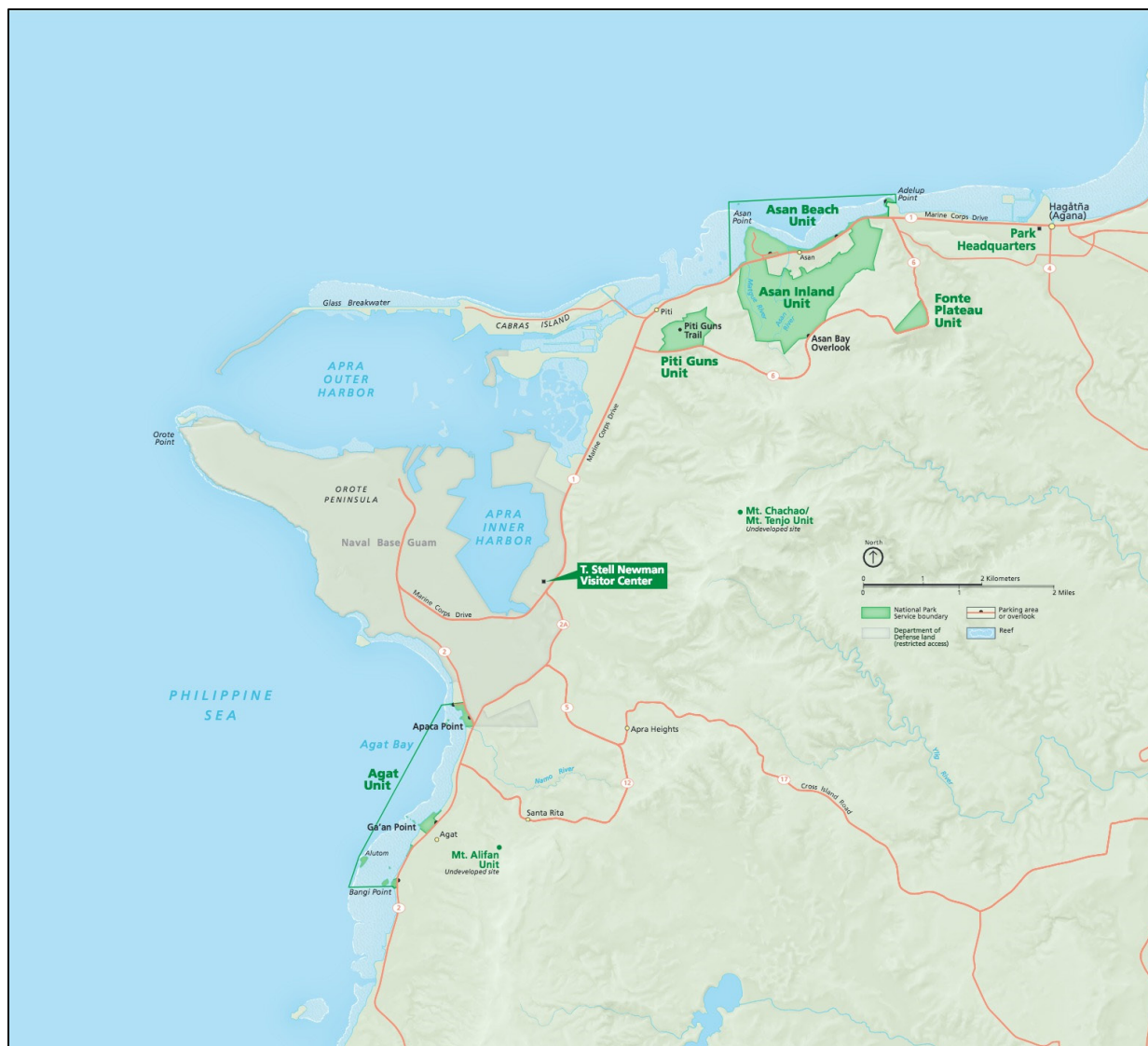


Figure 50. Park map of WAPA, Guam (NPS).

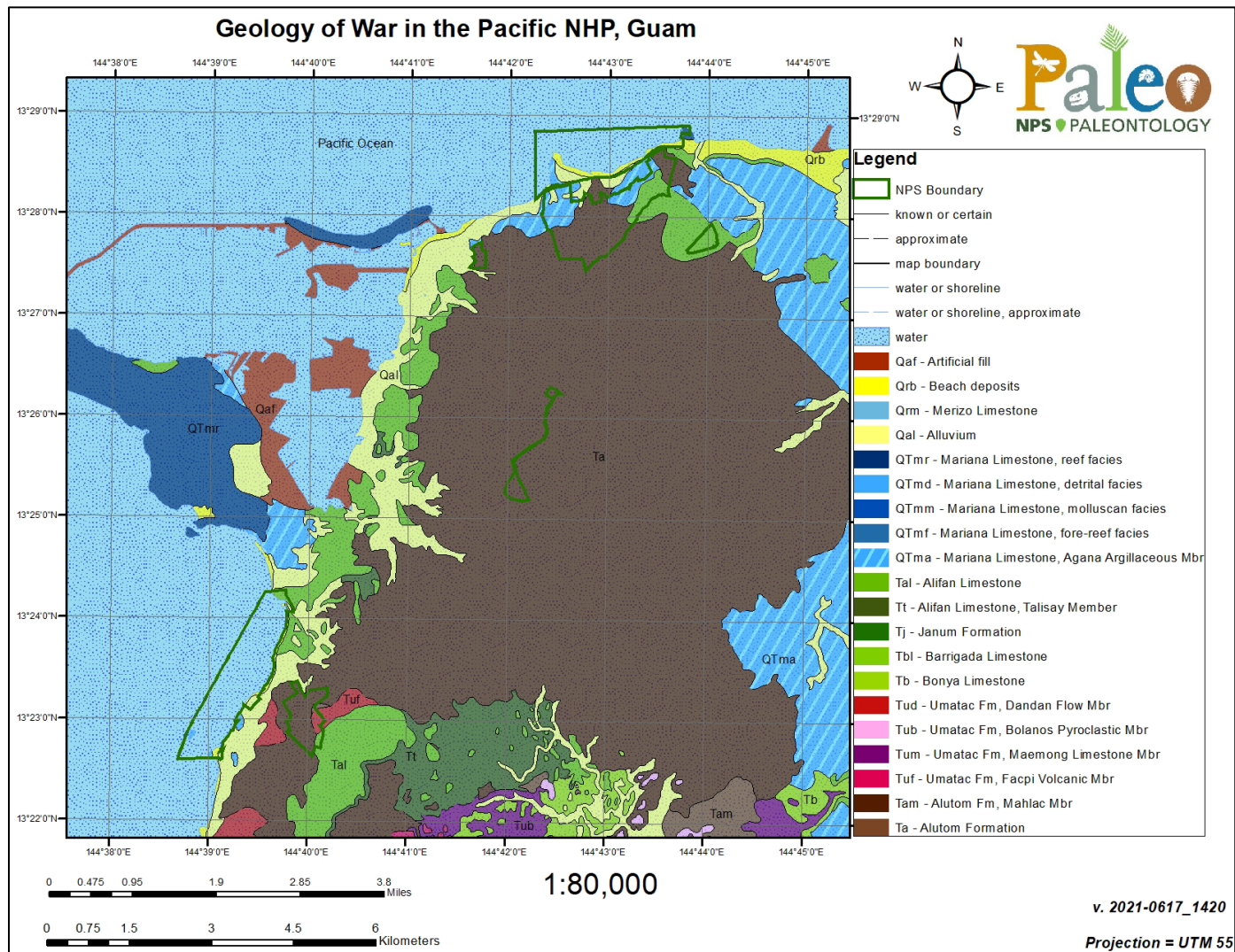


Figure 51. Geologic map of WAPA, Guam.

Table 6. List of WAPA stratotype units sorted by age with associated reference publications and locations.

Unit Name (GRI map symbol)	Reference	Stratotype Location	Age
Alifan Limestone (Tal)	Tracey et al. 1964	Type section: in Alifan quarry of the Naval Ammunition Depot above Santa Rita on the north slope of Mount Alifan, island of Guam.	Miocene–Pliocene

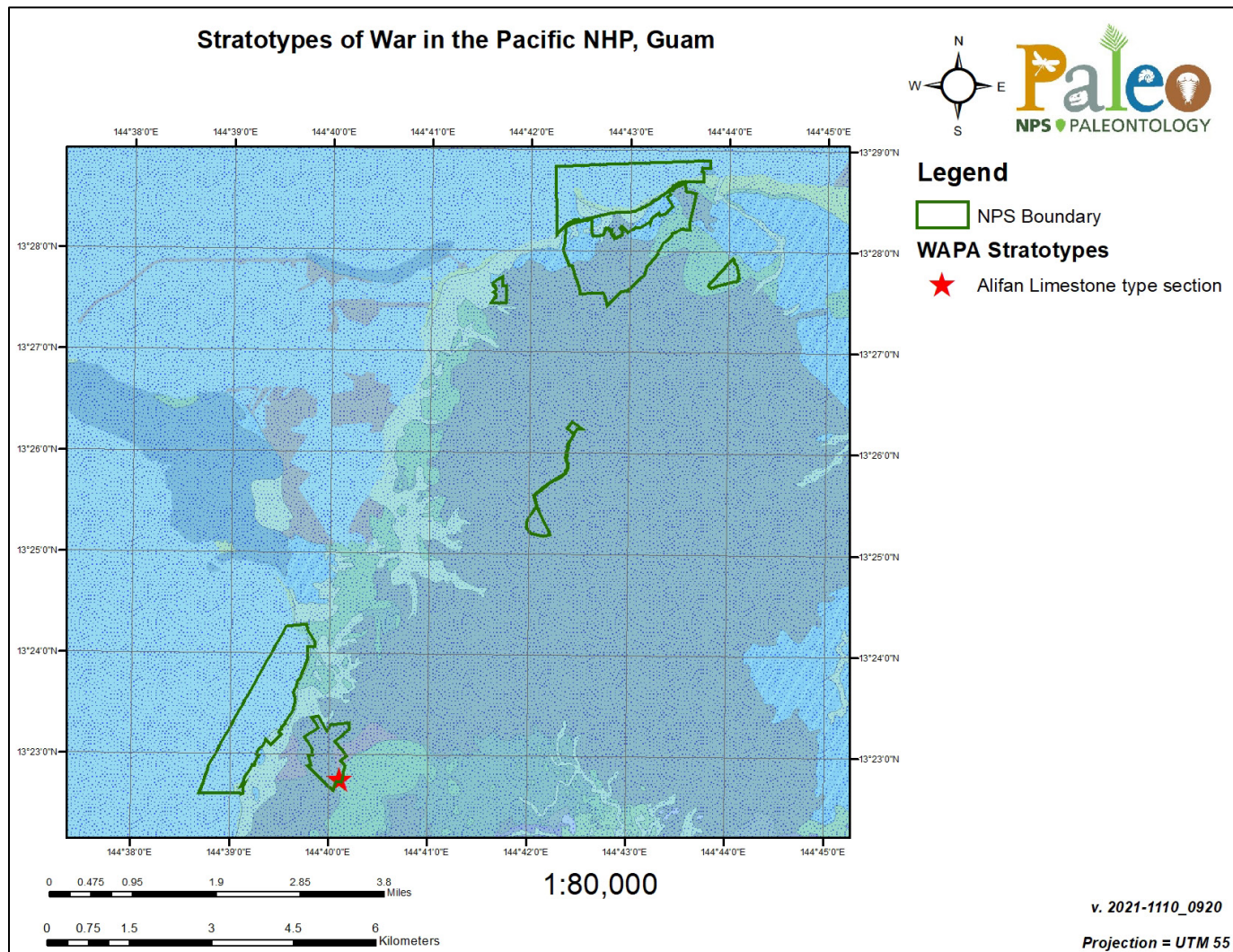


Figure 52. Modified geologic map of WAPA showing stratotype locations. The transparency of the geologic units layer has been increased.

Alifan Limestone

The Miocene–Pliocene Alifan Limestone was named by Tracey et al. (1964) after its type section exposure in the Alifan quarry of the Naval Ammunition Depot above Santa Rita on the north slope of Mount Alifan, Guam (Table 6; Figures 52 and 53). The type section exposure consists of red to pink fine detrital limestone gradationally overlain by white coral-rich limestone that measures approximately 46 m (150 ft) thick (Tracey et al. 1964). In the central Guam region adjacent to the type section, the limestone caps the mountain ridge from Mount Alifan to Mount Lamlam, the highest point in Guam (Tracey et al. 1964). At the type section the basal Alifan Limestone is in probable fault contact with the Alutom Formation and underlies the Mariana Limestone (Tracey et al. 1964).

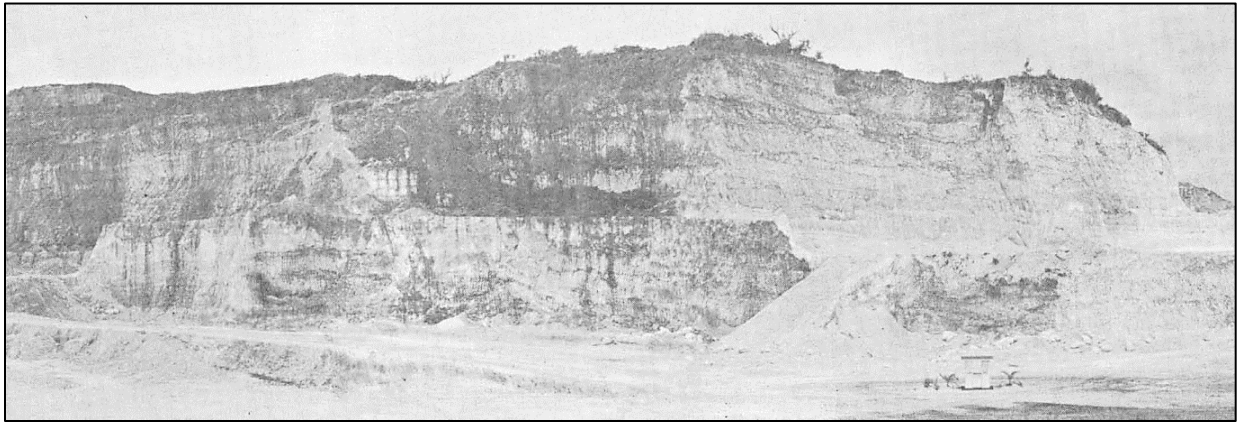


Figure 53. Alifan Quarry type section exposure of the Alifan Limestone, consisting of 46 m (150 ft) of red to pink limestone overlain by white coral-rich limestone. Figure 13 from Tracey et al. (1964).

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 PACN Geologic Type Section Inventory report is finalized, the NPS Geologic Resources Division should schedule a briefing for the staff of the PACN 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 infrastructural 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.
- 5) From the assessment in (4), NPS staff should focus on registering new stratotypes at state and local government levels where current legislation allows, followed by a focus on registering at federal and state levels where current legislation allows.
- 6) The NPS Geologic Resources Division should work with park and network staff to compile and update a central inventory of all designated stratotypes and potential future nominations.
- 7) The NPS Geologic Resources Division should ensure the park-specific Geologic Type Section Inventory Reports are widely distributed and available online.
- 8) The NPS Geologic Resources Division should work with park and network staff to regularly monitor geologic type sections to identify any threats or impacts to these geologic heritage features in parks.
- 9) The NPS Geologic Resources Division should work with park and network staff to obtain good photographs of each geologic type section within the parks. In some cases, where there may be active geologic processes (rock falls, landslides, coastal erosion, etc.), the use of photogrammetry may be considered for monitoring of geologic type sections. GPS locations should also be recorded and kept in a database when the photographs are taken.

- 10) The NPS Geologic Resources Division should work with park and network staff to consider the collection and curation of geologic samples from type sections within respective 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.
- 12) The NPS Geologic Resources Division should work with park and network staff in developing conservation protocols of significant type sections, either by appropriate fencing, walkways, and information boards or other means (e.g., phone apps).

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Appendix A: Source Information for GRI Maps of PACN Parks

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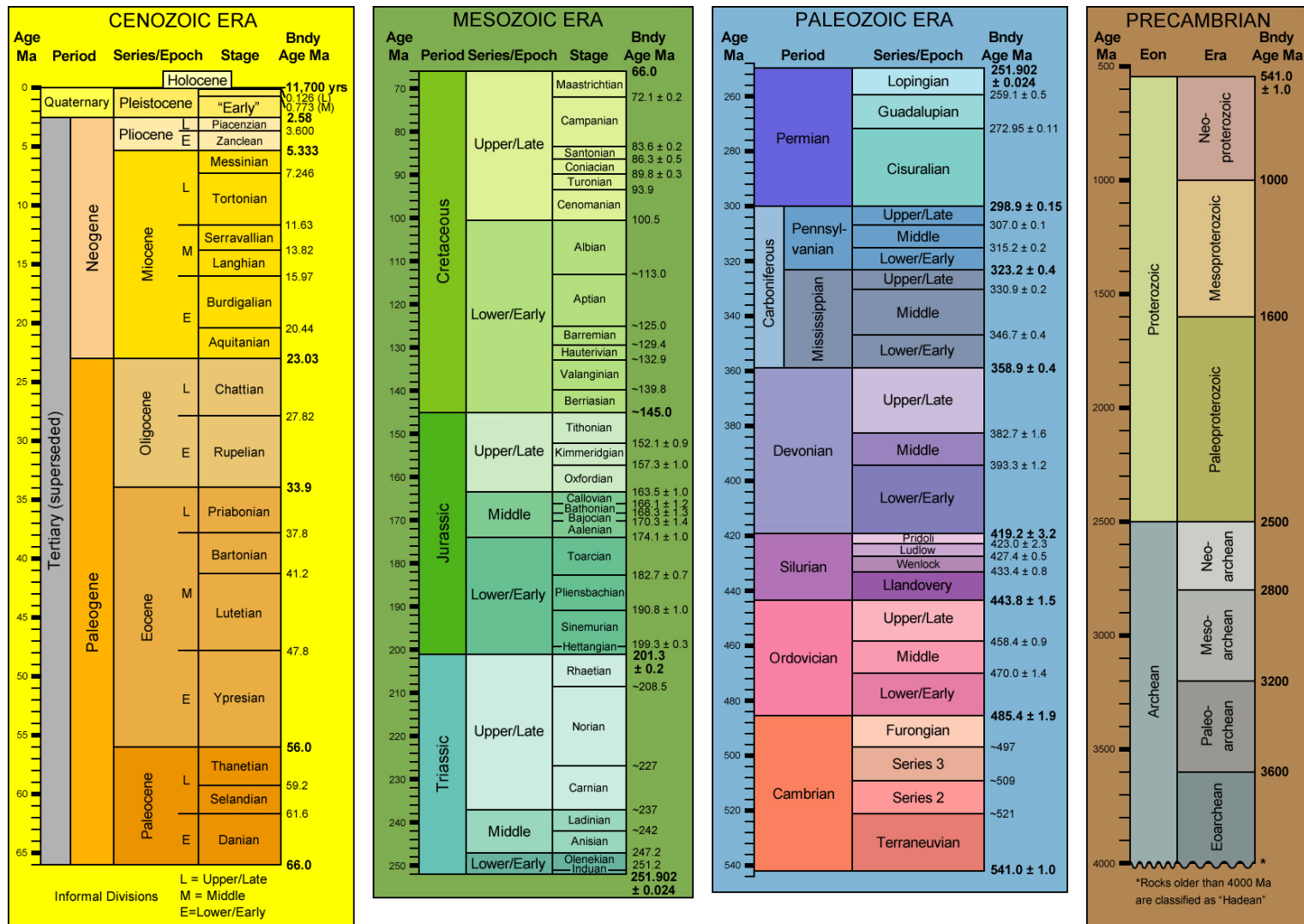
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Appendix B: Geologic Time Scale



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

NPS 963/180059, April 2022

National Park Service
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