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American Memorial Park

Geologic Resources Inventory Report

The Court of Honor and Flag Circle was dedicated on June 15, 1994. The American flag is displayed at the center of the Flag Circle and is surrounded by the flags of the US Navy, US Marine Corps, US Army, and US Coast Guard. The Court of Honor memorial consists of 26 granite panels inscribed with the names of the 5,204 service men who perished during the operation.

(public domain image is available at https://npgallery.nps.gov/AssetDetail/775d6315-df2a-4ae9-ba7c-c172d88b42f8)

American Memorial Park: Geologic resources inventory report

Science Report NPS/SR—2024/147

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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.

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Abstract

Geologic Resources Inventory reports provide information and resources to help park managers make decisions for visitor safety, planning and protection of infrastructure, and preservation of natural and cultural resources. Information in GRI reports may also be useful for interpretation. This report synthesizes discussions from a scoping meeting held in 2003 and a follow-up conference call in 2021. Chapters of this report discuss the geologic heritage, geologic history, geologic features and processes, and geologic resource management issues of American Memorial Park. Guidance for resource management and information about the previously completed GRI GIS data and poster (separate products) is also provided.

Acknowledgements

The GRI team thanks the participants of the 2003 scoping meeting and the 2021 follow-up conference calls for their assistance in this inventory. The lists of participants reflect the names and affiliations at the time of the meeting and call. The names of participants are listed in alphabetical order by last name. Because the GRI team does not conduct original geologic mapping, we are particularly thankful for the US Geological Survey for its map of the island. This report and accompanying GIS data could not have been completed without them.

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Executive Summary

Comprehensive park management to fulfill the National Park Service (NPS) mission requires an accurate inventory of the geologic features of a park unit, but park managers may not have the needed information, geologic expertise, or means to complete such an undertaking; therefore, the Geologic Resources Inventory (GRI) provides information and resources to help park managers make decisions for visitor safety, planning and protection of infrastructure, and preservation of natural and cultural resources. Information in the GRI report may also be useful for interpretation.

American Memorial Park was created to honor the American and Marianas people who died in the World War II Marianas Campaign. Situated on the western side of the volcanic island of Saipan, the park is in a geologically active area of the western Pacific Ocean. The geologic story of American Memorial Park, herein called the "park," and the island of Saipan involves the construction of a volcanic island along the Ring of Fire, the subsequent buildup of carbonate reefs, and then the uplift of volcanic and carbonate rocks. Volcanism was associated with the subduction of the Pacific Plate beneath the Philippine Sea Plate along the Mariana Trench. Rocks in the park area record only a brief portion of Earth's 4.5-billion-year history; Saipan's history in the geologic record began just 45 million years ago, during the Eocene Epoch. The geologic history of the island greatly influenced its cultural history and the history commemorated by the park. Ongoing, dynamic coastal and weathering processes continue to shape the landscape.

While much information exists about Saipan geology, this report is significant in that it is a compilation document of the geology of the park. This report is supported by the GRI-compiled map of the surficial/bedrock geology of the park. References to the geologic map and management of geologic resources are key components of this report. The GRI report consists of the following seven chapters:

Geologic Resources Inventory—This chapter introduces the Geologic Resources Inventory (GRI), highlights the GRI process and products, and recognizes GRI collaborators. A geologic map in GIS format is the principal deliverable of the GRI. This chapter highlights the source map used by the GRI team in compiling the GRI GIS data for the park and provides specific information about the use of these data. It also calls attention to the poster that illustrates these data.

Introduction—This chapter provides background information about the establishment of the park, park significance, and its geologic setting.

Geologic Heritage of American Memorial Park—This chapter highlights the significant geologic features, landforms, landscapes, and stories of the park preserved for their heritage values. It also draws connections between geologic resources and other park resources and stories.

Geologic History of Saipan—This chapter describes the chronology of geologic events that formed the present landscape.

Geologic Features and Processes—This chapter describes the geologic features and processes of significance for the park and highlights them in a context of geologic time. The features and processes are discussed in relative order of geologic time, from oldest to youngest, and include Tagpochau Limestone and karst landscape development; emerged carbonate sand; wetlands and mangrove forest; normal faults; earthquakes; paleontological resource potential; Micro Beach and coastal features and processes; and disturbed lands.

Geologic Resource Management Issues—This chapter discusses management issues related to the park's geologic resources (features and processes). Issues, which are discussed in order of management priority, are erosion; wetland preservation; stormwater contamination and karst permeability; groundwater withdrawal; earthquakes, tsunami, and volcanic hazards; climate change and sea level rise; artificial fill concerns; and paleontological resource inventory, monitoring, and protection.

Guidance for Resource Management—This chapter follows and is a follow up to the "Geologic Resource Management Issues" chapter. It provides resource managers with a variety of ways to find and receive management assistance with geologic resources. A summary of laws, regulations, and policies which apply to geologic resources is also provided.

Additional References, Resources, and Websites—This chapter provides a thorough list of additional sources of information (e.g., websites, tools, publications, organizations) that may be useful to further explore the topics presented in this report.

In addition to these chapters, "Literature Cited" compiles all the references cited in this GRI report. It serves as a source of park-specific geologic information that is applicable to the protection, management, and interpretation of the historic site's geologic resources.

Geologic Resources Inventory

The Geologic Resources Inventory (GRI), which is administered by the Geologic Resources Division of the National Park Service (NPS) Natural Resource Stewardship and Science Directorate, provides geologic map data and pertinent geologic information 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 NPS Inventory and Monitoring Program. Most inventories were point-in-time surveys to learn about the location or condition of resources, including the presence, distribution, or status of plants, animals, air, water, soils, landforms, and climate, and were completed by 2010, but several of the more extensive or complex inventories, such as vegetation and geology, are still in progress in some parks.

GRI Products

Starting in 2003, the GRI team—which is a collaboration between staff at the NPS, Geologic Resources Division, and Colorado State University, Department of Geosciences—completed three tasks as part of the GRI for American Memorial Park (referred to as the "park" throughout this report): (1) conducted a scoping meeting and provided a scoping summary; (2) provided digital geologic map data in a geographic information system (GIS); (3) provided a GRI report (this document); and (4) created a poster to display the GRI GIS data. GRI products are available on the "Geologic Resources Inventory—Products" website and through the NPS Integrated Resource Management Applications (IRMA) DataStore portal (see "NPS Reference Tools").

GRI Scoping Meeting

On 20–21 March 2003, the NPS held a scoping meeting in Hawai'i for all parks in the Pacific Island Inventory and Monitoring Network. The scoping meeting brought together park staff and geologic experts, who reviewed and assessed available geologic maps, developed a geologic mapping plan, and discussed geologic features, processes, and resource management issues to be included in the final GRI report. A scoping summary (Rutherford and Kaye 2006) summarizes the geological findings of that meeting as part of an overall vital signs monitoring plan for the Pacific Island Network of parks.

GRI Report

On 16 and 18 November 2021, the GRI team hosted follow-up conference calls for park staff and interested geologic experts. The calls provided an opportunity to get back in touch with park staff, introduce "new" (since the 2003 scoping meeting) staff to the GRI process, and update the list of geologic features, processes, and resource management issues for inclusion in the final GRI report.

This report is a culmination of the GRI process. It synthesizes discussions from the scoping meeting in 2003, the follow-up conference calls in 2021, and additional geologic research. The selection of geologic features was guided by the previously completed GRI map data, and the writing reflects the data and interpretation of the source map author. Information from the park's foundation document (National Park Service 2017) was also included as applicable to the park's geologic resources and resource management.

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 in this report and associated GRI GIS data.

GRI GIS Data

A geologic map is the fundamental tool for depicting the geology of an area. A geologic map in GIS format is the principal deliverable of the GRI program.

Introduction to Geologic Maps

Geologic maps are two-dimensional representations of the three-dimensional geometry of rock and sediment at or beneath the land surface (Evans 2016). Geologic maps are generally one of two types: bedrock or surficial. Bedrock geologic maps encompass older, typically more consolidated (i.e., hard, solid rock) sedimentary, metamorphic, or igneous rocks. Sedimentary rocks form from fragments of other rocks or chemical precipitation. Igneous rocks form by the cooling of molten material. Metamorphic rocks are those that have been altered by high temperature, high pressure, and/or fluids. Bedrock map units are generally differentiated based on age and rock type. Surficial geologic maps typically encompass deposits that are unconsolidated (i.e., loose pieces and not solid rock) and formed during the past 2.6 million years (Quaternary Period). Geomorphic surfaces, geologic processes, or depositional environments differentiate surficial geologic map units.

The colors and labels on a geologic map indicate the rocks or deposits and their ages. In addition to color, map unit symbols on geologic maps delineate the ages and types of rocks and their formations. Usually, a map unit symbol consists of an uppercase letter indicating age (e.g., **T** for Tertiary, **QT** for Quaternary and Tertiary, and **Q** for Quaternary) and lowercase letters indicating the rock formation's name or the type of deposit (Table 1). Other symbols on geologic maps depict the contacts (boundaries between two rock units identified on the basis of a compositional, textural, structural, or temporal difference) between map units or structures such as faults or folds. A fault is a fracture in rock along which movement has occurred. Folds are geologic structures formed by bodies of rock being bent or flexed. Some map units, such as landslide deposits, delineate locations of past geologic hazards that may be susceptible to future activity. Geologic maps may also show human-made features, such as artificial fill, wells, or mines.

Table 1. Geologic time scale. The geologic time scale puts the divisions of geologic time in stratigraphic order, with the oldest divisions at the bottom and the youngest at the top. The table groups geologic units in the GRI GIS data by age and identifies significant local and global geologic events that occurred during each interval of time.

Geologic Time Unit [A]	Age [B]	Geologic Map Unit Symbols	Geologic Events
Quaternary Period (Q): Holocene (H)	Less than 11,700 years ago	**Qmc, Qtd, Qx, Ql, Qst, Qa, Qc, Qm [C], Qrl [C], Qgs, Qrb, Qaf [C]**	Weathering and erosion; coastal processes; faulting. Human modifications to the landscape.
Quaternary Period (Q): Pleistocene Epoch (PE)	2.6 million to 11,700 years ago	**QTtvc, Qp, Qta, QTmr, QTma, QTmmp, QTmm, QTmh**	Global glaciations and sea level fluctuations; last limestone formed
Tertiary (T): Neogene Period (N): Pliocene Epoch (PL)	5.3 million to 2.6 million years ago	**Ttos, Tto1, Tdoc, Tdot, Tdos**	Periods of uplift and subsidence; cessation of volcanism on Saipan
Tertiary (T): Neogene Period (N): Miocene Epoch (MI)	23.0 million to 5.3 million years ago	**Ttv [D], Ttm, Ttl [D], Tff, Tf**	Volcanism slowed on Saipan; periods of submergence
Tertiary (T): Paleogene Period (PG): Oligocene Epoch (OL)	33.9 million to 23.0 million years ago	**Tmt, Tmp, Tmw, Thc, Thf, Tdm, Tdc, Tdcg, Tdb**	Volcanism and limestone deposition
Tertiary (T): Paleogene Period (PG): Eocene Epoch (E)	56.0 million to 33.9 million years ago	**Tsf, Tst,**	Philippine Sea plate grows; volcanism of Saipan begins
Tertiary (T): Paleogene Period (PG): Paleocene Epoch (EP)	66.0 million years to 56.0 million years ago	None mapped	Philippine Sea plate begins to form; Izu-Bonin-Mariana subduction begins
Cretaceous Period (K)	145.0 million to 66.0 million years ago	None mapped	Pacific plate continues to grow; Global mass extinction
Jurassic Period (J)	201.3 million to 145.0 million years ago	None mapped	Pacific plate begins to form
Triassic Period (TR)	251.9 million to 201.3 million years ago	None mapped	Panthalassa Ocean Global mass extinction

[A] Cell colors correspond to USGS suggested colors for geologic maps. Letters in parentheses are abbreviations for geologic time units. The Quaternary Period and Tertiary time are part of the Cenozoic Era. The Triassic, Jurassic, and Cretaceous Periods are part of the Mesozoic Era.

[B] Boundary ages follow the International Commission on Stratigraphy (2022).

[C] These geologic units are mapped within the park.

[D] These geologic units are mapped immediately adjacent to the park and impact processes occurring within the park.

The Park's Map

The digital geologic map for the island of Saipan includes both bedrock and surficial geologic data. Bedrock map units are primarily from the Tertiary Period (5.3 million to 2.3 million years ago) and the early part of the Quaternary Period (2.6 million years ago to the present). They include some volcanic (igneous) and sedimentary rocks. No metamorphic rocks are mapped on Saipan (Weary and Burton 2011). The bedrock units have formalized names, from oldest to youngest: Sankakuyama Formation, Hagman Formation, Densinyama Formation, Matansa Limestone, Tagpochau Limestone, Fina-sisu Formation, Donni formation, Mariana Limestone, and Tanapag Limestone. Most of these units have subunits and/or surficial units that formed as a product of weathering (breakdown) or erosion of the unit. The surficial units on the map are named for the environment in which they were deposited (e.g., marsh deposits or beach deposits) or the processes responsible for their formation (e.g., landslide deposits or slumped limestone blocks). The chronology and formation of these units are discussed in "Geologic History of Saipan."

On the geologic map for the island of Saipan, pink to red colors represent the very oldest rocks, which are from the Tertiary Period. In general, as the units on the map become younger, the colors change to pale blue and purple, and then to brownish colors. Green to yellow colors represent the youngest deposits, which are beach, marsh, and alluvium (river) deposits from the Quaternary Period (2.6 million years ago to the present). The map includes contacts: known or certain, approximate, concealed, inferred, and water or shoreline contacts. Deformation areas, places where the rocks are broken and deformed that are large enough to map, are included for Saipan. Faults are the only geologic structures included on Saipan's geologic map. The map also includes points locating mines and borrow pits, places where rocks were sampled to determine their age, and observation localities where the orientations of the rocks were measured (Weary and Burton 2011).

The park itself is only a small portion of the island of Saipan, so many features that appear on the island-wide map are not mapped in the park. Within park boundaries, only surficial units (marsh deposits and emergent carbonate sands) and human-made features (artificial fill) and the contacts between them are mapped. No bedrock, faults, deformation areas, or points are mapped at American Memorial Park (Weary and Burton 2011).

Source Map

The GRI team does not conduct original geologic mapping. Scoping participants and the GRI team identified the best available source geologic maps for a park unit. Determinations were made based on coverage (extent of area mapped), map scale, date of mapping, and compatibility of the mapping to the current geologic interpretation of an area. The GRI team may compile multiple source maps to cover a park boundary or provide a greater extent as needed for resource management. The GRI team then compiled and converted digital data to conform to the GRI GIS data model and digitized paper maps.

The following map was the source for the GRI GIS data for the park. This source map also provided information for this report.

- Preliminary geologic map of the island of Saipan, Commonwealth of the Northern Mariana Islands (Weary and Burton 2011)

GRI Geodatabase Model and Data Set

The GRI team standardizes map deliverables by using a data model. The GRI GIS data for the park was compiled using data model version 2.3, which is available at http://go.nps.gov/gridatamodel.

This data model dictates GIS data structure, including layer architecture, feature attribution, and relationships within ESRI ArcGIS software.

The GRI GIS data are available on the GRI publications website, http://go.nps.gov/gripubs, and through the NPS Integrated Resource Management Applications (IRMA) DataStore portal, https://irma.nps.gov/DataStore/Search/Quick. Enter "GRI" as the search text and select a park from the unit list.

The following components are part of the GRI GIS data for the park:

- A GIS readme file (amme_geology_gis_readme.pdf) that describes the GRI data formats, naming conventions, extraction instructions, use constraints, and contact information.
- Federal Geographic Data Committee (FGDC)–compliant metadata (amme_geology_metadata_faq.pdf);
- An ancillary map information document (amme_geology.pdf) that contains information captured from source maps such as map unit descriptions, geologic unit correlation tables, legends, cross-sections, and figures;
- Data in ESRI 10.x file geodatabase;
- ESRI map documents for use in ArcMap 10.x (amme_geology.mxd) and ArcGIS Pro (amme_geology.mapx) that display the GRI GIS data;
- Layer files with feature symbology (Table 2);
- Open source geopackage with a QGIS project file (amme_geology.qgz); and
- A version of the data viewable in Google Earth (amme_geology.kmz; Table 2)

Table 2. GRI GIS data layers for American Memorial Park. Some GRI GIS data layers are not displayed on the accompanying poster or in the Google Earth file. This table lists all the data layers in the GRI GIS data and indicates which are included on the poster and Google Earth.

Data Layer	On Poster	On Google Earth
Geologic Attitude Observation Localities	No	No
Geologic Cross Section Lines	No	No
Geologic Sample Localities	No	No
Mine Point Features	No	No
Map Symbology	No	No
Faults	Yes	Yes
Deformation Area Boundaries	Yes	Yes
Deformation Areas	Yes	Yes
Geologic Contacts	Yes	Yes
Geologic Units	Yes	Yes

GRI Poster

A poster of the GRI GIS data draped over a shaded relief image of the park and surrounding area is the primary figure referenced throughout this GRI report. The poster is not a substitute for the GIS data but is supplied as a helpful tool for office and field use and for users without access to ArcGIS. Not all GIS feature classes are included on the poster (Table 2). Geographic information and selected park features have been added to the poster. Digital elevation data and added geographic information are not included in the GRI GIS data but are available online from a variety of sources.

Use Constraints

Minor inaccuracies may exist regarding the locations of geologic features relative to other geologic or geographic features on the poster. Based on the source map scale (1:25,000) and *Map Accuracy Standards* (US Geological Survey 1999), geologic features represented in the GRI GIS data are horizontally within 13 m (43 ft) of their true locations.

Introduction

Park Significance and Establishment

American Memorial Park (on Saipan) and War in the Pacific National Historical Park (on Guam) both tell the history of the Pacific Theater of World War II, and particularly the devastating loss of life during the Marianas Campaign. The Mariana Islands were strategic colonial outposts governed by the United States and Japan. They became battlefields for control of the entire Pacific during World War II. More than 70,000 Japanese, American, and Mariana Islands civilians died over the 61 days of the Marianas Campaign in 1944 (Figure 1). The park's concept of a "living memorial" offers activities similar to those enjoyed more than half a century ago by American servicemen and women: picnicking, fishing, photography, water sports, tennis, jogging, and bicycling. Today, the park is a major venue for community gatherings, fiestas, formal ceremonies, and island-wide events. The park is a place that provides year-round cultural, natural, historical, and recreational opportunities for more than 80,000 visitors annually (National Park Service 2017; Greene et al. 2019).

Established in 1978, the park is an affiliated area owned by the Government of the Northern Mariana Islands and leased to and managed by the NPS. It encompasses 54 ha (133 ac) along Puntan Muchot on the western side of the island of Saipan, which is part of the Commonwealth of the Northern Mariana Islands. This is a US territory consisting of 15 islands north of Guam that make up the Marianas archipelago (Figure 2 and Figure 3). The entire arc of the Mariana Islands extends about 900 km (560 mi) north to south in western Micronesia (Rutherford and Kaye 2006). Saipan is about 5,950 km (3,695 mi) southwest of Honolulu, Hawai‘i and 2,350 km (1,460 mi) south of Tokyo, Japan. The island is about 23 km (14 mi) long and 10 km (6 mi) wide and ranges in elevation from sea level to about 466 m (1,529 ft; elevation from the basemap used by Weary and Burton 2011) above sea level at the peak of Okso Takpochao (also called Mt. Takpochau, Tagpochau, or Tapochau) in the middle of the island (Mitchell et al. 2020). Geographical place names commonly have several spellings with CHamorro (the indigenous people of the Mariana Islands), Carolinian (an ethnic group of people with origins in the Caroline Islands), or other iterations. Wherever possible, this document will follow the US Geological Survey's (USGS) place name data.

Figure 1. Map showing the sequence of events during the Battle of Saipan and island locations. The park is located just north of Garapan. The extent of figure 4 is noted by a red dashed box. NPS graphic is an excerpt from the park's brochure (American Memorial Park 2014) with annotation and modifications by Trista L. Thornberry-Ehrlich (Colorado State University).

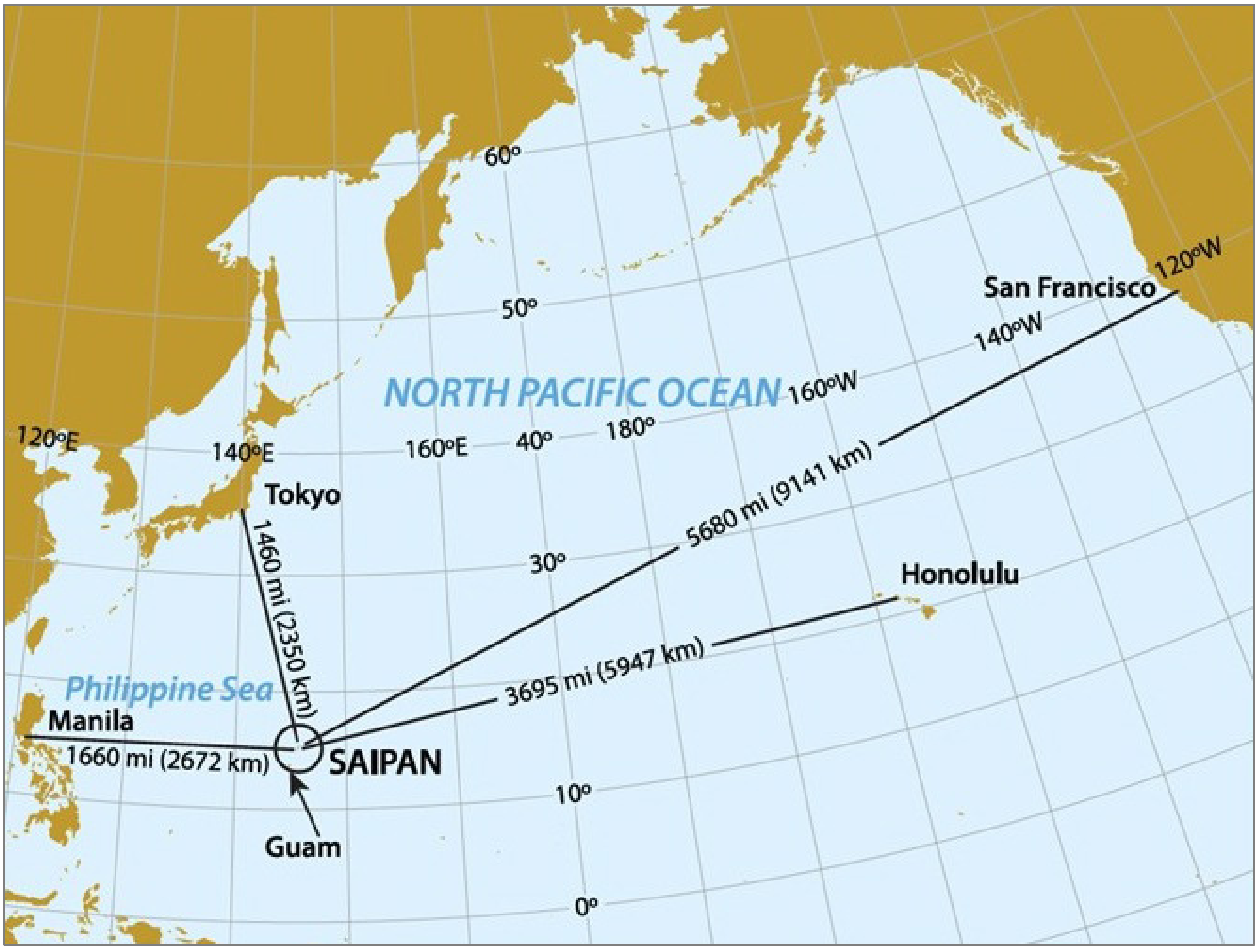


Figure 2. Map of the western Pacific Ocean basin showing the location of Saipan. Saipan (circled) and the rest of the Commonwealth of Northern Mariana Islands are far from any large landmass. Graphic is figure 1 from Weary and Burton (2011).

About 30% of Saipan is undeveloped, consisting of grassland, secondary forest, and isolated regions of primary forest. Residential and commercial land cover 35% and 20% of the island, respectively. The remaining 15% is public land, which includes the airport, seaport, schools, cemetery, agricultural cooperatives, Lake Susupe and adjacent wetland areas, beaches, and areas such as the park (Carruth 2003). The park functions as an urban open space at Tanapag Harbor Reservation; it provides one of the few open spaces for recreation and cultural gatherings (National Park Service 2017). Notable features and landmarks within the park include the Court of Honor and Flag Circle (erected in 1994), the Marianas Memorial (erected in 2004), the Saipan American Memorial and Carillon Bell Tower and Museum (erected in 1995), Smiling Cove Marina, Outer Cove Marina, Micro Beach, tennis courts, a view of Managaha Island, wetlands, and mangrove forest (Figure 4, Figure 5, Figure 6, and Figure 7).

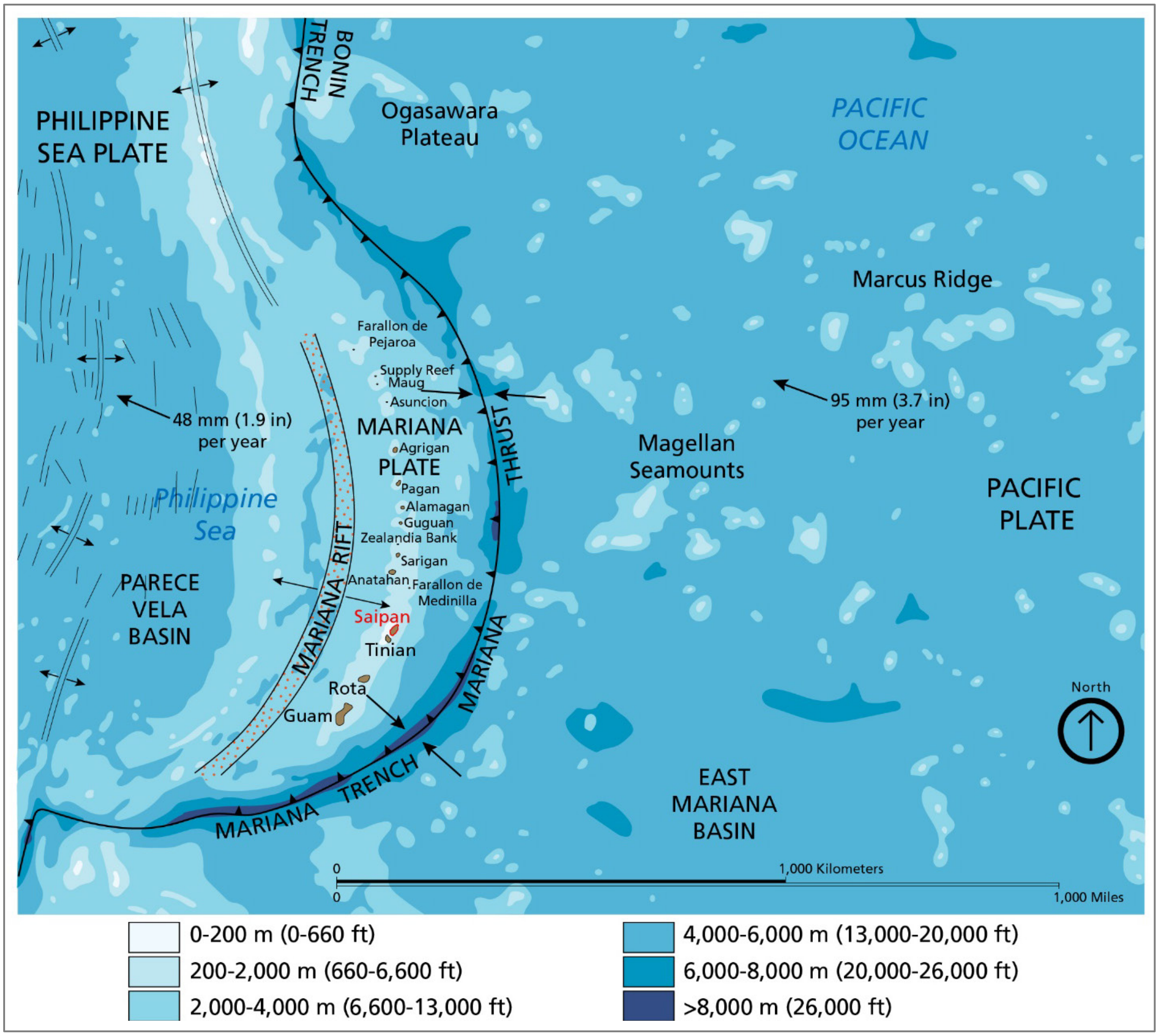


Figure 3. Map of the tectonic setting of Saipan. Saipan (red outlined island) is the largest island of the archipelago that makes up the Commonwealth of Northern Mariana Islands. Saipan and all the islands of the Marianas archipelago are on the Mariana tectonic plate. The Mariana plate is bordered on the west by the Mariana rift, a spreading center where two plates diverge from each other. To the east is the Mariana Trench, a zone of plate convergence. The Mariana Trench is the deepest oceanic trench on Earth. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after figure 3 in Muhs et al. 2020, with information from Moore et al. (1991).

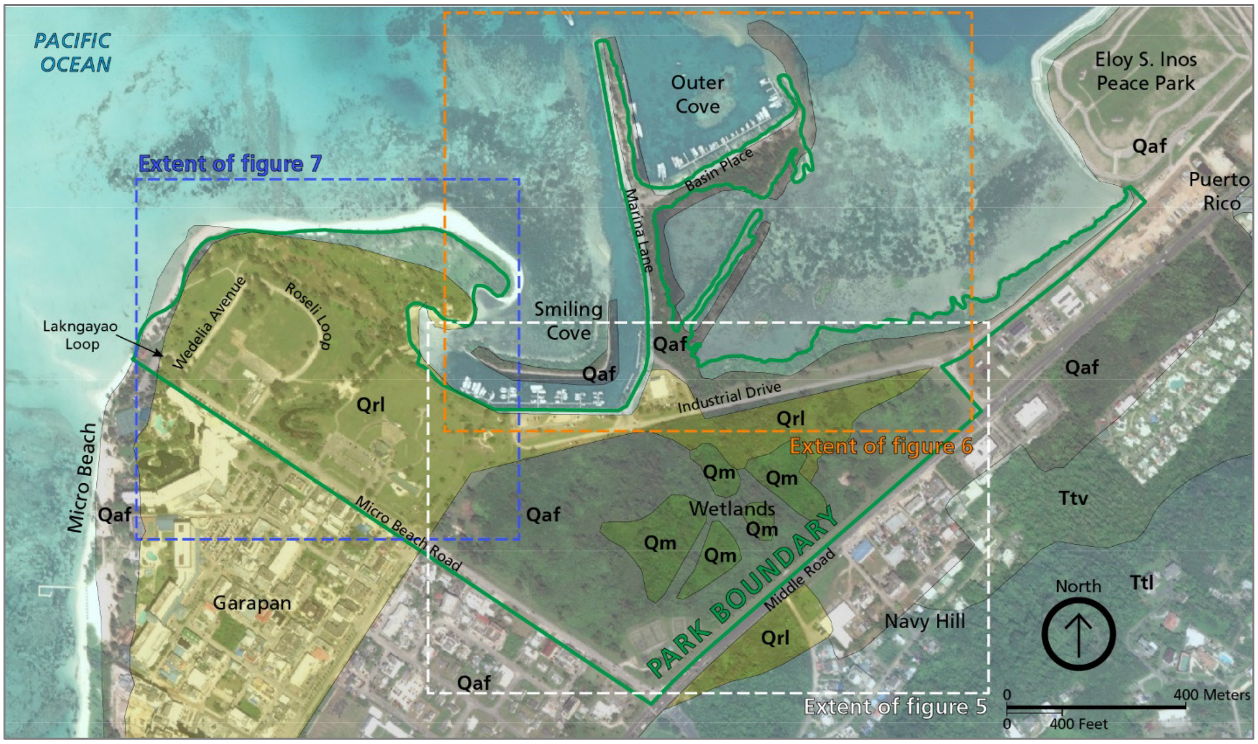


Figure 4. Aerial image of American Memorial Park with geologic map units. Three geologic units are mapped in the park: emerged carbonate sand (Qrl), artificial fill (Qaf), and marsh (Qm). Just east of the park boundary, Tagpochau Limestone (Ttv and Ttl) is mapped near Navy Hill. Extents of figures 5, 6, and 7 are noted here with dashed boxes. Park boundary is a green line and labeled. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) using GRI GIS data and ESRI World Imagery basemap.

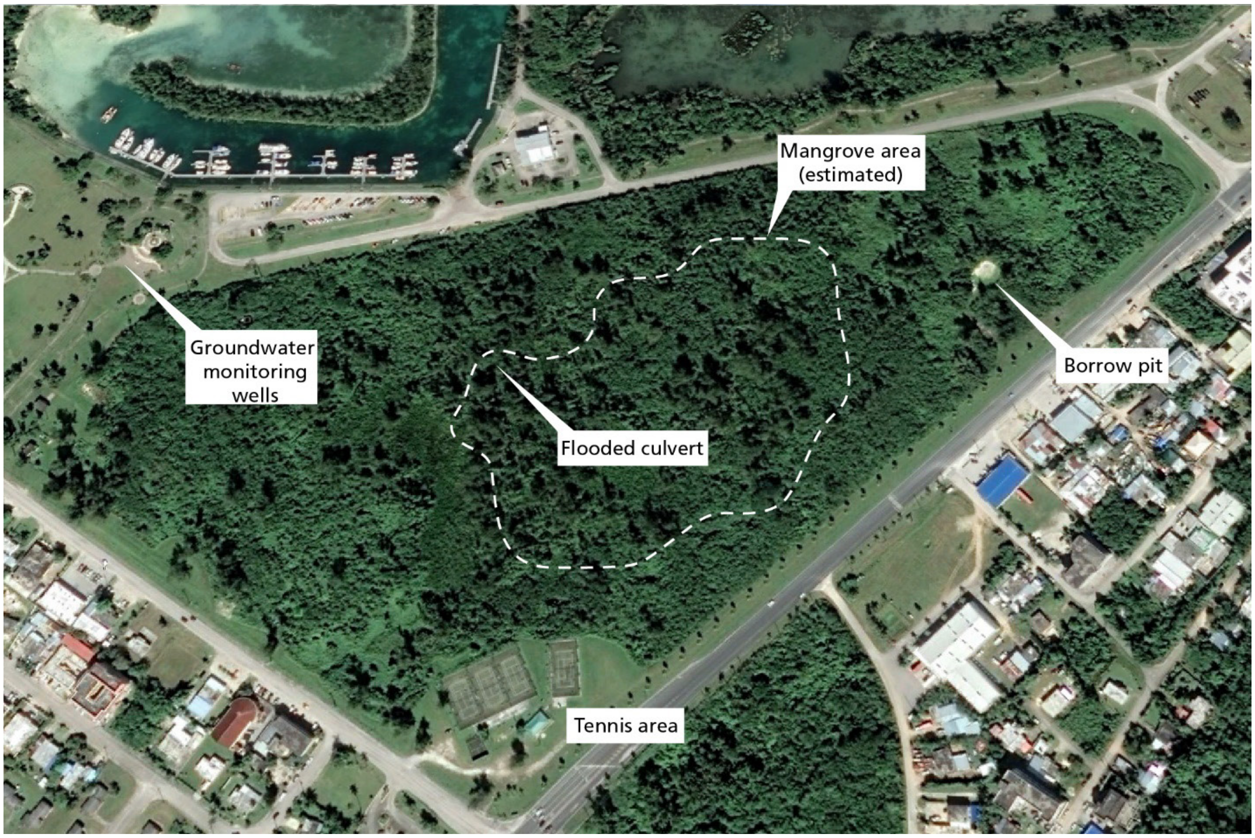


Figure 5. Features of the central part of American Memorial Park. This area is the wildest part of the park with wetlands (Qm) and mangrove forests near a flooded culvert. The flooded culvert is causing localized changes to the wetland areas surrounding it. A dashed line represents the estimated mangrove area. Groundwater monitoring wells (west of the mangroves) can be used to test groundwater quality, level, and salinity; however, some flooding is impeding this potential. The tennis area (south of the mangroves) is a visitor recreation area. A borrow pit exists east of the mangroves. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) using GRI GIS data and ESRI World Imagery basemap.

Figure 6. Features of the northern part of American Memorial Park. Most of this land area is mapped as artificial fill (Qaf). Noted are two ongoing renovation projects to repair roads leading to the local harbors. Smiling Cove and an access channel are regularly dredged to maintain navigable access. Sediment coming in from the south and west is causing the beach west of Smiling Cove to migrate eastward. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) using GRI GIS data and ESRI World Imagery basemap.

Figure 7. Features of the western part of American Memorial Park. Many of the visitor facilities and memorials are in this part of the park. Most of this area is underlain by emergent carbonate sands (Qrl). Overflow stormwater is channeled through manmade drainage. The manmade drainage is easily recognized on the image by the dense vegetation and trees that have grown along it. Longshore drift is transporting sediments northward and eastward, causing the Micro Beach to migrate and forested beach ridges along the north shoreline to also change in size, shape, and extent. Forested beach ridges show clear successional patterns of the forest following accretion and growth of a new shoreline (Greene et al. 2019). Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) using GRI GIS data and ESRI World Imagery basemap.

Despite its small size and emphasis on culture and history, the park harbors significant biodiversity. Wetlands, mangrove forests, and Micro Beach are among the important resources and values identified in the park's foundation document (National Park Service 2017). Park managers emphasize connectivity among all the ecosystems of Saipan with a "ridge-to-reef" concept. This means activities happening on the heights of the island will ultimately impact conditions on the coral reefs surrounding the island and the areas in between (Greene et al. 2019).

Geologic Setting

The Mariana Islands, including Saipan, are part of the greater Izu-Bonin-Mariana volcanic island arc system, marking a convergent tectonic plate boundary (a place where two or more of Earth's tectonic plates come together) that extends over 2,800 km (1,700 mi) from Tokyo, Japan, south to beyond Guam. The Izu-Bonin-Mariana arc system is located along the eastern margin of the Philippine Sea tectonic plate, which also contains a smaller Mariana Plate. The Mariana Trench, which contains the deepest point on Earth's solid surface, divides the Philippine Sea tectonic plate from the greater Pacific tectonic plate to the east (see Figure 3).

The Pacific Plate currently encompasses most of the North Pacific Ocean basin and is relatively young in geologic terms. It is currently moving northward and westward at a rate of 95 mm (3.7 in) per year, whereas the Philippine Sea Plate is moving in about the same direction more slowly at about 48 mm per year (1.9 in per year) (Smoczyk et al. 2013). Along its western edge, the Pacific Plate is older and denser than the adjacent Philippine Sea Plate. The denser, faster Pacific Plate plunges or subducts beneath the Philippine Sea Plate. Subduction and the resultant creation of magma fuel the volcanoes that, where they reach above sea level, form islands such as the Marianas.

Over time, repeated volcanic eruptions built up the volcano from the seafloor. The volcano created shallow marine areas where limestone was deposited, and coral reefs formed, adding more limestone. Further volcanism layered volcanic rocks atop the existing limestone. Limestone terraces formed as sea level changed and the volcano was uplifted or subsided. About 90% of the island's land surface is composed of 20 uplifted limestone terraces from ancient coral reefs. Generally, terraces are elevated portions of land that are mostly flat and level, overlooking a shoreline, valley, or plain. The remaining land surface is made of weathered volcanic rocks (Carruth 2003). The episodically uplifted limestone terraces created a layer-cake topography with a succession of nearly horizontal limestone platforms and terraces, separated by scarps or very steep slopes, which ascend from the seashore toward central uplands in the northern three-quarters of the island (Carruth 2003; Whistler 2009). In contrast to the western coast (where the park is located), which is formed by a narrow coastal plain of limey sand, the eastern, southern, and northern coasts are backed by limestone cliffs of varying relief separated intermittently by small beaches and coves. Off the western shore of the park and along the length of the island is a shallow lagoon bordered by a barrier reef (Carruth 2003). Weathering and erosion of the island are ongoing, ultimately transporting sediments from high places to low places. Humans significantly modified the western coastline with large areas of artificial fill to create flat coastal areas for cities and infrastructure. Much of the land in the park is actually artificial fill (geologic map unit **Qaf**; Table 1; see Figure 4).

The surface landforms are separable into six principal physiographic subdivisions: central uplands, low limestone platforms, low terraced benches, the Donni clay hills belt, southeastern coastal fault ridges, the western coastal plain, and wetlands (Figure 8; Cloud et al. 1956; Carruth 2003). The park is part of the western coastal plain, defined as an area of emerged calcium carbonate sands (**Qrl**; see Figure 4) that extends continuously south from the beaches at San Roque on the northwest coast to Agingan Point at the southwest point of the island. The plain ranges in width from 0.21 to 2 km (0.13 to >1 mi). Its surface rises gradually inland to elevations generally not more than 5 to 6 m (15 to 20 ft). Part of the coastal plain contains wetland areas, including parts of the park (**Qm**; see Figure 4), the largest of which surrounds the brackish-water Lake Susupe (see Figure 8); the park wetlands are too small for the island-wide scale.

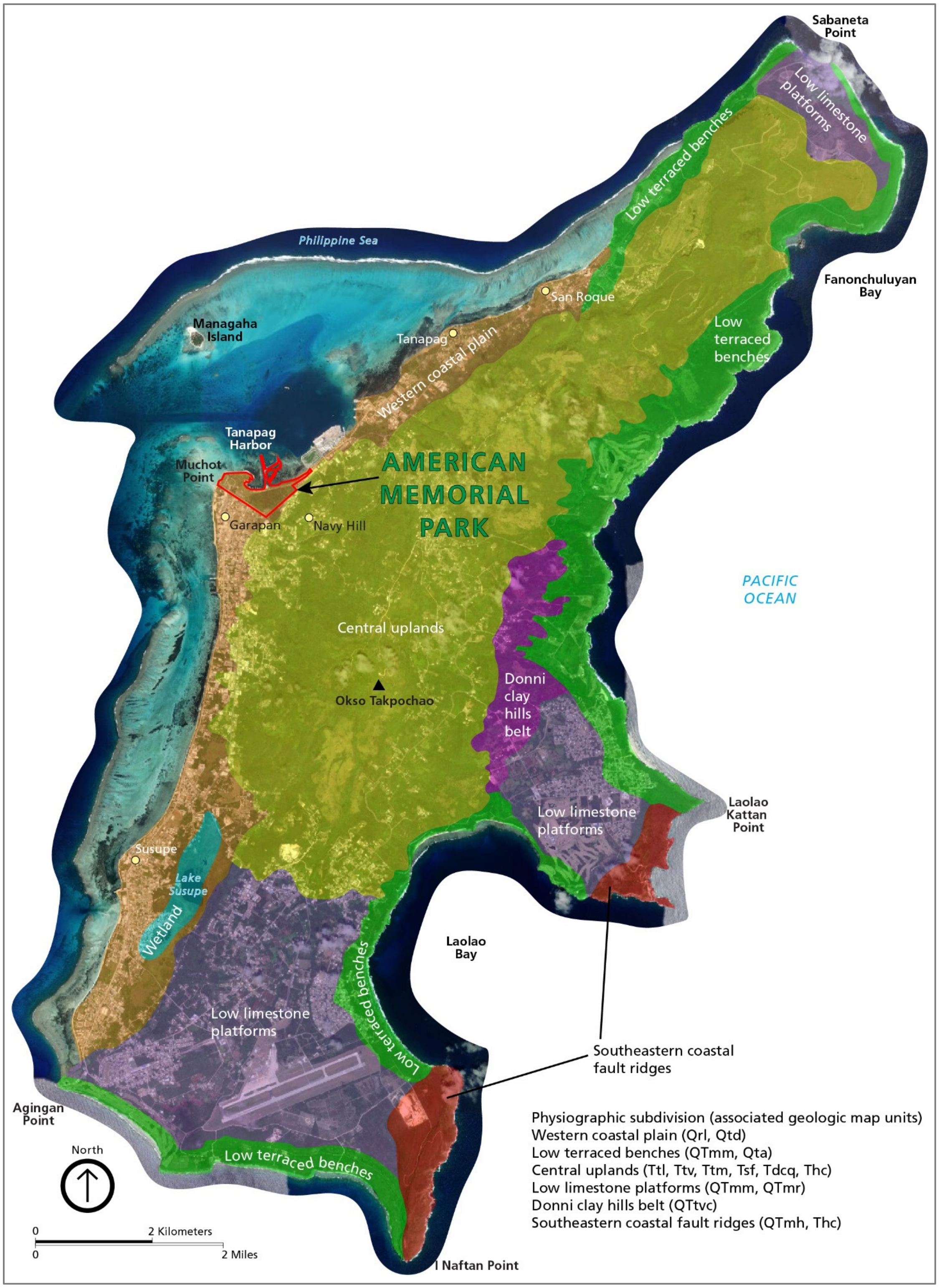


Figure 8. Physiographic map of Saipan. Landforms are broadly grouped into six physiographic subdivisions on the island. American Memorial Park is part of the western coastal plain physiographic subdivision. Some of the subdivisions are strongly connected to specific geologic map units. These are noted where clear. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after Cloud et al. (1956), Carruth (2003), and using ESRI ArcMap imagery as a base layer.

Geologic Heritage of American Memorial Park

The park is on the volcanic island of Saipan, in a geologically active area of the western Pacific Ocean. This chapter highlights the significant geologic features, landforms, landscapes, and stories of the park preserved for their heritage values. It also draws connections between geologic resources and other park resources and stories.

Geologic Heritage

Geologic heritage, also known as geoheritage, encompasses the significant geologic features, landforms, and landscapes characteristic of the US that are preserved for the full range of values that society places on them. The NPS also identifies geologic heritage aspects of museum collections, soils, and scientific data sets (National Park Service and American Geosciences Institute 2015).

Geoheritage sites are conserved so that their lessons and beauty will remain as a legacy for future generations. Such areas generally have great potential for scientific studies, use as outdoor classrooms, and enhancing public understanding and enjoyment. Geoheritage sites are fundamental to understanding dynamic earth systems, the succession and diversity of life, climatic changes over time, the evolution of landforms, and the origin of mineral deposits. The park preserves cultural, scientific, ecosystem, aesthetic, and recreational geologic heritage values. For example, the geologic history of the Pacific Plate crafted volcanic islands (e.g., Marianas) that were strategically important in World War II. The Marianas in particular provided a base close enough for US bombers to reach Japan (another set of volcanic islands). The limestone bedrock and faults on Saipan created the weathered limestone (karst) landscape that controls the hydrology and surface water (or lack thereof), which influenced human history. The karst landscape includes the caves that people have utilized during times of war and relative peace. The geologic landforms include the dramatic elevation of cliffs (e.g., Banaderu Cliff [Suicide Cliff]) in the northern part of island that became the location for hundreds of suicides.

Geologic Connections to Cultural Resources and Park Stories

Over 3,500 years ago, seafaring ancestors of the CHamorro people discovered and settled the Mariana Islands, and geologic resources heavily influenced their land-use choices. Surface water on the island is not readily available and is a precious resource. Locations where freshwater was accessible on the ground surface, at coastal plain seeps and high-level springs, undoubtedly influenced where people chose to settle in villages and establish farms (Mink 1987). Petroglyphs and other archeological evidence at Chalan Piao, south of the park near Lake Susupe, indicate the first people came from southeast Asia (National Park Service 2019; Encyclopaedia Britannica 2022). Using local sands and clays weathered from the island's limestone (e.g., geologic map units **Qc**, **Qmc**, **QTtvc**, and **QTma**), the people created distinctive, red-slipped pottery, sometimes incised with lime-filled decoration that is similar to Philippine ceramics; by 800 CE, unslipped pottery was in use (Herman 2017; Encyclopaedia Britannica 2022). Local stone also functioned as mortars for hulling rice (Thompson 1940). A beach within the park was once used for celestial navigation training (Snyder 2006; Greene et al. 2019).

About 1,000 years ago, the CHamorro began constructing two-piece megalithic pillar structures out of the local limestone and volcanic rock, called “latte” (Figure 9). The material for latte varied with the local geology. Latte located near the coast had upright pillars of limestone with caps of inverted brain coral heads. In volcanic regions, the latte were laboriously hewn out of the volcanics and resembled those made from limestone (Thompson 1940; Herman 2017). Parallel rows of upright pillars (“halege”) were topped by hemispheric capstones (“tasa”). The pillars were supports for latte structures, which were built up to a horizontal plane. These may have served as houses or canoe sheds (Thompson 1940; National Park Service 2019). Latte stones still exist on several Mariana Islands, including Saipan (National Park Service 2019). Possible candidates for the local source material on Saipan are either the Tanapag Limestone (**Qta**) or the Mariana Limestone (**QTmh**, **QTmm**, **QTmmp**, **QTma**, **QTmr**) because they are relatively soft for excavating and shaping and located on flat land near the coast for easier transport (Dave Weary, geologist, US Geological Survey, written communication, 28 August 2023).

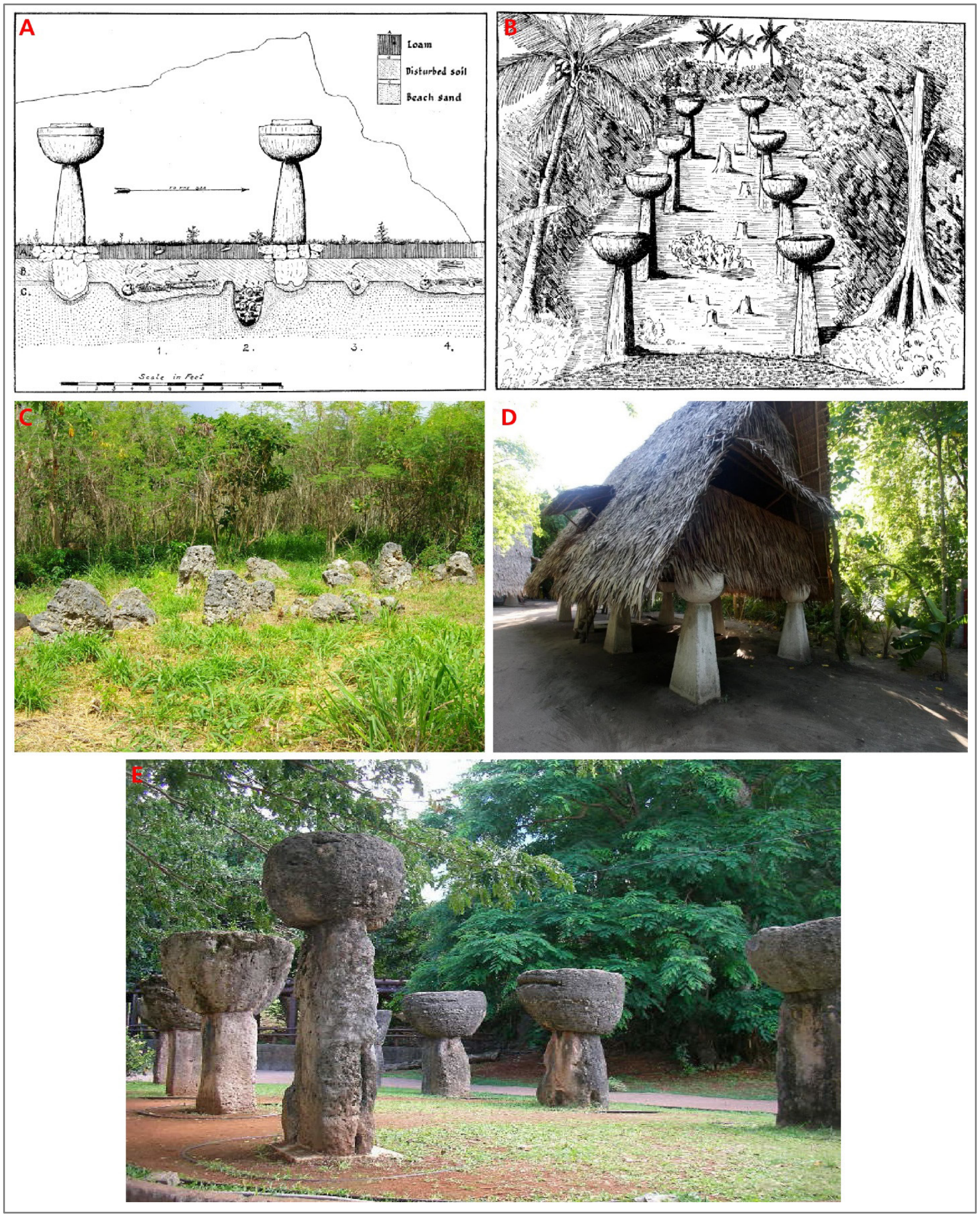


Figure 9. Sketches and photographs of latte. Latte, composed of stone pillars with a flattened capstone (commonly coral heads), were used as foundations for CHamorro buildings. Typically, they are about 2 m (6 ft) tall. No latte are known near American Memorial Park. The top two images (A and B) are sketches from Thompson (1940) showing, (A), a below ground cross-section view of the dimensions and construction of the latte stones, and (B), a sketch of the parallel rows of latte structures in a jungle. (C) shows the weathered remnants of latte structures at LoaLoa Kattan archeological site on Saipan. (D) from (Herman 2017) shows a reconstruction (on Guam) of a CHamorro house atop latte stones. (E) shows relatively intact latte remnants, photo taken by Hajime Nakano in summer 2006 on Guam, available at https://www.flickr.com/photos/jetalone/162915806/ (accessed 18 April 2022).

In 1521, Portuguese explorer Ferdinand Magellan sighted the volcanic islands of the Marianas on his Pacific crossing. Saipan was claimed as a Spanish colony in 1565 as a valuable island outpost in the vast Pacific Ocean. A series of revolts, collectively called the "CHamorro wars," resulted in many CHamorros seeking refuge in the inland hills and caves in limestone of Saipan (Encyclopaedia Britannica 2022). CHamorros were forcibly removed from Saipan, and the island remained uninhabited for decades until Carolinians from Satawal, part of the now-Federated States of Micronesia some 900 km (560 mi) south of Saipan, sought refuge there after a typhoon destroyed their island. They landed at Micro Beach (National Park Service 2017; Greene et al. 2019). Around 1815, the Carolinians founded a village called Arabwal at what is now the location of the park (National Park Service 2019). They used Micro Beach as a primary site for elders to teach burial rituals (National Park Service 2017; Greene et al. 2019).

Agricultural demands (for sugar cane) changed the landscape even further. Widespread agricultural development required the systematic distribution of fresh water. After losing the Spanish-American War, Spain sold the islands to Germany, which held them until the breakout of World War I. At this time, large coconut plantations were started to produce copra (dried coconut meat for oil and animal feed; Encyclopaedia Britannica 2022). Japan took control of the island in 1914, transforming the local agriculture economy by exporting and importing a wide range of food products (National Park Service 2019). The Japanese dug shallow wells and collected rainwater directly (Mink 1987). By 1944, thousands of Japanese, Okinawans, Koreans, and Taiwanese immigrants inhabited the island (National Park Service 2019).

During their time on Saipan, the Japanese took advantage of the local geology to prepare defenses of the island. Much of the island of Saipan inland from the park is karst, which is an area of land formed of soluble rock such as limestone that is worn or dissolved away by water to make caves, conduits, alcoves, pillars, and other formations. Tunnels were excavated into the limestone, and natural caves were modified for use as command posts, hospitals, combat positions, storage, and shelter (Mushynsky et al. 2018). Natural caves were modified and strategically chosen, so caves for active weapons were chosen for their field of fire, caves for personnel needed a safe location and protection, and storage caves needed accessibility and geographic dispersal (Phelan 1945; Mushynsky et al. 2018). At least 73 "karst defenses" of Saipan were used by three groups: the Japanese military, civilians of the Marianas, and the United States during post-war activities (Mushynsky et al. 2018). On Saipan, the karst defenses are distinct from features such as bunkers and pillboxes constructed of concrete and rebar and found in coastal areas and on the surface of the landscape (Mushynsky et al. 2018).

Because of its strategic location, size, and natural break in the fringing reef, Saipan was considered a strategic asset during World War II and part of the last line of defenses for the Japanese homeland. The island had a Japanese military air base that supported its imperial expansion to the south and east (Encyclopaedia Britannica 2022). At that time, extensive fill of limestone rubble (geologic map unit **Qaf**) was used to flatten areas and render low-lying wetlands useful space for the development of defenses such as batteries, shore defenses, underground fortifications (karst defenses), and an airstrip (Hess and Pratt 2006; Mushynsky et al. 2018). Like other Pacific Island struggles, the Japanese military's use of karst features likely prolonged the battle of Saipan (Mushynsky et al. 2018). Because of the natural break in the reef west of the park, it was a natural place to establish a harbor. Furthermore, the harbor was the site of one of the largest military invasions and occupations during the war (Hess and Pratt 2006).

Geologic resources are also part of memorializing the human sacrifice of World War II at the park. In June and July 1944, US-led Allied forces invaded and eventually captured the island in one of the fiercest land battles of the Pacific theater—5,204 Allied service personnel, nearly all the 30,000 Japanese defenders, and many CHamorro and Carolinian civilians were killed during the invasion. The names of those who sacrificed their lives during the Battle of Saipan are inscribed on the memorials in the park and across the island, made mostly of imported granite because the local limestone would have been too soluble. Nine hundred twenty-nine names of CHamorros and Carolinians are listed on the granite Marianas Memorial at the park as victims of war between 1944 and 1946 (National Park Service 2019; Encyclopaedia Britannica 2022; National Park Service 2022).

Consistent access to fresh water was historically a problem on Saipan. After the Allied forces expelled the Japanese in 1944, the water supply problem was addressed by extracting groundwater directly via deep wells, tunnels, and other excavations; however, this shift to forced water extraction threw the system out of balance and often induced saltwater intrusions into the potable water supply of the shallow coastal aquifers (Mink 1987). Today, subsistence agriculture includes taro, cassava, yams, breadfruit, and bananas. Tourism is the island's economic mainstay (Encyclopaedia Britannica 2022).

Geologic Connections to Biodiversity

Saipan's geologic setting, climate, and history of human use are all inextricably linked to the island's ecosystems. Geologically, the volcanic and limestone rocks weather to create varied and fertile soils (Whistler 2009). The rapid underground drainage prevents much standing surface water, precluding many hydrophilic (water-dependent) species except in coastal areas. Saipan commonly experiences tropical storm conditions with strong winds and pelting rains. These affect the island's vegetation, creating forests dominated by relatively short trees (Whistler 2009). In August 2015, category 4 Typhoon Soudelor caused nearly 90% of the park's trees to be blown down (Greene et al. 2019). Before the full impact of that storm could be inventoried and evaluated, category 5+ Supertyphoon Yutu made a direct hit to Saipan in October 2018 and Typhoon Hagibis struck in October 2019 (National Park Service 2019; Department of Homeland Security 2021).

Much of the island's ecosystems have been severely impacted and/or changed as a result of its human history (Whistler 2009). Biologists surmise the original forest that covered nearly the entire island before human occupation (3,500 years ago) was a "mixed limestone forest." The typical dominant species included the Katong Laut tree (*Cynometra ramiflora*), the tiger's claw (*Erythrina variegate*), and the fish-poison tree (*Barringtonia asiatica*) (Whistler 2009). Only small, isolated remnants of this forest exist today. Though the subject of relatively little formal study, the flora of the island includes ferns, flowering plants, a cycad, and other vascular plants, 44% of which are indigenous.

Though small in area, the park is an ideal location to observe the biodiversity of Saipan. Park habitats include beaches, wetlands, mangrove forests and saltwater swamps, reed marshes, ironwood groves, and open spaces (National Park Service 2015a). Two endangered species of sea turtle, the green turtle (*Chelonia mydas*) and hawksbill turtle (*Eretmochelys imbricata*), have also historically nested at the park's sandy beaches (Summers et al. 2018; Greene et al. 2019). The 12-ha (30-ac) wetland (geologic map unit **Qm**) consists of mudflats, marshes, and mangroves, a remnant habitat that was once extensive in the Commonwealth of the Northern Mariana Islands but is now uncommon. The mangrove ecosystem is now developed exclusively on Saipan Island, and it includes mangroves (*Bruguiera gymnorrhiza*), looking-glass mangrove (*Heritiera littoralis*), and cedar mangrove (*Xylocarpus moluccensis*). The majority of the mangroves are located in the park wetland or adjacent areas to the Puerto Rico mudflats (Tahzay Jones, deputy assistant regional director, US Fish and Wildlife Service, written communication 3 November 2023). This environment also harbors Partulid tree snails (*Partula* spp.), a rare orchid (*Zeuxine fritzii*) as well as native bird species, including some endangered and endemic species such as the Gold White-eye (*Cleptnornis marchez*), the Nightingale Reed-warbler (*Acrocephalus luscinia*), Marianas Common Moorhens (*Gallinula chloropus guami*), Mariana Swiftlet (*Aerodramus bartschi*), and the Micronesian Megapode (*Megapodius laperouse*; Hess and Pratt 2005; Whistler 2009; Greene et al. 2019).

The following vegetation communities were mapped in the park and are connected to the underlying landscape or geologic features and processes, as well as the interplay between freshwater from Saipan's highlands and the saltwater of the ocean:

- mangrove—wet, saline areas along the coast at sea level with mangroves (*Bruguiera gymnorrhiza*; Rhizophoraceae); mapped as geologic map unit **Qm** in the middle of the central forested area of the park
- freshwater swamp forest—an area of freshwater ground saturation near sea level; found near the margins of the mangrove community
- freshwater marsh—wetlands near sea level with fresh or brackish water; located southwest of the mangrove community
- littoral strand—a weedy, brushy shrubland on scraped limestone with a veneer of soil; this occurs on the jetty at the park
- secondary shrub—small tree and shrub species in disturbed areas (**Qaf**); found in the area between Micro Beach Road and Route 30
- secondary forest—open mesic (type of habitat with a moderate or well-balanced supply of moisture) areas on coastal plains; occurs only in a grove at the east end of the park; could be a remnant of secondary forest that was left standing when the park was developed
- managed land—open dry areas on coastal plains with mown grass, planted ornamentals; occupies most of the western half of the park (**Qrl**)

Geologic History of Saipan

This chapter describes the order of geologic events that formed the present landscape of the island of Saipan. Emphasis is placed on the history recorded in the geologic units mapped on the island. A geologic time scale (see Table 1) shows the chronology of geologic events (bottom to top) that led to the park's present-day landscape; this story covers more than 45 million years. The GRI GIS source map by Weary and Burton (2011) and Cloud et al. (1956) primarily informed this section. Additional references are cited herein.

More than 45 million years ago, undersea volcanic eruptions began the process of constructing what would become the island of Saipan. The eruptions were associated with the development of the Izu-Bonin-Mariana arc system. In the area of the arc system, the Pacific Plate subducts beneath the Philippine Sea Plate, resulting in the formation of the volcanic islands. Where plates subduct, rocks melt. The resulting molten rock is forced upward, ultimately emerging at the surface via volcanic eruption (Figure 10A). As the arc system was developing, the earliest volcanoes explosively erupted viscous, silica-rich rhyolite lavas. Because of its specific, low iron and magnesium, silica-rich composition, rhyolite does not flow like typical fluid Hawaiian-style. They are sticky and thick (viscous) and cause explosive volcanism. These are mapped as the Sankakuyama Formation (geologic map units **Tsf**, **Tst**) and are the oldest rock mapped as part of the foundation of Saipan, exposed on the north-central part of the island but below the surface in the park area. They are approximately 45 million years old.

Since its inception, Saipan has experienced periods of uplift and subsidence, resulting in abundant normal faulting (i.e., faulting in which the block above the fault has moved downward relative to the block below; see "Normal Faults" section), the formation of marine bench erosional surfaces, and the complex deposition of younger volcanic and sedimentary rocks above the volcanic basement (the island's core). These sedimentary rocks are commonly carbonates (containing calcium carbonate, e.g., limestone) or contain clasts or rock fragments of volcanic origin. The oldest of these rocks on Saipan belong to the Hagman Formation (**Thc**, **Thf**), which is a mixture of volcanic and sedimentary rocks. Their age remains in question, but they were emplaced and deposited at least 26 million years ago. Deposited atop the Hagman Formation is the younger Densinyama Formation (**Tdm**, **Tdc**, **Tdcq**, **Tdb**). This unit comprises a sequence of mixed volcanic and sedimentary rocks, indicating volcanism was concurrent with sedimentation (Figure 10B and C).

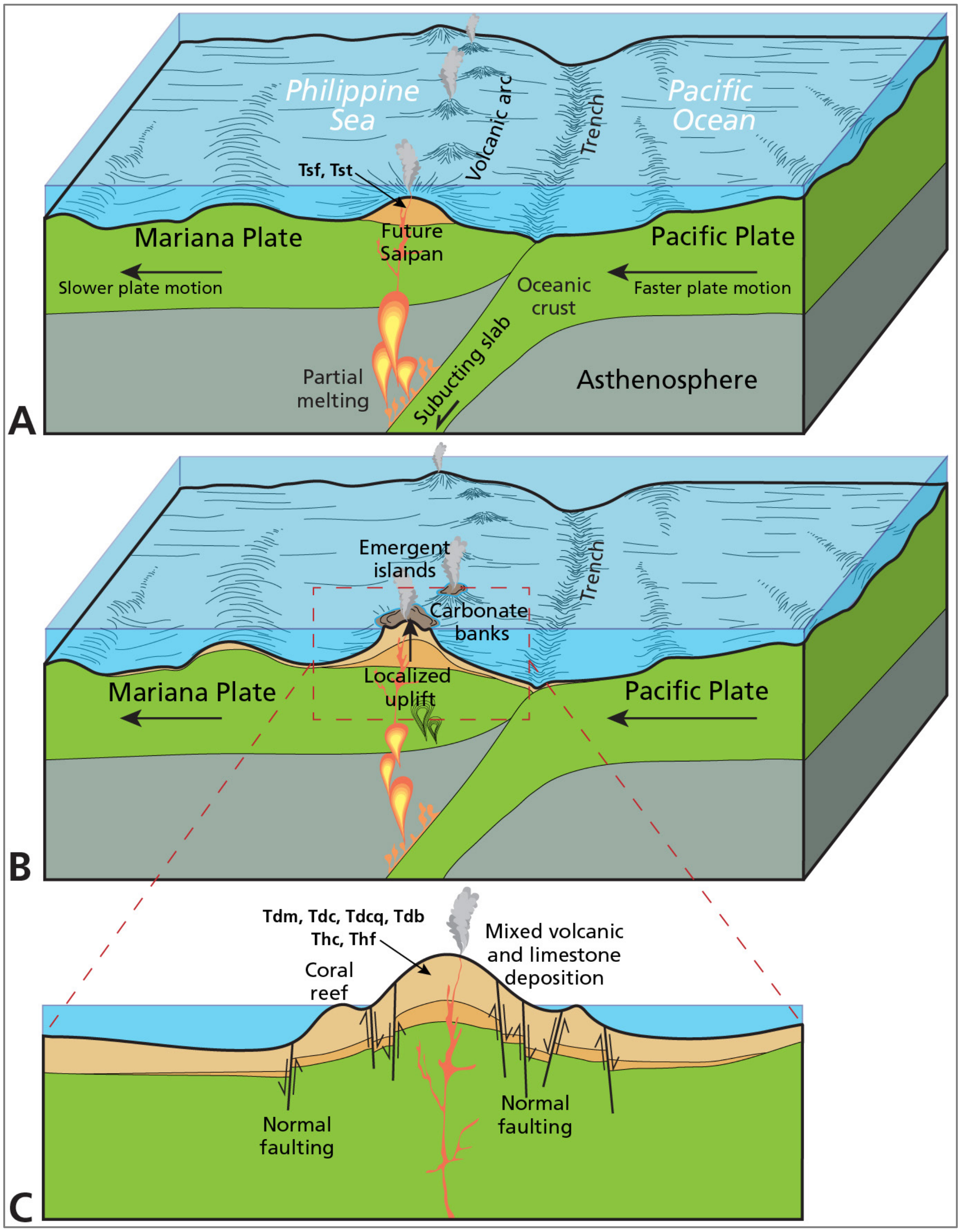


Figure 10. Diagrams of the early (Eocene-Oligocene) geologic evolution of Saipan. A) More than 45 million years ago, submarine volcanic eruptions within the Mariana Plate caused by subduction of the Pacific Plate at the Mariana Trench began to build a volcanic arc from the seafloor, including what would become the island of Saipan. Rocks of the Sankakuyama Formation accumulated around this time. B) Continued eruptions and localized uplift caused the volcanoes to emerge as islands. Carbonate banks formed around the perimeters of Saipan. At 26 million years ago, volcanic eruptions were still occurring. Carbonate sediments (limestone) mixed with ongoing volcanic deposition. Rocks of the Hagman Formation and Densinyama Formation formed at this time. C) Normal faults formed across the island as the crust stretched and uplifted (see “Normal Faults” section). Colors are USGS standards for geologic time periods (see Table 1). Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) with information from Weary and Burton (2011).

During a period of subsidence of the island below sea level, the Matansa Limestone (**Tmt**, **Tmp**, **Tmw**) was deposited atop the Densinyama Formation. Some layers of this unit are nearly pure limestone, possibly indicating a prolonged period of volcanic inactivity and shallow to moderate depth conditions. In the trend of changing relative sea levels, the regionally extensive Tagpochau Limestone (**Ttv**, **Ttm**, **Ttl**) records a period of the complete submergence of Saipan beneath the sea during the early Miocene, less than 23 million years ago (Figure 11A). Its bottom layer has material derived from the weathering and erosion of older rocks (see Figure 11A). Its upper layers contain almost entirely carbonate sedimentary rocks. This indicates submersion because clastic sediments were no longer being shed from subaerially (i.e., not underwater) exposed rocks. Significant coral masses are absent from this unit, indicating greater depths than those that would support coral reef development.

Volcanism continued to contribute to the construction of Saipan, as recorded by the tuffs and flow rocks of the Fina-Sisu Formation **(Tff**, **Tf).** Volcanism was less explosive due to the lower silica content of the basalt lavas compared to the older silica-rich rhyolites. This unit also contains marine fossils, which point to depositional environments that were submerged or partially submerged around 15 million years ago, though some inconsistencies with this age persist (Figure 11B). Then, about 3.7 million to 4.3 million years ago, at the beginning of the Pliocene, the sequence of sediments that recorded a marine transgression (rise of sea level) were deposited over an irregular surface of older sedimentary and igneous rocks as part of the informal Donni formation (**Tdoc**, **Tdot**, **Tdos**; Figure 11C; Dave Weary, geologist, US Geological Survey, written communication 25 August 2023). Within these layers, terrestrial to nearshore deposits grade upward to deeper water sediments. At that time, a period of subduction quiescence caused a deep marine setting to develop along the eastern side of the island of Saipan.

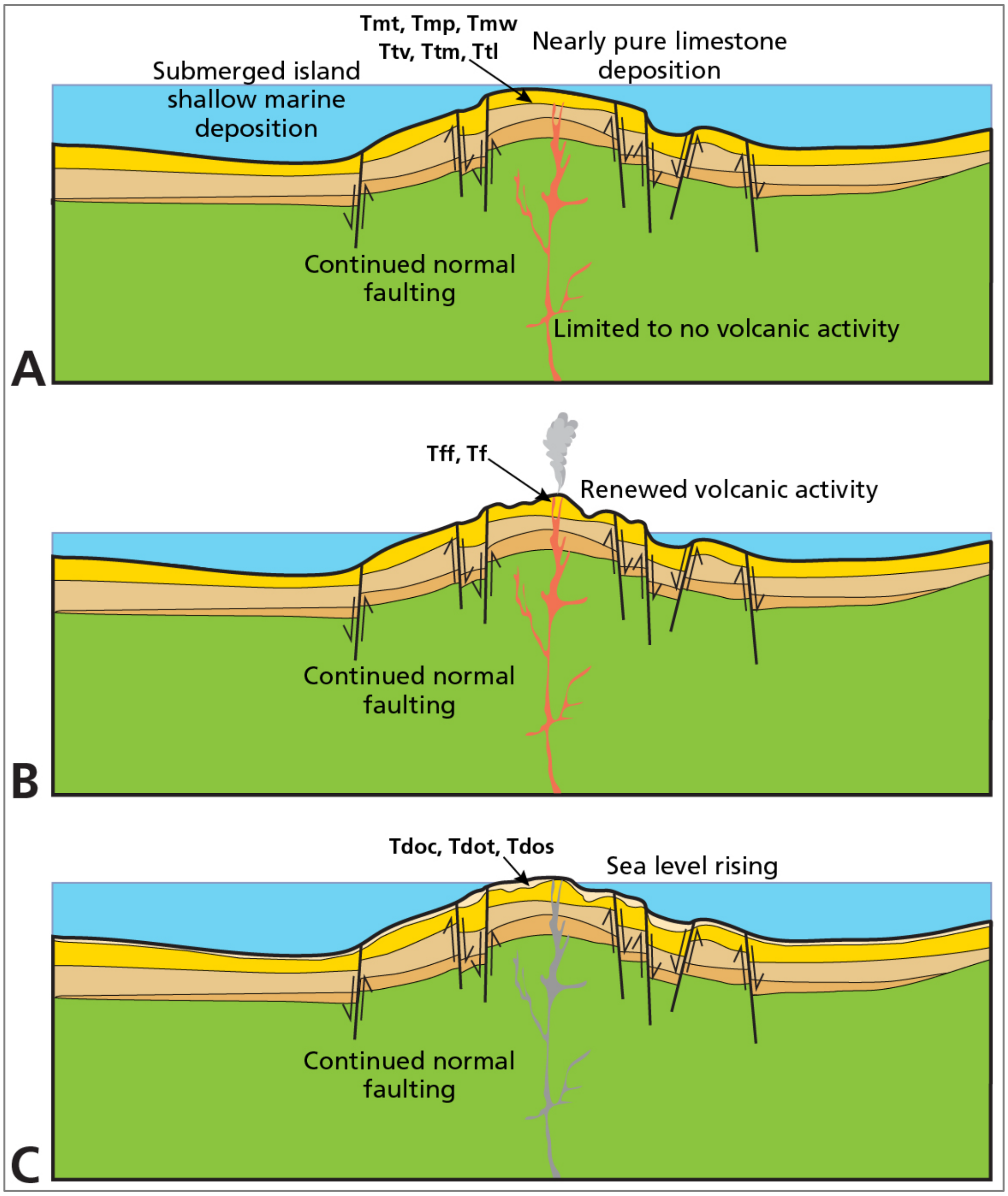


Figure 11. Diagrams of the later (Miocene-Pliocene) geologic evolution of Saipan. A) Less than 23 million years ago, the island was completely submerged. Volcanism had ceased and nearly pure limestone was deposited. Rocks of the Matansa and Tagpochau Limestones accumulated around this time. B) Around 15 million years ago, volcanism resumed on Saipan leading to the deposition of the Fina-sisu Formation. C) 3.7 million to 4.3 million years ago, at the beginning of the Pliocene, the sequence of sediments recorded a marine transgression (rise of sea level). Some of the island was exposed above sea level and sandstones accumulated after the volcanism, during the deposition of the Donni formation. Colors are USGS standards for geologic time periods (see Table 1). Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) with information from Weary and Burton (2011) and Dave Weary (geologist, US Geological Survey, written communication, 25 August 2023).

Later in the Pliocene, about 2.6 million to 3.7 million years ago, subaerial conditions indicated a fall in sea level or a period of relative island uplift as terrace deposits accumulated between 152 and 177 m (499 and 581 ft) and 171 and 216 m (561 and 709 ft) in elevation (**Tto2** and **Tto1**, respectively; Figure 12A). Saipan terraces were erosional in nature and accumulated sediments from adjacent sources that were then left perched at distinctive elevations when the sea level dropped. The sediments in these units are all reworked (i.e., tumbled and displaced after initial deposition) and coarse-grained. This may indicate high-energy depositional environments such as steep streams or wave-impacted shorelines. In addition to the weathering of the surface and the formation of terraces, the dissolution of limestone and the development of karst landscapes were likely happening any time the island was exposed (Jensen et al. 2006).

The accumulation of the units that make up the Mariana Limestone (**QTmr**, **QTma**, **QTmmp**, **QTmm**, **QTmh**), which occurred less than 3 million years ago, marks a period of coral reef and lagoon development (see Figure 12A). Broken and displaced coral suggests high-energy nearshore depositional environments, whereas intact coral, massive limestone, and algal mats indicate less intensive wave action or submarine conditions. Where units were exposed to wind and rain, weathering and erosion continued. Deep weathering of exposed units caused clay layers (**QTtvc**) to form, and further terrace deposits (**Qp**) to accumulate. The clay was derived from the erosion of the Tagpochau Limestone (**Ttv**, **Ttm**, **Ttl**) and the breaking down of the component minerals, leaving behind about 12 m (39 ft) of residual clay.

Another marine transgression took place as either the sea level rose, the island subsided, or both, and the Tanapag Limestone (**Qta**) accumulated as a fringing coral reef during the Pleistocene, between 2.6 million and 10,000 years ago. That was also a time of global ice ages intermittent with warmer climates. During an ice age, sea water was entrained or soaked up in continental glaciers and the sea level was lower, but during the warmer periods between ice ages, sea level rose. Lower sea level conditions created paleoshoreline flats, which are level landforms that record former shorelines (Dickinson 2000). The paleoshorelines from this time are now as much as 2 m (6 ft) higher than their modern counterparts (see low terraced benches on Figure 8; Dickinson 2000).

The Tanapag Limestone (**Qta**) is the youngest bedrock unit mapped on Saipan (Figure 12B). Mapped along the southern and eastern coastlines, it is a large component of the low terraced benches physiographic subdivision (see Figure 8). Residual clay (**Qmc**) developed from the Mariana Limestone (**QTmr**, **QTma**, **QTmmp**, **QTmm**, **QTmh**) less than 10,000 years ago. After the Pleistocene ice ages, sea level rose again, and mid-Holocene (about 5,000 years ago) high water carved paleoshoreline notches on Saipan (see low terraced benches on Figure 8; Dickinson 2000). Terrace deposits (**Qtd**) of reworked sediments accumulated at low elevations.

Over the past 2 million years (Figure 12C and Figure 12D), weathering, erosion, and earthquakes fractured bedrock, and blocks of rock moved downslope and accumulated at the base of slopes. Slope movements are recorded in the mapped units of Saipan as blocks of slumped limestone (**Qx**), mixed landslide deposits (**Ql**), and shoreline talus deposits (**Qst**). Talus is rock debris that accumulates at the base of a slope. Emerged sands and gravels (**Qgs**, **Qrl**) record shoreline depositional settings that were then uplifted away or stranded from the active shoreline by lowered sea level. The youngest geologic units of Saipan are accumulating in and being reworked by streams as alluvium (**Qa**, **Qc**), settling in wetlands (**Qm**), and along shorelines of the island as beach deposits (**Qrb**). In areas such as the park, humans have modified the landforms to a mappable extent. This is reflected in the areas of artificial fill (**Qaf**) used to provide a foundation for infrastructure along coastal areas.

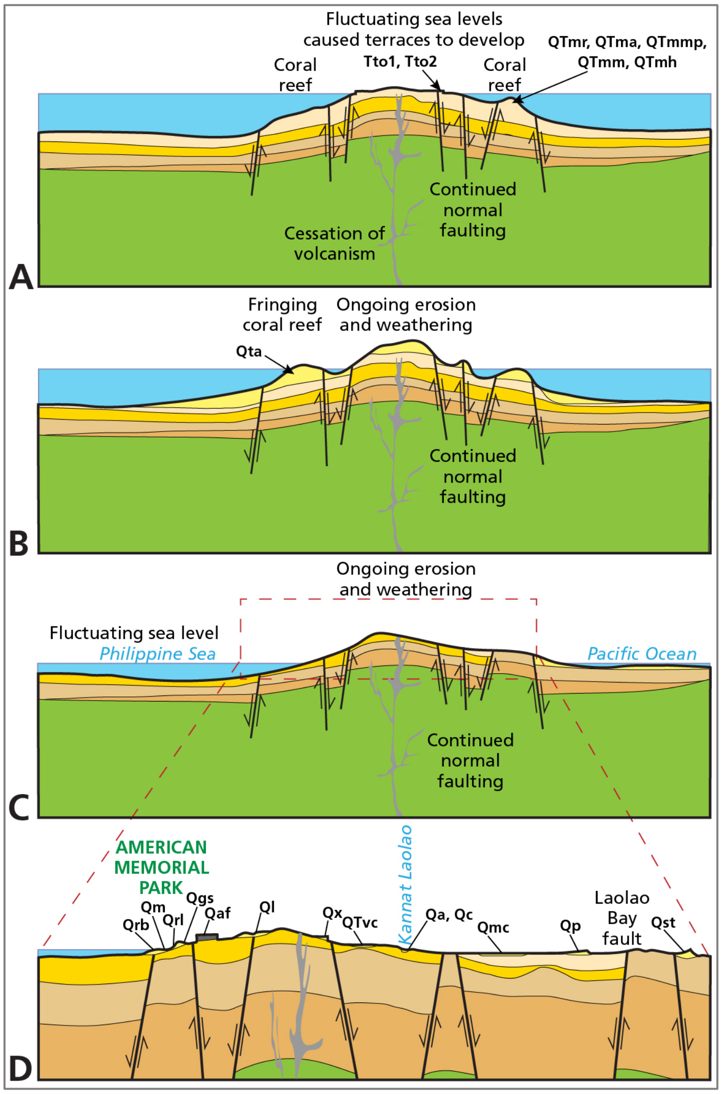


Figure 12. Diagrams of the latest (Pliocene to present) geologic evolution of Saipan. A) During the late Pliocene (2.6 million to 3.7 million years ago), sea level fluctuated. Wave cut terraces marked former sea level stands or extended periods of a certain sea level. These events are recorded as older terrace deposits. Volcanism ceased and the Mariana Limestone accumulated. B) During the Pleistocene (2.6 million to 10,000 years ago), a fringing coral reef formed around Saipan. This composes the Tanapag Limestone. C) Whenever the island is above sea level, weathering and erosion are constantly reshaping the landscape. Erosion has locally exposed all of the bedrock units down to the Eocene Sankakuyama Formation. D) Saipan experiences regular earthquakes as some areas are dropping down relative to others. Carbonates continue to accumulate in the ocean while the uplifted parts above the waves are exposed to erosion, which results in slope deposit deposition and weathering, which produces clays. Humans have modified the landscape excavating some places and using artificial fill in others. Colors are USGS standards for geologic time periods (see Table 1). Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) with information from Weary and Burton (2011) and Dave Weary (geologist, US Geological Survey, written communication, 25 August 2023).

Geologic Features and Processes

The geologic features and processes highlighted in this chapter are significant to the park's landscape and history. Selection of these features and processes was based on input from scoping and conference-call participants, analysis of the GRI GIS data, and research of the scientific literature and NPS reports. These features and processes are discussed more or less in order of geologic age (oldest to youngest). Table 3 summarizes the occurrence of each geologic map unit inside the park and the features, processes, and issues associated with each.

Table 3. Geologic map units in and adjacent to American Memorial Park. Units within this table are listed in order from greatest percentage of total area within park boundaries at the top of the table to units adjacent to the park at the bottom.

Geologic Map Unit (symbol) [A]	**Occurrence within American Memorial Park and Unit Description** [B]	**Geologic Features and Processes**	**Geologic Resource Management Issues** [C]
Artificial fill (Qaf)	**Qaf** is mapped in 44% of the park; it is the most prevalent unit. Compositionally, **Qaf** is mostly limestone rubble, coral, and sandy material. It is mapped where underlying geologic map unit contacts are buried. **Qaf** was likely sourced from local quarries. Mines, borrow pits, pits, and quarries are part of the GRI GIS data beyond park boundaries. The closest, geographically, being a borrow pit in **Ttl**. An undocumented pit occurs in the park.	• Micro Beach and Coastal Features and Processes • Disturbed Lands	• Erosion
Emerged carbonate sands (Qrl)	**Qrl** is mapped in 40% of the park, emerged to as much as 6 m (20 ft) above sea level in areas outside the park. **Qrl** is very fine to very coarse carbonate sand with local gravelly areas.	• Emerged Carbonate Sands • Paleontological Resource Potential • Micro Beach and Coastal Features and Processes	• Paleontological Resource Inventory, Monitoring, and Protection
Water	**Water** is mapped in 9% of the park. It is included in the mapped units where the park boundary extends offshore in the marina area.	• Micro Beach and Coastal Features and Processes	• Erosion
Marsh deposits (Qm)	**Qm** is mapped in 6% of the park; it is the least prevalent unit. **Qm** described as soft, sticky, bluish gray to grayish brown clay. **Qm** underlies and is accumulating in wetlands.	• Wetlands and Mangrove Forest • Paleontological Resource Potential	• Wetland Preservation
Tagpochau Limestone, limestone member (Ttl)	**Ttl** is not mapped in the park; however, it is mapped immediately adjacent to the park's southeast corner and impacts processes occurring within the park. **Ttl** is massive to well-bedded, mostly pure limestone. **Ttl** is the second most widespread geologic unit mapped on Saipan.	• Tagpochau Limestone and Karst Landscape Development • Paleontological Resource Potential • Disturbed Lands	• Stormwater Contamination and Karst Permeability • Groundwater Withdrawal

[A] Cell colors correspond to the colors used in the GRI GIS data and on the poster.

[B] Detailed descriptions of each geologic unit are in the ancillary map document (amme_geology.pdf) which is part of the GRI GIS data.

[C] Some geologic resource management issues are not associated with a geologic map unit and therefore are not included in this table. See "Geologic Resource Management Issues" section.

Table 3 (continued). Geologic map units in and adjacent to American Memorial Park. Units within this table are listed in order from greatest percentage of total area within park boundaries at the top of the table to units adjacent to the park at the bottom.

Geologic Map Unit (symbol) [A]	Occurrence within American Memorial Park and Unit Description [B]	Geologic Features and Processes	Geologic Resource Management Issues [C]
Tagpochau Limestone, tuffaceous facies (Ttv)	**Ttv** is not mapped in the park; however, it is mapped immediately adjacent to the park's eastern edge and impacts processes occurring within the park. **Ttv** is massive to well-bedded, mostly impure limestone with some silica-rich material and clasts derived from volcanic rocks. Deep weathering of **Ttv** forms clay deposits (**QTtvc**; not described here).	• Tagpochau Limestone and Karst Landscape Development • Disturbed Lands	• Stormwater Contamination and Karst Permeability • Groundwater Withdrawal

[A] Cell colors correspond to the colors used in the GRI GIS data and on the poster.

[B] Detailed descriptions of each geologic unit are in the ancillary map document (amme_geology.pdf) which is part of the GRI GIS data.

[C] Some geologic resource management issues are not associated with a geologic map unit and therefore are not included in this table. See "Geologic Resource Management Issues" section.

Tagpochau Limestone and Karst Landscape Development

Map units: Tagpochau Limestone, tuffaceous facies (**Ttv**), Tagpochau Limestone, marly facies (**Ttm**) and Tagpochau Limestone, limestone member (**Ttl**)

Limestone is composed of carbonate minerals, primarily calcium carbonate ($CaCO_3$) or calcite. The Tagpochau Limestone is the second most widespread mapped geologic unit on Saipan. It is the most common unit exposed in the higher cliffs and uplands at the center of the island. Although not mapped at the surface in the park, it underlies the **Qaf**, **Qm**, and **Qrl** map units that are mapped inside the park (visible in cross section; Weary and Burton 2011). It is mapped adjacent to the park, east of Middle Road, on the flank of Navy Hill. It is a major component of the island's ridge-to-reef setting. At its maximum thickness, about 300 m (1,000 ft) of tuffaceous, marly, and relatively pure limestone layers are present. The term tuffaceous refers to a rock made of fragments, primarily volcanic debris and ash, that make up 25% to 75% of the rock. The marly layers contain abundant clay, which are left behind (geologic map unit **QTtvc**) after the carbonates and other minerals in limestone weather away (Weary and Burton 2011).

Sea levels were rising to cover nearly all of Saipan when the Tagpochau Limestone was forming less than 23 million years ago. The lower layers of the unit contain abundant fragments or clasts derived from older units (e.g., volcanic clasts, weathered clays), whereas the upper layers contain much purer limestone deposited when submergence was complete, thereby shutting off the sources of clastic sediments derived from older rocks (Weary and Burton 2011).

Limestones, as opposed to volcanic rocks, provide the primary groundwater aquifers or reservoirs on Saipan. The Tagpochau Limestone underlies the Mariana Limestone (**QTmh**, **QTmm**, **QTmmp**, **QTma**, **QTmr**), both of which form widespread aquifers on the island. Most recoverable fresh groundwater is found in limestones that extend from the land surface to some distance below sea level (Figure 13; Carruth 2003).

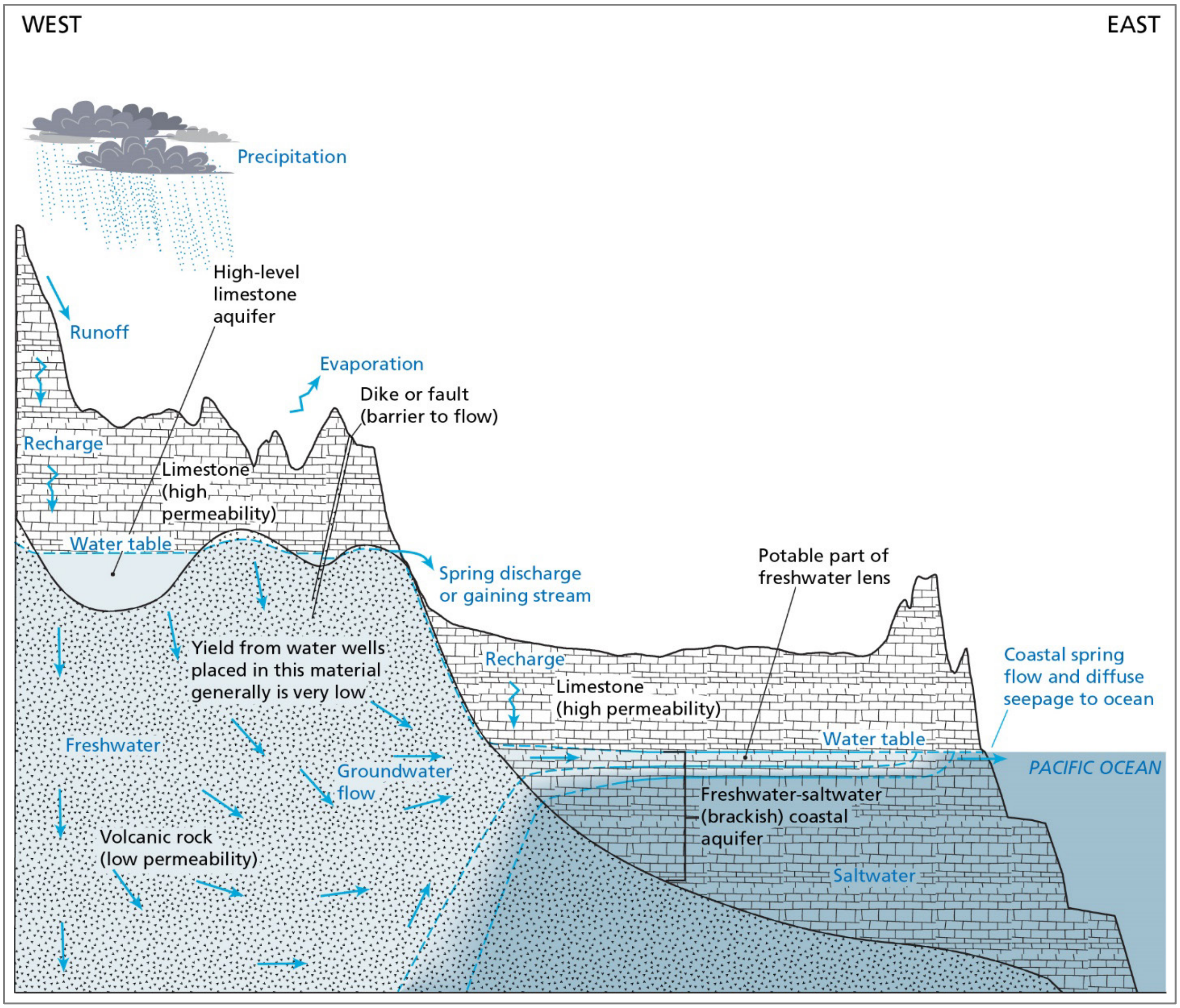


Figure 13. Cross-section of the groundwater flow model for Saipan. Groundwater occurrence, movement, and salinity structure is controlled by the geology. Limestones form the most productive aquifers with high permeability. Volcanic rocks have low permeability and do not function as efficient aquifers for Saipan. Inland, the freshwater aquifer is quite thick, but it is relatively impermeable due to the presence of volcanic rocks. Because of their high permeabilities, groundwater moves relatively rapidly through the limestone aquifer and leaves little to no time for any contaminants to be absorbed or broken down in transit. Near the coast, only a thin lens of freshwater is floating atop a brackish transition atop saltwater from the ocean. Graphic is adapted from figure 8 in Mitchell et al. (2021) by Trista L. Thornberry-Ehrlich (Colorado State University).

Limestones such as the Tagpochau Limestone readily dissolve in acidic solutions, such as carbonic acid, and the features (e.g., caves, alcoves, conduits, pinnacles, disappearing streams, and sinkholes) formed via dissolution are collectively called karst. The natural formation of carbonic acid requires carbon dioxide, which is present in the atmosphere but is produced more efficiently in the soil through the microbial degradation of organic material (White 1988). The increased saturation of water with carbon dioxide augments the ability of groundwater to dissolve limestone (White 1988).

Karst on small carbonate islands is different from karst on continents (Mylroie and Mylroie 2003; Jenson et al. 2006). In particular, carbonate islands like Saipan are made up of limestones that have not been extensively compacted or cemented; they retain a lot of the pores that existed when they were deposited, and water moves through them differently than the "solid" limestones of continental karst (Jensen et al. 2006). Research from Saipan and the other Mariana Islands revealed various components that control cave and karst development on carbonate islands: (1) mixing of fresh and salt water to create aggressive dissolution; (2) movement of the freshwater lens, thus mixing environments by 100 m (330 ft) or more; (3) sea level changes with local faulting activity; and (4) dissolution of relatively immature (less compacted) carbonate rocks (Mylroie and Mylroie 2003). Thus, brackish groundwater, such as that near the coastal areas of Saipan, creates a zone of enhanced chemical reactivity and increased dissolution that is particular to carbonate coasts and small islands like Saipan (Jenson et al. 2006). Zones of increased dissolution are associated with former sea-level stands or periods of time when sea level was consistently at one elevation (Mitchell et al. 2020).

Located in a tropical climate, Saipan receives an average of nearly 200 cm (80 in) of precipitation per year, resulting in extensive limestone dissolution, caves, sinkholes, and springs—important features of the local aquifer system—yet the island lacks a comprehensive inventory of these features (Cloud et al. 1956; Jenson et al. 2006; Whistler 2009; Mitchell et al. 2020). On Saipan, most of the limestone is not extensively compacted or cemented and is therefore rather porous (Jenson et al. 2006). Nearly every limestone surface on Saipan is pitted, pinnacled, creviced, and ridged from dissolution (Cloud et al. 1956). Karst development within saturated young limestones, such as those of Saipan, is enhanced horizontally instead of vertically (Mitchell et al. 2020). Caves and sinkholes are forming through the dissolution by percolating groundwater. The caves of Saipan are diverse (Figure 14) and numerous, with two large ones, Liyang As Teo (Kalabera Cave) and Liyang I Falingun Hanum (Cave of Disappearing Water near Marpi Point), within the Tagpochau Limestone (Cloud et al. 1956). Cave types include vertical pit caves, fault-controlled fissure caves, laterally expansive water-table caves, and fracture- and joint-controlled fissure caves.

Detailed geologic mapping and topographic maps reveal the locations of many sinkholes across the island as hatched depression lines. Drainage through some of these sinkholes is connected with the sea (Figure 15; Cloud et al. 1956). Springs factored heavily in the search for potable water on Saipan. Springs may form at geologic contacts where water, percolating downward from the surface, encounters a relatively impermeable layer and flows laterally. The spring emerges where the impermeable layer meets the surface. Notable springs on Saipan include Donni springs, Talofofo springs, Achugau springs, and Nicholson spring (Cloud et al. 1956).

The karst landscape of Saipan is the most complicated of all the five southernmost Mariana Islands. This is due in part to its complex history of volcanism mixed with limestone deposition (the two were at times syndepositional or deposited at the same time); uplift, subsidence, and associated normal faulting; and global sea level changes (Cloud et al. 1956; Jenson et al. 2006). The island has complex, isolated aquifers, including confined aquifers (under hydrostatic pressure by layers of impermeable material above and below the aquifer) drained by phreatic lift tubes (see Figure 14), which act as a straw or siphon of sorts to pump the water to the surface (Jenson et al. 2006).

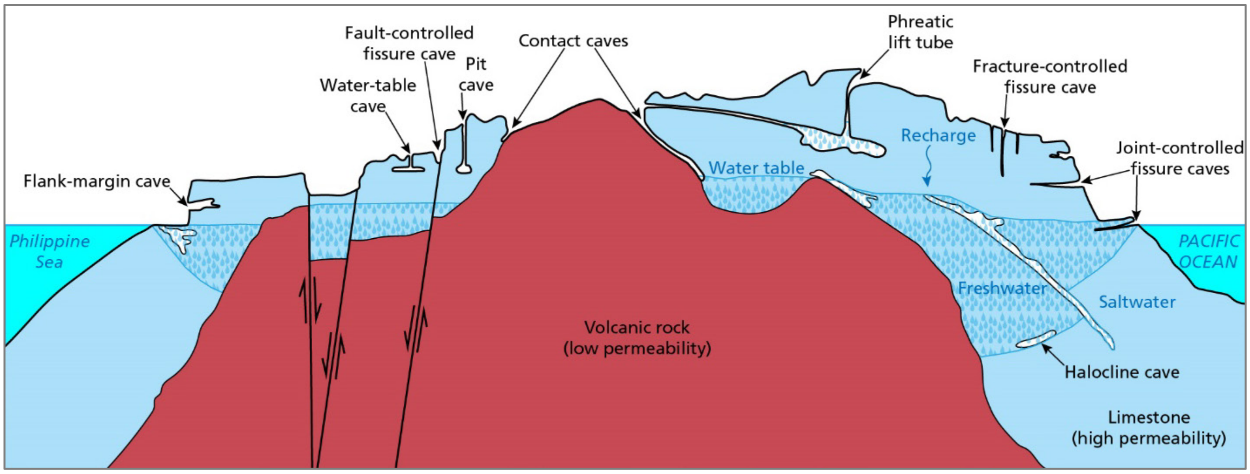


Figure 14. Cross-section of the cave types forming on Saipan. The normal faults, terraced limestone, interlayered volcanics, and volcanic core all contribute to the complexity of the karst landscape of Saipan. Contact caves form where percolating groundwater is intercepted above sea level by the less conducive volcanic rock. It concentrates in a stream descending along the contact, where it erodes large chambers. Fissure caves (fault-controlled, joint-controlled, and fracture-controlled) form where breaks or zones of weakness in the rock channel water—dissolving and enlarging the conduits. Pit caves, water-table caves, and flank margin caves form without obvious entrances because the water enters and leaves by diffuse flow instead of a concentrated stream. Phreatic lift tubes act as siphons or release valves when water under pressure (confined by impermeable layers) is forced upward along fractures. Halocline caves form at the interface between the fresh or brackish water lens (less dense) and the saltwater aquifer (denser) below. At this location, decaying organic material trapped at the density interface may enhance dissolution. The graphic is not to scale and is intended to function as a model, not a specific landform depiction of Saipan. Graphic is adapted from figures 2 and 3 in Jenson et al. (2006) with information from Mylroie and Mylroie (2003) by Trista L. Thornberry-Ehrlich (Colorado State University).

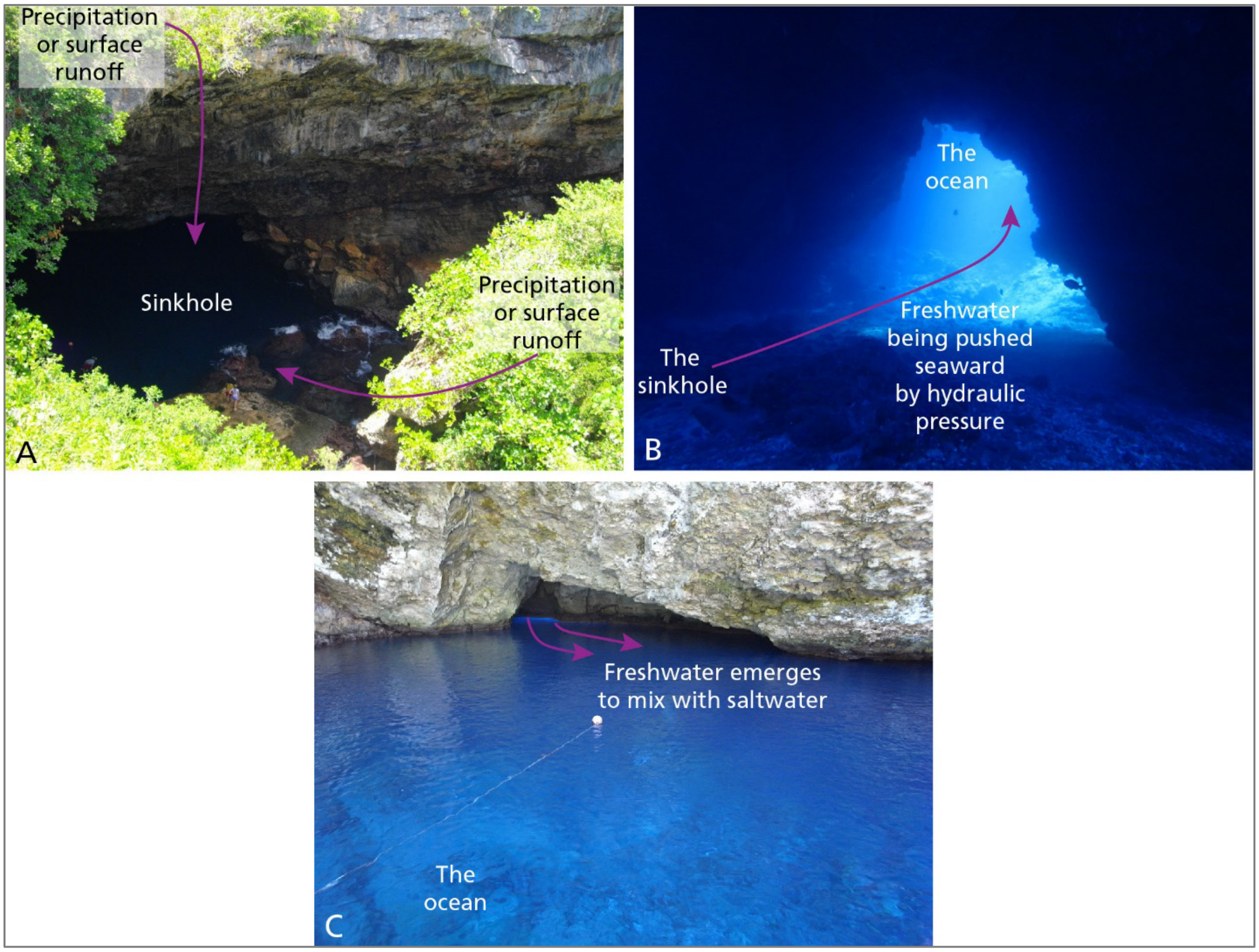


Figure 15. Photographs of the Grotto on Saipan. On the northeastern tip of Saipan, water drains through the surficial sinkhole (A), through passages (B) that are connected to the sea. This flow emerges in the ocean as a coastal spring (C). The openings are large enough to permit human passage. Photograph (A) by Abasaa taken in 2011 available at https://commons.wikimedia.org/wiki/File:Grotto_in_Saipan_2.JPG. Unmodified and used under public domain license. Photograph (B) by Canadie taken in 2016 available at https://commons.wikimedia.org/wiki/File:Saipan_Grotto_Underwater.jpg, CC BY-SA 4.0 DEED (https://creativecommons.org/licenses/by-sa/4.0/deed.en). Photograph (C) by rambler.panoramio taken in 2009 available at https://commons.wikimedia.org/wiki/File:Grotto,_Saipan,_Commonwealth_of_the_Northern_Mariana_Islands_-_panoramio.jpg, CC BY-SA 3.0 DEED (https://creativecommons.org/licenses/by-sa/3.0/deed.en). Graphic compiled and annotated by Trista L. Thornberry-Ehrlich (Colorado State University). All photographs accessed 14 November 2023.

Emerged Carbonate Sand

Map unit: Emerged carbonate sands (**Qrl**), Tanapag Limestone (**Qta**), Tagpochau Limestone (**Ttv**, **Ttl**)

Emerged carbonate sand is an unconsolidated surficial deposit from the Holocene and Pleistocene that is mapped within much of Saipan's western coastal plain, including about 40% of the park's area (Cloud et al 1956; Weary and Burton 2011; Mitchell et al. 2020). Surficial deposits can reach up to 6 to 9 m (20 to 30 ft) in thickness (Cloud et al. 1956). At the park, emerged carbonate sand is the most abundant natural material present in the GRI GIS data. It is commonly mapped landward of beach deposits (**Qrb**) and likely accumulated as a result of a combination of processes including, but not limited to, storms washing sediments landward, weathering of inland rocks such as the Tagpochau Limestone (**Ttv**, **Ttl**), biophysical breakdown of coral reef building structure (e.g., parrotfish nibbling on coral and depositing sand in the lagoon), and almost continuous wave action unrelated to storms.

Emerged carbonate sands (**Qrl**) is called "emerged" because recent sea level changes caused by global climate shifts and local tectonic uplift have caused what were nearshore and beach deposits to be perched above sea level. Recently emerged carbonate sand (**Qrl**) underlies the coastal plain that extends from the southwestern corner of Saipan northward along the west coast to Achugau point (Cloud et al. 1956; Weary and Burton 2011). This western coastal belt ranges from 2 km (1 mi) to less than 100 m (330 ft) wide and includes a total area of about 10 km^2 (4 mi^2) of carbonate sand and artificial fill (**Qaf**) over sand. The sands normally range from very fine- to very coarse-grained, can be even gravelly at some places, and contain many shells and shell fragments (e.g., mollusks and foraminifera—a single-celled planktonic animal with a perforated chalky shell). In appearance, they resemble present beach and lagoonal sands; however, they extend to altitudes as high as 6 m (20 ft) or more, well beyond the current shoreline altitude. They rest upon a westward-sloping, flat surface that is partly underlain by the Tanapag limestone (Cloud et al. 1956; Weary and Burton 2011).

This flat undersurface was likely once geographically continuous with the Tanapag bench along the south side of the island. However, local faulting caused a portion of this benchlike surface to drop downward about 6 m (20 ft) to the west. This fault activity occurred after the deposition of the Tanapag Limestone (**Qta**), but before a 2-m (6-ft) eustatic drop in sea level that is estimated to have begun about 3,000 (±1,500) years ago (Cloud 1954; Cloud et al. 1956). The limestone then formed a surface for the sands to accumulate, likely in lagoonal, beach, and supratidal (above mean tide) conditions, transported by water, wind, and storms (Cloud et al. 1956).

Wetlands and Mangrove Forest

Map unit: Marsh deposits (**Qm**), artificial fill (**Qaf**)

Wetlands provide a broad range of habitat and areas of recreational value (Horsley Witten Group 2004). Wetlands, such as marshes, swamps, seeps, pools, and bogs, are transitional areas between land and water bodies where water periodically floods the land or saturates the soil. Wetlands in the park are covered in shallow surface water or have water within the root zone most of the year. Wetlands are defined by, and entirely dependent upon, surface and near-surface hydrologic conditions (water levels to within 30 cm [12 in] of the surface of the ground), which support wetland vegetation and hydric soils (soils permanently or seasonally saturated by water) (Horsley Witten Group 2004). Wetlands provide several significant functions, for example (1) provision of bird and other wildlife habitat, (2) surface water detention, (3) nutrient transformation, and (4) retention of sediments.

The 11–12 ha (27–30 ac) of several wetlands within the park, mapped as **Qm**, are rare on Saipan and vulnerable (Perreault 2007; Burton and Weary). A man-made, constructed wetland (not mapped separately in the GRI GIS data) is also within the park. Wetlands respond significantly to water level changes and alterations to water inputs. Three freshwater surface inputs into the park's wetlands are possible: direct rainfall, seaward-flowing groundwater, and overland flow. Direct rainfall commonly exceeds evapotranspiration (processes by which water moves from the earth's surface into the atmosphere) both seasonally and per storm. The seaward flow of groundwater supplies freshwater because groundwater generally has an upward vertical component in the nearshore environment due to the density difference buoying the less dense freshwater above the denser saltwater (see Figure 13). Overland surface flow from highlands east of the park has the potential to contribute a significant amount of fresh water during periods of intense rainfall, but roads flanking the park's perimeter act as barriers to most surface water (Perreault 2007). Groundwater and overland flow also have the potential to introduce wastewater and contaminants (see "Stormwater Contamination and Karst Permeability" section). The constructed wetland ("manmade drainage" on figure 6, created in 1997–1998) in the park augments the storm drainage infrastructure of the community of Garapan, whose reverse osmosis desalinization facilities discharge highly saline wastewater into the storm-drainage system (Perreault 2007; Greene et al. 2019). This drainage leads into Smiling Cove (Greene et al. 2019).

Most of the wetlands in the park do not function naturally. This is likely due to the artificial fill (**Qaf**) installed over time to shape the land surface for human use. During World War II, many wetlands were filled and leveled (Cloud et al. 1956). A "lake or swamp" was filled at Puntan Muchot, the northern end of Micro Beach where the shoreline curves around like a horn into Smiling Cove (Cloud et al. 1956). Though now protected under federal and local law, the wetlands in the park were used as a landfill until about 1978 and have been cut off from regular tidal inundation by the construction of the marina, surrounding roads, and fill; however, the salinity remains high enough to support the mangroves (Hess and Pratt 2005; Greene et al. 2019). Dense thickets of vines and invasive woody species are also part of the wetlands (Hess and Pratt 2005). Today, a culvert within the wetlands floods regularly (see Figure 4). East and west of this culvert, the vegetation changes dramatically, with hydrophilic (water-loving) plants preferring the flooded side (Cogan et al. 2013; Tahzay Jones, regional coastal ecologist, National Park Service-Alaska, conference call 16 November 2021).

Normal Faults

Map units: Tagpochau Limestone, limestone member (**Ttl**), deformation areas (**breccia zone**)

Faults are formed where rocks have been fractured and moved. They are common structural features in tectonically active areas such as the Mariana Trench and the island arc. Faults are classified based on the motion of rocks on either side of the fault plane, as described in Figure 16. The three primary types of faults are normal faults, reverse faults, and strike-slip faults (Figure 16). For normal faults, the block above the fault plane moves down relative to the block below. For reverse faults, the opposite is true, with the block above the fault moving up relative to the block below. For strike-slip faults, the blocks slide laterally past each other with little to no vertical movement.

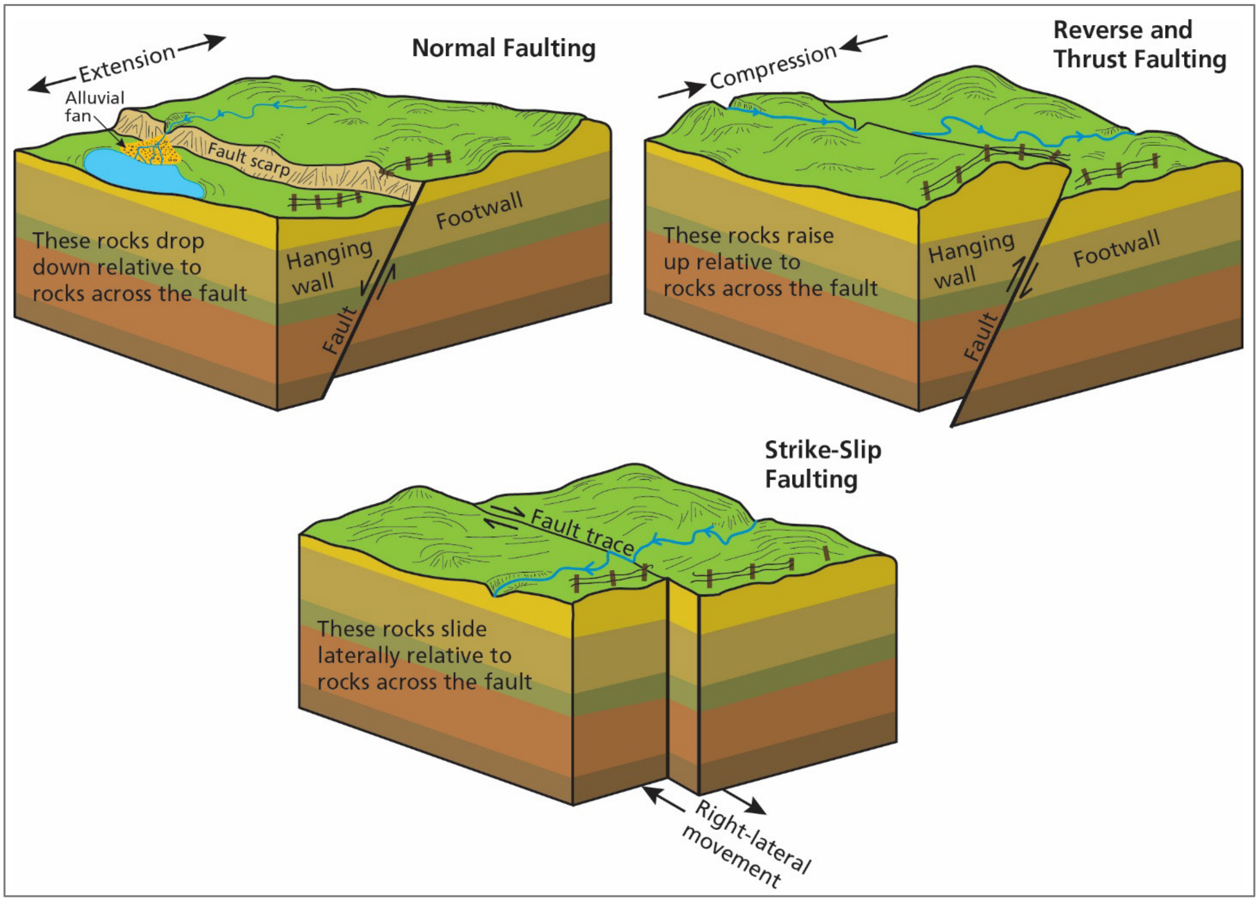


Figure 16. Graphic of fault types. Movement occurs along a fault plane. Footwalls are below the fault plane, and hanging walls are above. In a normal fault, such as those mapped on Saipan, crustal extension (pulling apart) moves the hanging wall down relative to the footwall. In a reverse fault, crustal compression moves the hanging wall up relative to the footwall. A thrust fault is a type of reverse fault that has a dip angle of less than 45°. In a strike-slip fault, movement is horizontal. When movement across a strike-slip fault is to the right, it is a right-lateral strike-slip fault, as illustrated above. When movement is to the left, it is a left-lateral strike-slip fault. A strike-slip fault between two tectonic plates is called a transform fault. Transtension (transform plate motion and extension) is characterized by strike-slip and normal faulting. Transpression (transform plate motion and compression) is characterized by strike-slip faulting and reverse and thrust faulting. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

All faults on Saipan were mapped as normal faults by Weary and Burton (2011). None of the faults are mapped within the park boundaries; the nearest fault is about 777 m (850 ft) east of the park (see poster and Figure 17). Most of the faults trend northeast to southwest, parallel to the overall trend of the Mariana archipelago (Mitchell et al. 2020). This orientation suggests that, at least in part, faulting has long been influenced by the submarine ridge from which the island rises and therefore its tectonic setting (Cloud et al. 1956). Along these faults, portions of the island dropped down relative to other portions prior to, during, and subsequent to the deposition of sedimentary (carbonate) rocks (Cloud et al. 1956; Rutherford and Kaye 2006; Weary and Burton 2011). Faulting has resulted in vertical displacement of as much as 30 m (100 ft) on conspicuous faults, but more displacement could be possible on some faults that are not measurable at the surface (Cloud et al. 1956; Mitchell et al. 2020).

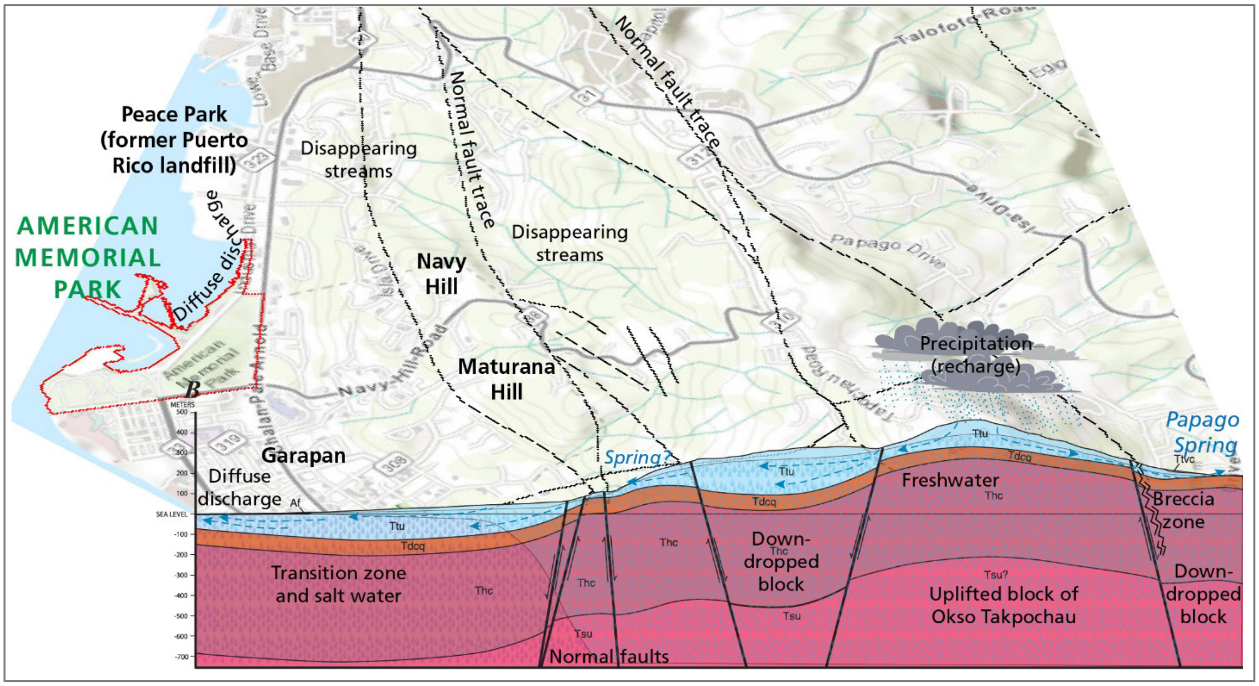


Figure 17. Cross-section of Saipan south of the park. The cross section shows the uplifted block of Okso Takpochau relative to down-dropped blocks to the east and west. Groundwater flows away from the uplifted block toward adjacent down-dropped blocks; paths are marked by dashed blue arrows. Geologic map unit Tsu is the Sankakuyama Formation, undivided. Thc is the Hagman Formation, conglomerate, and sandstone. Tdcq is the Densinyama Formation, quartzose conglomerate, and sandstone. Ttu is the Tagpochau Limestone, undivided. Ttu does not appear as such in the GRI GIS data. The source mappers, Weary and Burton (2011), used this symbol to lump the three different facies of the Tagpochau together (Ttl, Ttm, Ttv) for this cross section. Diffuse discharge is occurring along the coast in the park area. Discharge is not concentrated in discrete channels. Because of the extreme karst permeability of the Tagpochau Limestone, surface streams rapidly disappear underground and contribute to the diffuse discharge. Normal faults occur across the island separating blocks of uplifted or down-dropped rocks. Okso Takpochau is bound to the east and west by normal faults, across which blocks of rock have dropped down. Some of the larger faults have brittle fracturing in a zone adjacent to the fault (breccia zone). Springs emerge where groundwater flow intersects the surface, commonly when forced to the surface by an impermeable layer or a fault. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) with portions of the cross section from Garapan through Mt. Takpochao to Forbidden Island (B-B’ in the GRI GIS data) taken from Weary and Burton (2011). Basemap from ESRI World Topographic Map

Fault activity was part of the growth of Saipan, dating back to the middle Tertiary to the present (no active volcanism) with even the youngest geologic map units showing offsets (Cloud et al. 1956; Weary and Burton 2011). Faults greatly impacted how the island of Saipan formed, how the landscape exists at present, and how groundwater moves through the subsurface. The GRI GIS data beyond the park boundaries include at least eight named faults, including the Achugau, Agignau, Dago, Falngun Hanom, Laolao Bay, Makpe, Matansa, and Obyan Faults (Weary and Burton 2011). The heights of Okso Takpochau and other upland areas are formed by blocks to the east and west dropping down adjacent to the core block that remains uplifted. This setting is visible in cross sections (see Figure 17). In some areas of the island, movement along faults has created brecciated zones, or areas where the rocks have been broken and crushed into a jumbled assemblage. These occur in the Tagpochau Limestone (**Ttl**). Twenty-three deformation areas (**breccia zone**) are part of the GRI GIS data (Weary and Burton 2011).

Faults tend to provide zones of weakness; some locations may be preferentially weathered and/or turned into clay layers. Weathered gaps at fault exposures suggest these represent narrow zones of higher permeability (Carruth 2003; Mitchell et al. 2020) Faults can also act as a barrier, where less permeable rock is juxtaposed with permeable rock, forcing groundwater to flow in another direction; this may give rise to springs. Test drilling near some island faults penetrated dense, hard rock, suggesting some compaction of the rock due to faulting and relatively lower permeability (Carruth 2003). Disparate groundwater levels measured on either side of the Obyan and Dago faults indicate that the faults may be acting as hydrologic barriers (Mitchell et al. 2020). More data is needed to characterize the spatial effects of faults on groundwater flow near the park as part of an effort to develop an island-wide water-budget model (Mitchell et al. 2020).

Earthquakes

Earthquakes occur when rocks suddenly move along a fault, releasing accumulated energy (Braile 2009). Earthquake intensity ranges from being imperceptible by humans to complete destruction of developed areas and alteration of the landscape. The “Richter magnitude” is a measure of the energy released by an earthquake on a logarithmic scale from 1 to 10; another way to measure earthquake intensity is via the Mercalli Intensity scale, which notes the types of damage an earthquake may cause on a qualitative scale from I to XII. Earthquakes can directly damage park infrastructure or trigger other hazards, such as slope movements, that may impact park resources, infrastructure, or visitor safety.

The Philippine Sea Plate, on which the park is located, is unusual in that its borders are primarily convergent boundaries with adjacent plates (Smoczyk et al. 2013). Earthquakes on Saipan are caused by the convergence of the Pacific Plate and the Philippine Sea Plate (Figure 3 and Figure 18). Earthquakes are common and may include large magnitude (greater than 4–5 magnitude) events (Rutherford and Kaye 2006). In a three-year study period from 1991 to 1994, at least 324 earthquakes occurred in the Saipan region (Sako et al. 1995). Five to eight earthquakes with a magnitude of 5–6 occur along the Mariana Trench each year (Rutherford and Kaye 2006; Smoczyk et al. 2013). In August 1993, a magnitude 8.0 (intensity IX [violent]) earthquake occurred near Guam causing landslides on the island of Guam and damaging the visitor center at War in the Pacific National Historical Park. The destructive earthquake formed an arcuate (arc-shaped) rupture zone where the surface visibly cracked, about 300 km (190 mi) long, centered on Guam. However, the main shock was also felt in Saipan and damaged some buildings (Sako et al. 1995). A 7.2 magnitude earthquake occurred north of Saipan in 2007 (US Geological Survey 2007). According to the USGS’s latest earthquake viewer (https://earthquake.usgs.gov/earthquakes/map/), in October 2021 alone, about 18 earthquakes occurred with magnitudes greater than 2.5 near Saipan, including one with a magnitude 5.0 southwest of San Jose Village on Tinian Island in the Northern Mariana Islands.

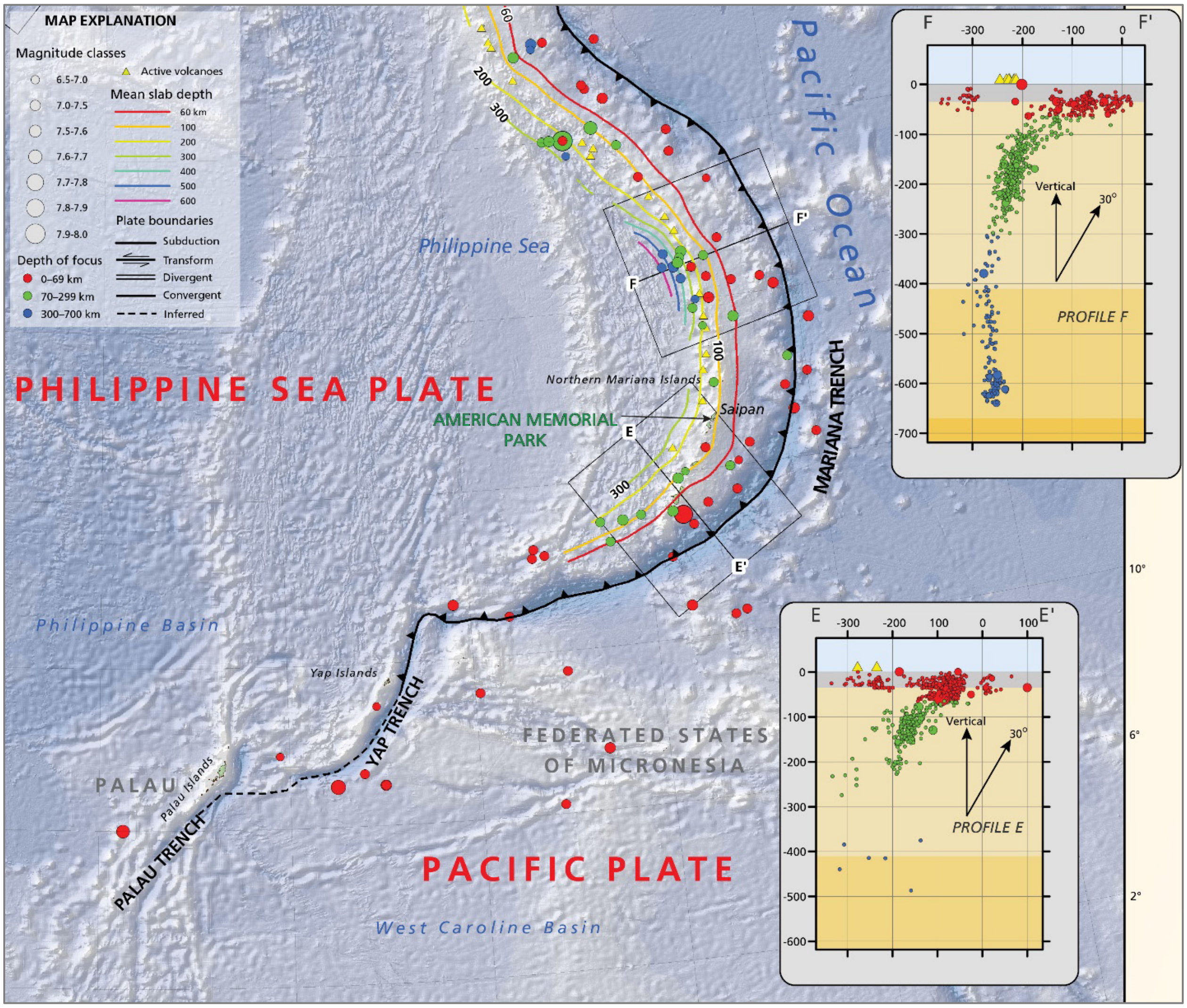


Figure 18. Map of earthquake epicenters (1900–2012) near Saipan and the Northern Mariana Islands. Earthquakes are abundant near the plate boundary (i.e., Mariana Trench). Inset graphics show cross section views of the depth of focus for earthquake epicenters and indicate that near Saipan the subduction angle is quite steep. Active volcanoes, including submarine volcanoes, parallel the plate boundary and are the surface expression of partial melting of the subducting slab of the Pacific Plate under the Philippine Sea Plate. Graphic is from Smoczyk et al. (2013) modified by Trista L. Thornberry-Ehrlich (Colorado State University).

Predicting seismicity can be tricky, particularly for a specific island in the Mariana island arc. Seismic source modeling using the historic earthquake record, known rock characteristics, and an understanding of the local structural geology yielded probabilistic seismic hazard assessments for Saipan. These included hazard maps showing peak ground acceleration, which is a measure of the maximum force experienced by a small particle located at the surface of the ground during an earthquake; in other words, it is an index to the hazard for short, stiff structures (Figure 19). These are commonly expressed as a fraction or a percentage of g (the standard acceleration due to Earth's gravity, equivalent to g-force). Accelerations were computed for exceedance probabilities of 2% and 10% in 50 years (corresponding to ground-motion return times of approximately 2,500 and 500 years, respectively; Mueller et al. 2015). For a 2% probability of exceedance in 50 years, the probabilistic peak ground acceleration is 0.57 gravitational acceleration (g) at Saipan. For a 10% probability of exceedance in 50 years, the probabilistic peak ground acceleration is 0.29 g at Saipan (Mueller et al. 2015). Even on the low end, this kind of shaking would cause widespread loss of surface cohesion in the unconsolidated coastal deposits and undermine building foundations.

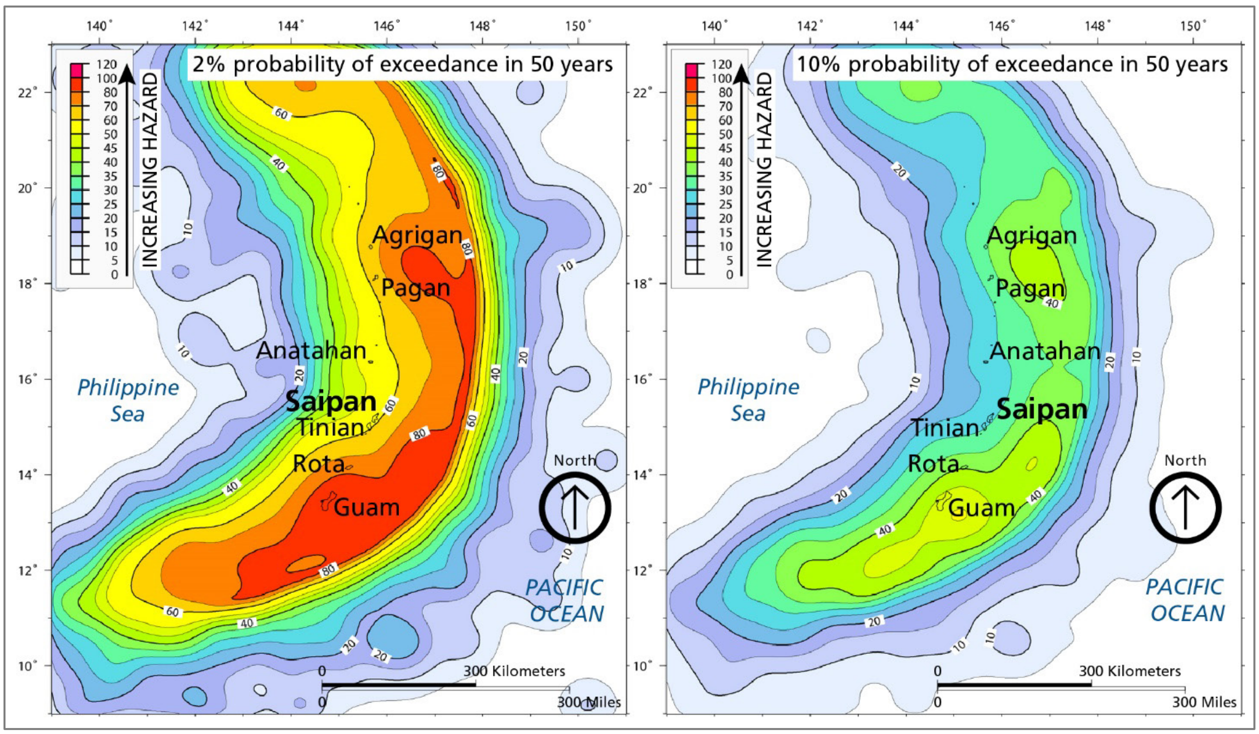
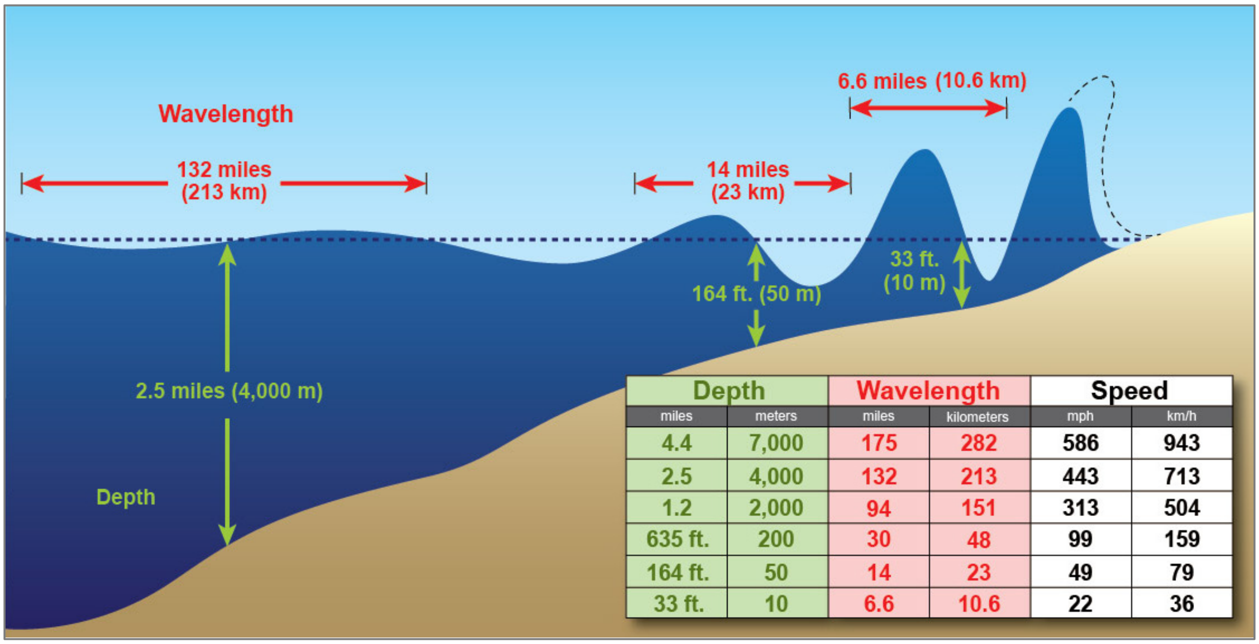


Figure 19. Earthquake hazard maps for Saipan and neighboring islands. The region, as a whole, is susceptible to earthquakes. Saipan is in a moderate to high earthquake hazard area relative to the surrounding islands. Cool to warm colors represent increasing peak ground acceleration (a percentage of g or Earth's standard gravitational acceleration; g-force) and, therefore, increasing earthquake hazarard. For exceedance probabilities of 2% in 50 years (left map), the peak ground acceleration for Saipan is between 50%g and 60%g. For exceedance probabilities of 10% in 50 years (right map), the peak ground acceleration for Saipan is between 25%g and 30%g. Graphic presented as figures 6A and 6B in Mueller et al. (2015) with some annotation by Trista L. Thornberry-Ehrlich (Colorado State University).

Tsunami

Another concern in a seismically active coastal area is tsunamis. A tsunami is a series of waves in a water body caused by the displacement of a large volume of water. Earthquakes, volcanic eruptions, and other underwater disturbances (including detonations, landslides, glacier and iceberg calvings, meteorite impacts) all have the potential to generate a tsunami. Tsunami waves are unlike normal ocean waves and tides, which are generated by wind or by the gravitational pull of the moon and the sun, respectively. Tsunami waves do not resemble normal waves because their wavelength is much longer, and instead of appearing as a breaking wave, a tsunami may initially resemble a rapidly rising tide. The tsunami consists of a series of waves with periods ranging from minutes to hours. They arrive on a shore in a train-like fashion, piling up on the shallow ocean floor offshore of a landmass (Figure 20). The largest events may generate waves tens of meters high and cause widespread destruction (Fradin and Brindell 2008).



Depth		Wavelength		Speed	
miles	meters	miles	kilometers	mph	km/h
4.4	7,000	175	282	586	943
2.5	4,000	132	213	443	713
1.2	2,000	94	151	313	504
635 ft.	200	30	48	99	159
164 ft.	50	14	23	49	79
33 ft.	10	6.6	10.6	22	36

Figure 20. Cross-section view through the generation of a tsunami. Speed, depth, and wavelength are all mathematically related. As a tsunami wave approaches a coastline, the decrease in ocean depth creates drag causing the wavelength to shorten and the wave crest (i.e., wave height) to rapidly rise; it is like the bunching up of folds in a rug. In a short distance offshore of Saipan (less than 10 km [6 mi]), depths reach more than 200 m (660 ft). The crests of a tsunami could stack up rapidly to strike the island. The degree of threat from a tsunami to the park also depends on the tsunami approach direction. Because of the opening in the fringing reef offshore of the park, a tsunami coming from the west would have a potentially dangerous impact on the park. However, Saipan is a small island and diverse wrap around effects and complications could arise from tsunamis from other directions. Graphic is from NOAA (2022), available at https://www.weather.gov/jetstream/tsu_prop (accessed 26 May 2022).

Fortunately, the high angle of the subducting Pacific tectonic plate to the east causes most local earthquakes to have deep epicenters that are less likely to generate tsunami. Tsunami caused by regional tectonic events (i.e., those associated with the Izu-Bonin-Mariana arc system) occurred in 1849, 1892, and 1990, whereas tsunami in 1952 and 1960 were from Kamchatkan and Chilean earthquakes, respectively (Rutherford and Kaye 2006). Those waves were transmitted across the Pacific Ocean. In 1990, a local underwater earthquake triggered a small tsunami, which did not exceed 24 cm (9 in) on Saipan (Department of Homeland Security 2021). Active volcanoes to the north and west of Saipan pose a slight risk of tsunami generation. Tsunami warnings signs are present throughout the island, and Navy Hill is a local high point underlain by Tagpochau Limestone (geologic map unit **Ttl**) (Weary and Burton 2011; Brooke Nevitt, lead ranger, American Memorial Park, conference call, 18 November 2021). Tsunami warnings were issued during the 2003 eruption of Anatahan and the 1995 eruption at Ruby Seamount; however, no tsunami were generated from these events (Rutherford and Kaye 2006), and no oral history of large tsunami exists for the island (Brooke Nevitt, lead ranger, American Memorial Park, conference call, 18 November 2021). The largest and most recent wave event was a 1-m (3.5-ft) swell from the destructive 2011 Japan tsunami. Fortunately for the park, that tsunami hit at low tide and was more oriented toward Hawai'i, not Saipan (Southern California Earthquake Center 2023).

Paleontological Resource Potential

Map units: Emerged carbonate sands (**Qrl**), marsh deposits (**Qm**), Tagpochau Limestone, limestone member (**Ttl**)

Paleontological resources (fossils) are any evidence of life preserved in a geologic context (Santucci et al. 2009). They may be body fossils (any remains of the actual organism such as bones, teeth, shells, or leaves) or trace fossils (evidence of an organism's activity such as nests, burrows, tracks, or coprolites [fossil dung]). Generally, they should be more than 10,000 years old. No paleontological resources of this vintage have yet been confirmed in the park.

Saipan's limestones are fossiliferous, meaning they contain paleontological resources; however, paleontological resources have yet to be definitively confirmed at the park. Fossils collected from Saipan are curated at the Smithsonian Institution and discussed in detail by Cloud et al. (1956). The emerged carbonate sands (geologic map unit **Qrl**) within the park are noted to contain abundant mollusk shells and foraminifera that are relatively recent, with a potential age of a few thousand years (Cloud et al. 1956; Weary and Burton 2011). Cores from the wetlands and mangrove forest in the park produced a pollen record that could possibly extend back as far as 3,000–4,000 years BP; however, given the history of ground disturbance in the area, the completeness of these cores is in doubt (Jarzen and Dilcher 2009; Greene et al. 2019; Justin Tweet, paleontologist, National Park Service, written communication 7 August 2023). The pollen record debunked misconceptions that coconut palm (*Cocus nucifera*) and ironwood trees (*Casuarina equisetifolia*), two prevalent species on Saipan, were introduced by human settlers (Jarzen and Dilcher 2009; Greene et al. 2019).

Hunt et al. (2007) provided a summary for all parks in the Pacific Islands Inventory and Monitoring Network. Body fossils are the predominant type and are from marine invertebrates such as algae, foraminifera, discoasters (a genus of extinct star-shaped marine algae), radiolaria (single-cell microorganisms that produce intricate mineral skeletons, typically with a central capsule), echinoids (sea urchins), corals, and mollusks (Hunt et al. 2007). These fossils are common in marine limestones, and the assemblages of species present on Saipan were used by paleontologists to suggest ages for the limestone mapped on the island (Cloud et al. 1956; refer to Weary and Burton 2011 for a discussion on the discrepancies among fossil ages and other dating techniques). The outwash, fill, beach, and alluvial/wetland deposits mapped within the park may contain fossil resources washed from other formations (e.g., the nearby Tagpochau Limestone, limestone member [**Ttl**]) (Hunt et al. 2007; Weary and Burton 2011).

Fossils in NPS units occur in rocks or unconsolidated deposits, museum collections, and cultural contexts such as building stones, memorials, or archeological resources. A cultural resource landscape report may illuminate such potential paleontological resources for the park. Kenworthy and Santucci (2006) presented an overview and detailed selected examples of National Park Service fossils found in cultural resource contexts.

Micro Beach and Coastal Features and Processes

Map units: Emerged carbonate sands (**Qrl**), artificial fill (**Qaf**)

Coastal environments—those areas along the interface between land and sea—of Saipan are dynamic. Patch reefs in the lagoon, Smiling Cove Marina infrastructure, and the 4-km (2 mi) wide gap in the fringe reef contribute to a complex system of coastal change at the park (Urena 2022a). The park contains about 1.31 km (0.81 mi) of sandy shoreline, though this metric fluctuates because of coastal processes (Greene et al. 2019). The leased land boundary that the park manages terminates at the mean high-water mark. For ecological management, nearshore areas in the lagoon (100 m [330 ft]) are discussed because their ecological function is directly tied to the status of the park's shoreline, especially with respect to erosion (see "Erosion"; Greene et al. 2019).

Offshore from the park and the beach is a 30.8 km^2 (11.9 mi^2) lagoon (Tanapag and Garapan Lagoons) protected by the fringing barrier reef. Carbonate pavement dominates the reef crest, which absorbs most of the oceanic wave energy (Kendall et al. 2017; Sea Engineering 2019). The lagoon has a benthic (below water) habitat of diverse corals and seagrass beds (Yuknavage and Palmer 2010; Kendall et al. 2017). NOAA and Division of Coastal Resources Management offshore mapping includes deep dredged areas, deep patch reefs, sand-dominated areas, macroalgae back reef flats, high energy reef crest, halodule (thick sea grass) mix, Pleistocene rock halodule patches, and thick enhalus (large flowering sea grass) zones (Division of Coastal Resources Management 2017; Kendall et al. 2017). Comparing habitat maps from 2001 and 2016 reveal formerly dense seagrass meadows have been replaced with patchy sand and algal bottom (Kendall et al. 2017). Some areas have been scoured to bare carbonate pavement (Kendall et al. 2017). The lagoon is broadest and deepest immediately north of the park. The barrier reef is 4 km (2 mi) offshore, and depths of 15 m (50 ft) are reached (Yuknavage and Palmer 2010; Sea Engineering 2019).

Micro Beach begins south of the park boundary, arcs around the western side of the park, acts as a sediment supply to the park, is heavily used, and is migrating northward (Division of Coastal Resources Management 2014; Tahzay Jones, regional coastal ecologist, National Park Service-Alaska, conference call 16 November 2021). As recently as the early 2000s, Micro Beach was primarily a sandy beach. It has since eroded significantly (Tahzay Jones, regional coastal ecologist, National Park Service-Alaska, conference call 16 November 2021). Where the beach slope is not steep, it is a bluff, and the adjacent lagoon includes sand, sea grass, and fallen trees (Division of Coastal Resources Management 2014). Some portions of the beach are anchored by trees and coastal engineering structures, but the current beach is largely unvegetated and consists of remnant broken coral pieces as the finer-grained sand has been transported north by storm-driven waves and longshore drift, which is the movement of material along the shore by wave action (Division of

Coastal Resources Management 2014; Tahzay Jones, regional coastal ecologist, National Park Service-Alaska, conference call 16 November 2021).

As wave action and longshore drift (Figure 21) move sediments northward along the coast, the arcing beach ridges are shifting, and plants and habitats follow suit. Fine sand, extremely low beach slope, and the flourishing of new vegetation (including entire sections of forest), demonstrate a strong trend of sediment accumulation or accretion (Division of Coastal Resources Management 2014). A line of new vegetation is growing northward from Micro Beach, toward Smiling Cove (see Figure 5 and Figure 6; Tahzay Jones, regional coastal ecologist, National Park Service-Alaska, conference call 16 November 2021). The cove must be periodically dredged to maintain boat access. Smiling Cove contains dense patches of sea grass that act as natural sand traps (Kendall et al. 2017). Smiling Cove also contains man-made objects (e.g., breakwaters and piers) associated with the marina (Kendall et al. 2017). At some point, if left in its natural state, the arcing beach ridges will connect with Smile Island, and the basin will no longer flush appropriately. This poses a water quality hazard because natural water transport or flushing would not happen and waste and contaminants would concentrate there, but the park does not manage the offshore environment nor is responsible for the dredging (Greene and Skeele 2014; Tahzay Jones, regional coastal ecologist, National Park Service-Alaska, conference call 16 November 2021).

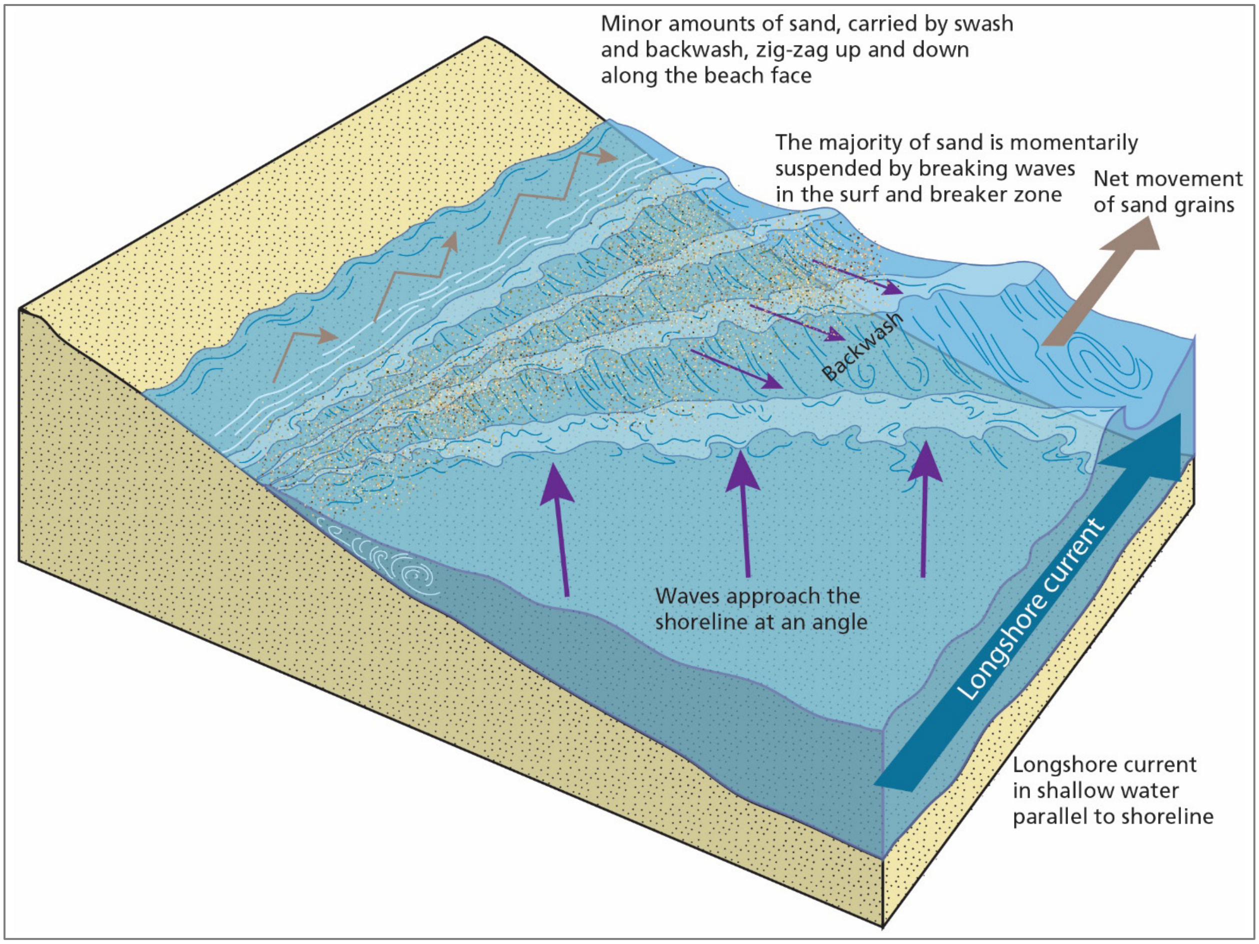


Figure 21. Diagram of longshore drift. Waves refract as they move onshore, and most of the longshore transport of sand occurs as the sand is suspended temporarily by breaking waves in the surf and breaker zone. Sand grains are transported by waves and longshore currents and are deposited in sheltered areas and leeward sides of landmasses. At the park, longshore drift is responsible for transporting grains from Micro Beach northward, building beach ridges into Smiling Cove. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) based on graphics from Capital Regional District (https://www.crd.bc.ca/education/in-your-community/geology-processes/coastal-sediment) and Rob's [Rob Croslinig] geoblog (http://robcroslinggeoblog.blogspot.com/2011_10_01_archive.html) and information from Peter Rosen and Duncan FitzGerald (Northeastern University and Boston University, respectively, coastal geologists, written communications, 24 and 25 May 2016).

Disturbed Lands

Map unit: Artificial fill (**Qaf**)

Low-lying and coastal areas along western Saipan are mapped as artificial fill, including about 44% of the park. At Puntan Muchot, the northern end of Micro Beach, a lake or swamp was filled, today mapped as **Qaf** and **Qrl** (Cloud et al. 1956). This fill reflects a longstanding attempt to reshape the landscape and control natural processes along the coast for human purposes. Low-lying, swampy areas were filled with limestone rubble and sandy material to increase the stability of the land surface (Tahzay Jones, regional coastal ecologist, National Park Service-Alaska, conference call 16

November 2021). During World War II, the park area was an airstrip and military camp, which required tons of infill material. The fill also contains archeological resources (Tahzay Jones, regional coastal ecologist, National Park Service-Alaska, conference call 16 November 2021), and paleontological resources may be present. After World War II, the US military continued to modify the Tanapag Harbor area with dredge and fill activities (American Memorial Park 2021).

A small gravel pit is located near the wetlands of the park. Aerial imagery shows it still has a bald area within the vegetated area, and it is still in use by the maintenance division (Tahzay Jones, regional coastal ecologist, National Park Service-Alaska, conference call 16 November 2021).

Geologic Resource Management Issues

Some geologic features, processes, or human activities may require management for human safety, protection of infrastructure, and preservation of natural and cultural resources. The NPS Geologic Resources Division provides technical and policy assistance for these issues (see "Guidance for Resource Management"). The issues are ordered with respect to management priority.

Erosion

The park is impacted by inundation and waves because of its sea-level location (Figure 22 and Figure 23; Helweg et al. 2014). Coastal erosion has been a longstanding resource management issue at the park (Greene et al. 2019). Shoreline and nearshore condition were listed as moderate, and with negative trends in the park's natural resource condition assessment (Greene et al. 2019). While coastal change, including erosion, is a continuous and natural process, it becomes an issue when park infrastructure and visitor use facilities are threatened and when the natural rate of change has been increased by human activities. The coastline on the far western edge of the park faces the biggest erosion challenges. Restroom facilities and other small structures were falling into the ocean, and cement casings became exposed (Figure 24 and Figure 25; Tahzay Jones, regional coastal ecologist, National Park Service-Alaska, conference call 16 November 2021). These features were listed as "threatened" several decades ago (Dean 1991) and the infrastructure was moved inland.

Historical shorelines from aerial photography indicate that portions of the shoreline recede while others advance. Sediment is supplied to the advancing portion from the eroding stretch and overall longshore drift (see Figure 21). From 1985 to 1987, portions of the park's shoreline at the southwestern corner eroded at a rate of 8 m (25 ft) per year (Dean 1991). The USACOE suggested hardened shorelines and marina infrastructure are blocking sand sources from the northeast and contributing to this localized erosion, but this has yet to be substantiated with study of the more than 70 years of shoreline modifications (USACOE 2004; Greene et al. 2019).

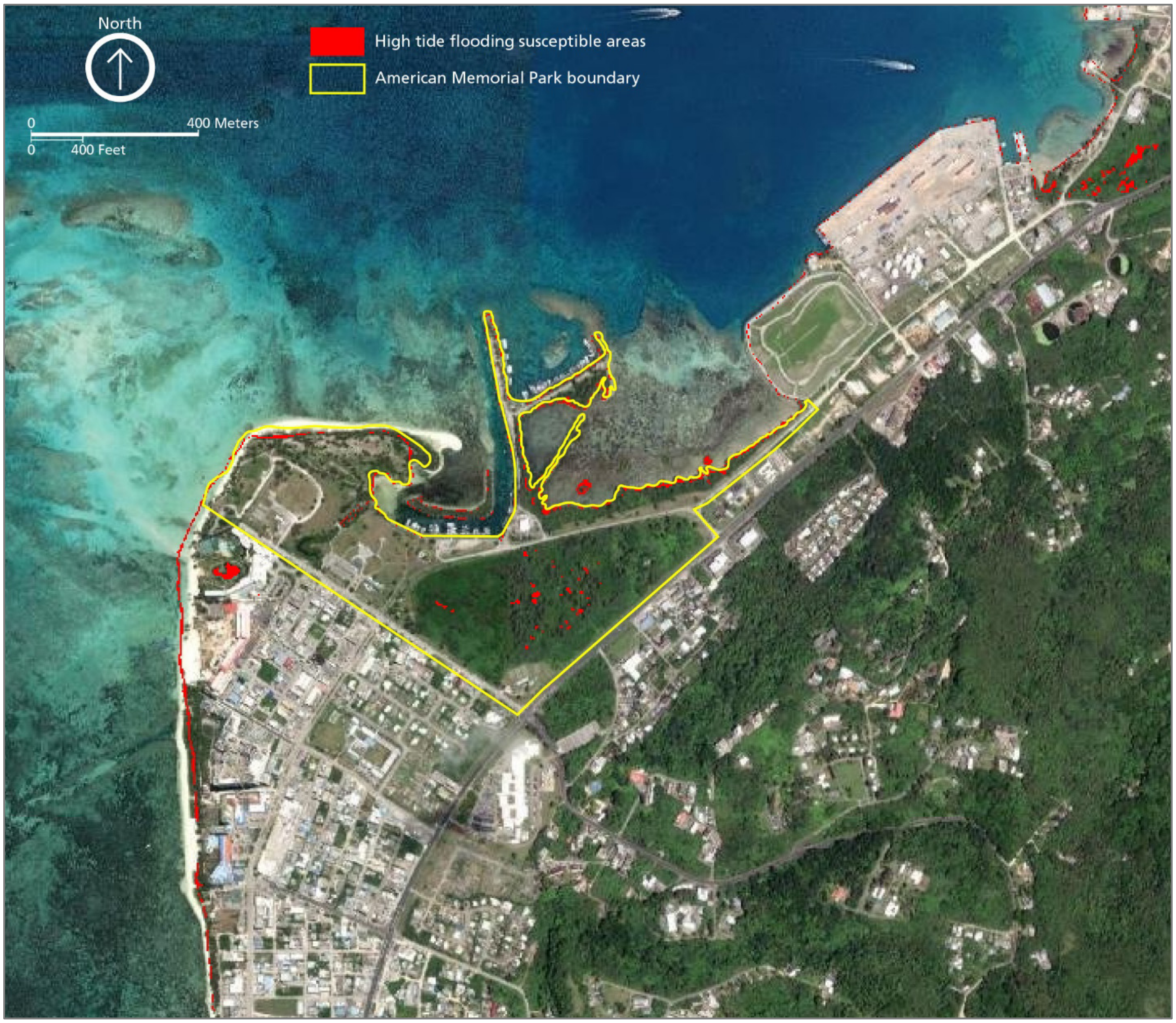


Figure 22. High-tide flooding susceptible areas within and surrounding the park. Most of the area within the park is low-lying and because of the extensive system of subterranean water flow paths, high tides can end up impacting areas inland of the coast. Red areas indicate the areas likely to flood at high tide. As expected, land along the coastline is red, but red is also present inland particularly within the interior wetlands of the park. The yellow outline denotes the park boundary. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) using the Coastal Flood Exposure Mapper from NOAA (https://coast.noaa.gov/digitalcoast/tools/flood-exposure.html, accessed 2 May 2023) with data coming from the National Tsunami Hazard Mitigation Program.

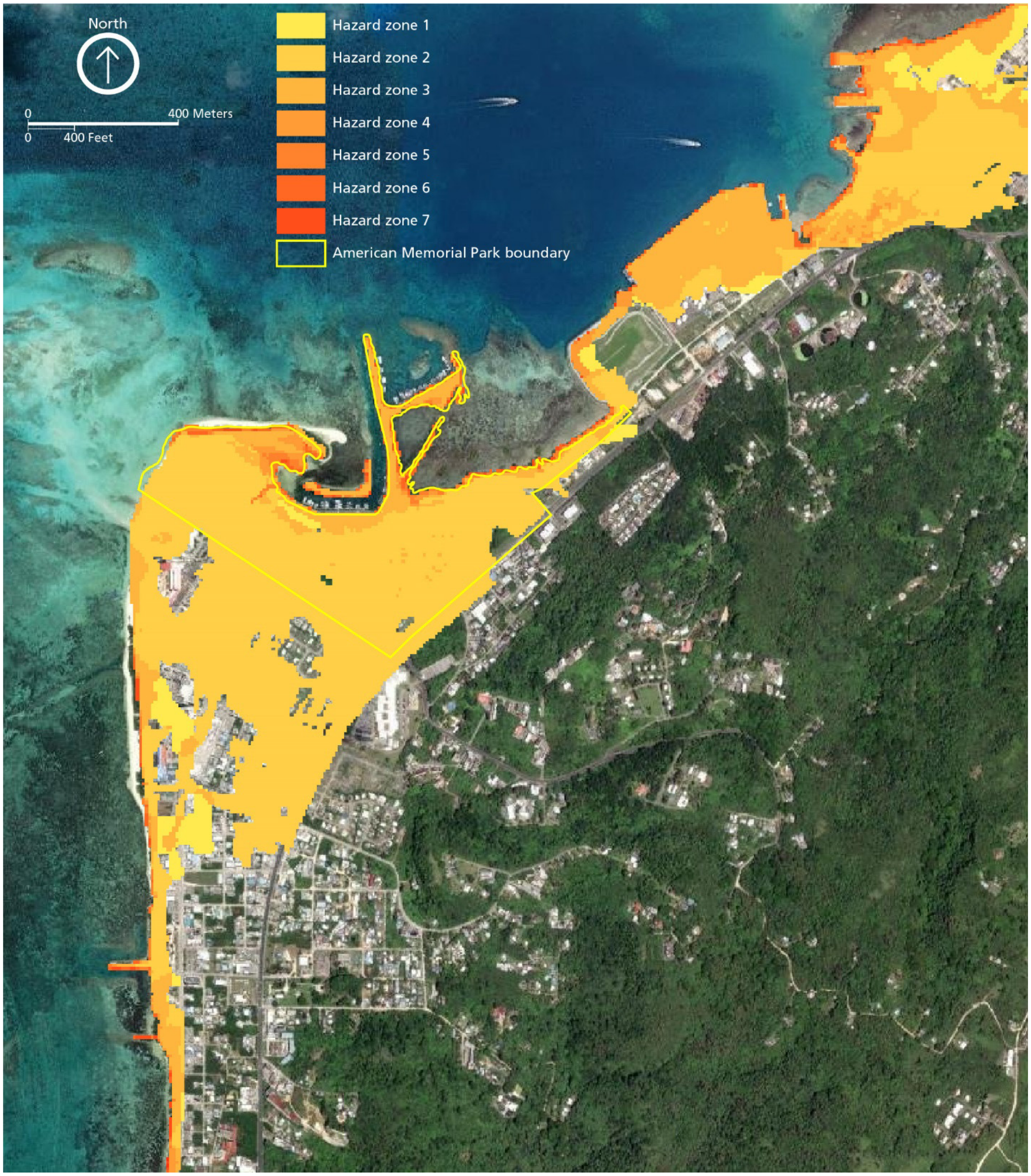


Figure 23. Coastal flood hazard areas within and surrounding the park. Most of the park is low-lying and in hazard zone 3 for diverse coastal hazards. Areas immediately adjacent to the coast have the highest composite hazard level (zones 4 to 7). The colors range from yellow (lowest hazard zone) to red (highest hazard zone). The hazard zones come from a composite hazard layer that combines high-tide flooding, Federal Emergency Management Agency (FEMA) flood data, storm surge for category 1, 2, and 3 hurricanes, sea level rise scenarios for 0.3, 0.6, and 0.9 m (1,2, and 3 ft) above mean high tide, and tsunami run-up zones. Yellow outline denotes the park boundary. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) using the Coastal Flood Exposure Mapper from NOAA (https://coast.noaa.gov/digitalcoast/tools/flood-exposure.html, accessed 2 May 2023) with data coming from the National Tsunami Hazard Mitigation Program.

Figure 24. Photograph of storm damage at a park restroom. Many of the coastal areas along the western side of the park are eroding away due to high-energy wave impact. These facilities have since been relocated further inland, about 100 m (330 ft) away from the shoreline along Wedelia Avenue. NPS photograph taken in 2007.

Figure 25. Photographs showing severe coastal erosion undermining a concrete walkway at the park. Stabilizing vegetation is all but destroyed along this section of the shoreline at the western edge of the park near the Japanese bunker site and Roseli Loop. Some threatened infrastructure was relocated inland. NPS photographs taken in 2012.

The Division of Coastal Resources Management monitors seven sites within the park with annual beach profile measurements. Since monitoring began in 2016, the four sites along the western side of the park are eroding, and the three sites along the northern edge of the park are accreting (Figure 26). From 2020 to 2021, shoreline loss at four of the sites was 11 m (35 ft) at the site furthest south and less than 21 m (70 ft) for the next four sites moving north. The two remaining sites were places of accretion, with gains in shoreline of more than 21 m (70 ft) since 2018 and more than 36 m (110 ft) since 2017 (see Figure 26; Urena 2022a).

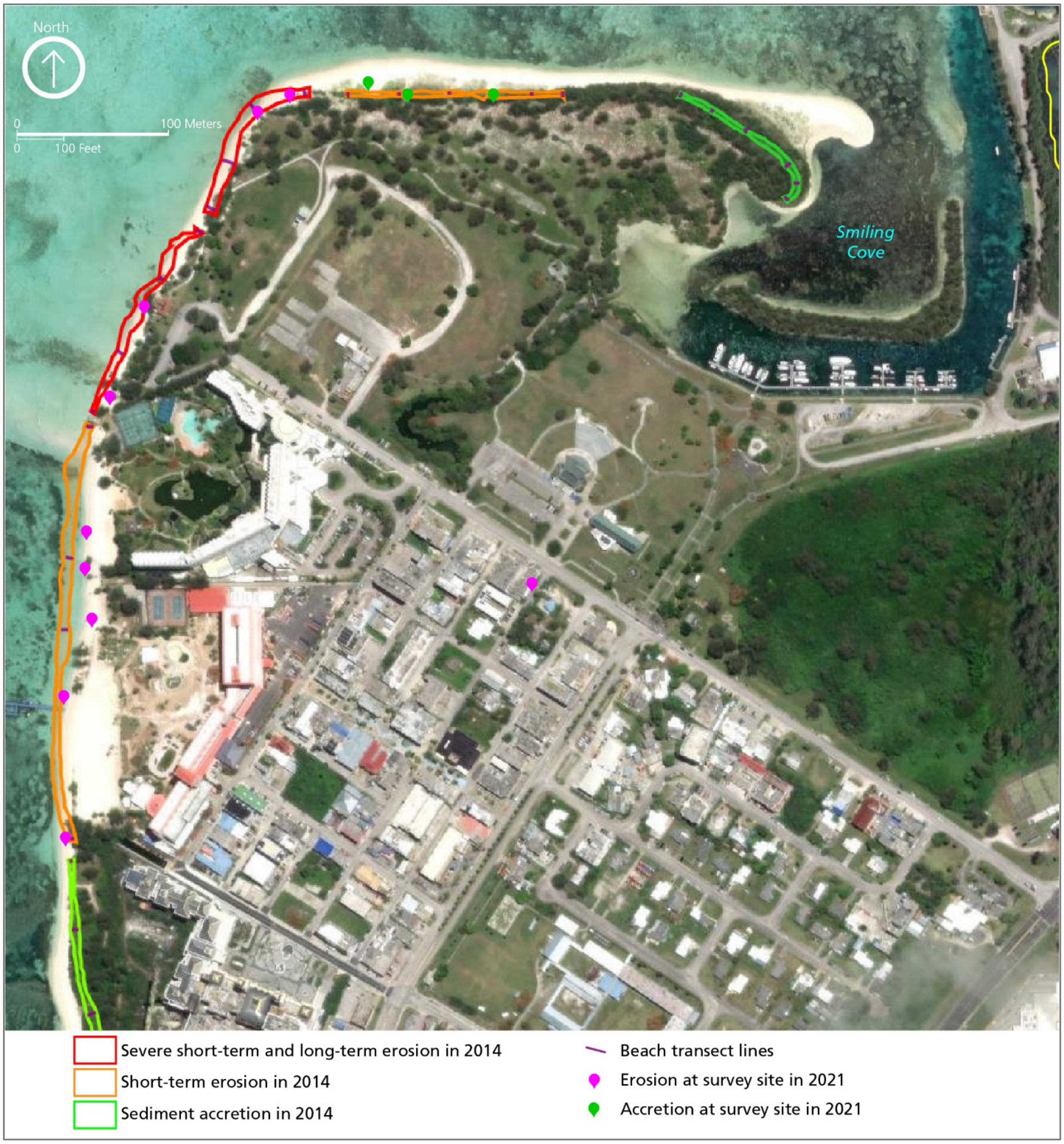


Figure 26. Shoreline change and monitoring at the park. The elongated polygons show the location of stretches of the shoreline in 2014; green polygons indicate areas of accretion and red and orange polygons indicate erosion. The small bulbs indicate survey sites that are monitored annually by the Commonwealth of the Mariana Island's Division of Coastal Resources Management; their color indicates either erosion (magenta) or accretion (green) observed during monitoring in 2021. The aerial image is from 2022; areas where the shoreline has shifted landward or seaward since 2014 are visible by comparing the colored polygons to the location of the shoreline on the image. In 2014, the north-facing beach within the park (orange outline on the north coast of park) was showing short-term erosion. In 2021, that same area was accreting. Both accreting areas (green outlines) from 2014 continued to accumulate sediment in 2021. Graphic by Trista L. Thornberry-Ehrlich using data from Division of Coastal Resources Management (2014; 2021) and Urena (2022a).

Storm surges related to typhoons have caused hundreds of millions of dollars of damage on Saipan and other Mariana Islands. The park is just above sea level (see Figure 22). The fringing reef of Saipan has a natural opening just west of the park (see Figure 8). Without this protective barrier, storm surge can proceed unimpeded directly to the park's coast (Tahzay Jones, regional coastal ecologist, National Park Service-Alaska, conference call 16 November 2021; Brooke Nevitt, lead ranger, American Memorial Park, conference call, 18 November 2021). The beach and adjacent coastal areas are typically washed over during typhoons and tropical storms, causing widespread erosion of beaches and reefs, deposition of debris and rocks, and destruction of infrastructure (Figure 27 and Figure 28; Yuknavage and Palmer 2010). Notable examples include Typhoons Ryan (1992), Gay (1992), Wilda (1994), Keith (1997), Winnei (1997), and Paka (1997), as well as Supertyphoon Soudelor (2015), which devastated the island (see "Climate Change and Sea Level Rise"). In 1992, Typhoon Ryan removed at least 5 m (15 ft) of beach width from Micro Beach (Rutherford and Kaye 2006). Extreme weather event response plans and storm damage assessments are resource management needs at the park (Greene et al. 2019).

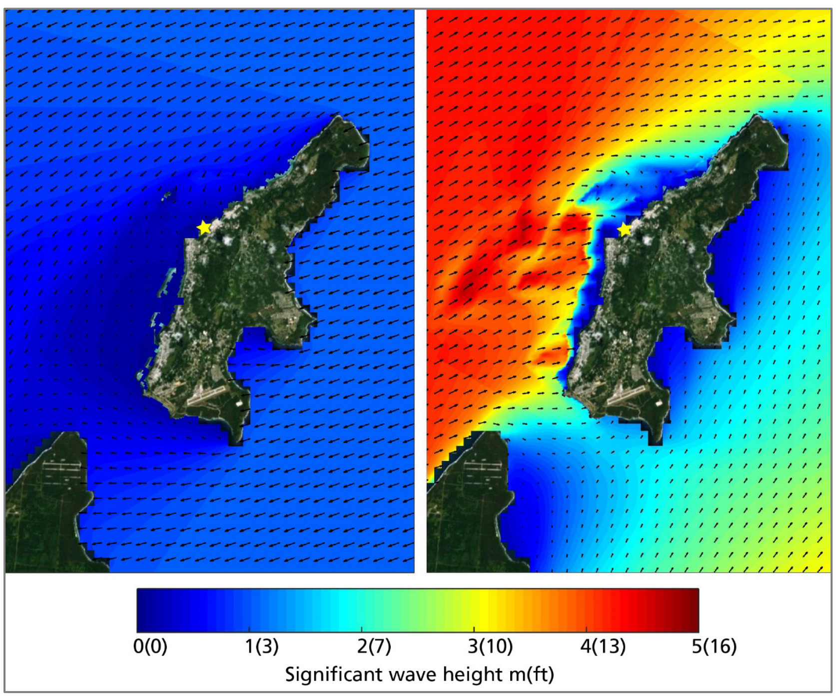


Figure 27. Hydrodynamic model results for summer trade winds versus 1-year typhoon wave patterns for Saipan. For the park, wave directions are nearly always directed towards the shore. During typical trade winds conditions (left), wave heights are tangentially hitting the western shore with heights of less than 1 m (3 ft). Most of the wave energy comes from the east-northeast where the island's cliffs and rocky elevated terraces protect the island. During typhoon conditions presented in the model (right), the waves are striking more directly with modeled heights of around 2 m (7 ft). The buffering effect of the fringing reef is evident for the typhoon scenario where high waves are lowered significantly on the western coast. Conditions will vary with the position of the typhoon relative to the island. Those passing north or south of the island will have different impacts. Direction of typhoon travel is also an important factor. Graphic presented as figures 3-47 and 3-65 in Sea Engineering (2019) adapted by Trista L. Thornberry-Ehrlich (Colorado State University).

Figure 28. Photographs of erosion monitoring sites in the park. An aerial image shows the location of the erosion monitoring sites. The smaller photographs show side-by-side views of shoreline monitoring sites from 2019-2022. The shorelines are dynamic, commonly showing dramatic changes from season to season depending on factors including prevailing wind direction, wave heights, storms, and stabilizing vegetation. In general, the southern shores are receding, and the northern shores are accreting sediments and the beach is advancing into Smiling Cove. In photographs where accretion is occurring, stabilizing plants are growing. Areas of bare sand are eroding. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) with pictures from Urena (2022a, pages 69 and 70) and using ESRI ArcMap imagery as a base layer.

Aerial photographs and satellite imagery of the park, particularly the coastal area, contain a record of landscape changes since before World War II. Overlaying these images and digitizing the shoreline to demonstrate changes over time would be a valuable data set. From 1948 to 2003, overlays show dramatic shoreline shifts (Figure 29; Yuknavage and Palmer 2010). Including layers for the conditions since 2003 and creating an animation of shoreline change may also help predict ongoing and future changes at the park. This would be an ideal Scientist-in-Parks (SIP) program project (see “Three Ways to Receive Geologic Resource Management Assistance” section). Management of shoreline change requires both examination of historic trends as well as projections of future positions based on multiple climate change scenarios (Greene et al. 2019). Current models to predict where the future shorelines might be are lacking. This creates a general deficiency in the data that could support management planning, mitigation, or adaptation options (Greene et al. 2019).

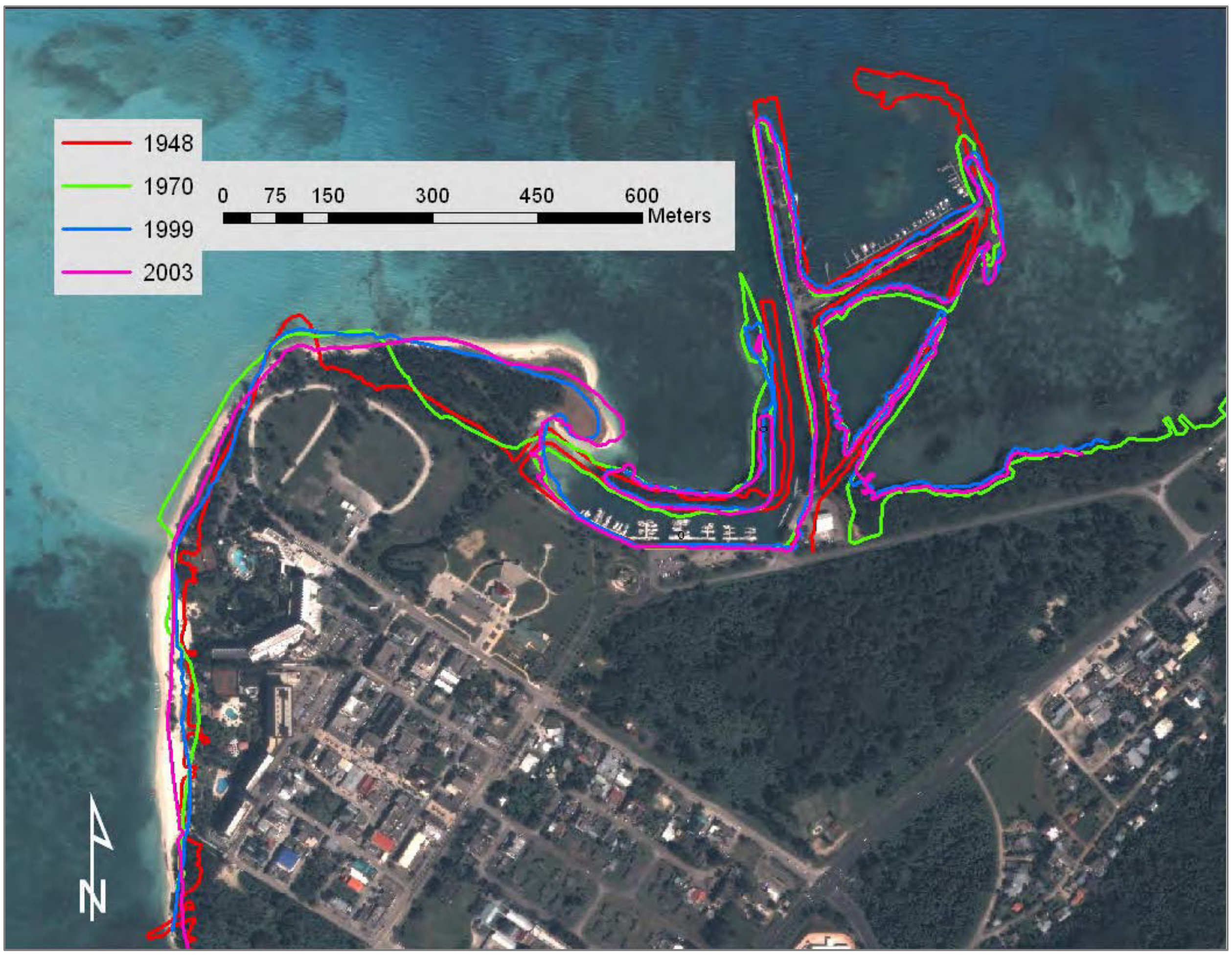


Figure 29. Aerial photograph showing the 2006 shoreline at the park with previous shoreline locations. Overlay analysis of historical aerial photographs reveals how the shoreline is shifting with time. On-the-ground monitoring and more aerial imagery since 2006 shows the shoreline continues to erode in some stretches and advance in others. The area of the most profound change is the spit of land that fingers into Smiling Cove. Graphic is appendix VII from Yuknavage and Palmer (2010).

Examination of aerial photography shows a positive correlation between seagrasses offshore and advancing shorelines. The seagrass may dampen the incoming waves and certainly act as sediment traps (Dean 1991; Greene et al. 2019). Benthic habitat mapping in 2016 compared with 2001 showed losses in sea grass areas in the lagoon adjacent to the park (Kendall et al. 2017). Severe coastal erosion within and adjacent to the park requires mitigation or adaptation. The solution is likely to be a multifaceted, multi-agency effort (Department of Homeland Security 2021). Shoreline armoring (e.g., bulkheads, seawalls, groins, and jetties) is often seen as the quick solution to tackling erosion. However, armoring often causes beach loss in adjacent areas, or other unexpected problems, such as degraded benthic habitats, and many coastal areas around the world are removing armoring and turning away from this traditional approach (Urena 2022b).

The park needs policy on addressing coastal zone management (i.e., wetlands and floodplains) (Tahzay Jones, deputy assistant regional director, US Fish and Wildlife Service, written communication 3 November 2023). Environmentally considerate, nature-based solutions are rising in recognition as cost-effective solutions for tackling shoreline erosion and other coastal hazards. The park can benefit from these approaches by increasing wildlife habitat and reducing unwanted shifting in coastal processes (Urena 2022b). The Commonwealth of the Northern Mariana Islands Division of Coastal Resources Management permitting requirements call for consideration of living shorelines and nature-based solutions when considering shoreline erosion mitigation and/or restoration efforts (Urena 2022b). A responsible approach will involve assessment, planning, and implementation. Coral reefs, mangroves, sea grass beds, and sandy beaches are nature-based solutions for the park that interact with the ocean's wave energies. These coastal ecosystems can reduce incoming wave heights by up to 71%; therefore, the high value of mitigation and adaptation services of these nature-based solutions justifies their continued protection and enhancement (Narayan et al. 2016; Urena 2022b). Native shoreline vegetation planting (e.g., beach morning glory, mangroves, and ironwoods), beach nourishment, reef ball breakwaters (pH-neutral concrete to grow corals), constructed wetlands (using salt-tolerant native plants), and planting sea grasses are all potential strategies to create nature-based solutions to local coastal erosion (Urena 2022b).

Projects are ongoing to determine the best strategies to preserve the shoreline while allowing natural processes to function and adapt. The Nature Conservancy created a living shoreline applicability index model to help determine appropriate living shoreline possibilities (see “Guidance for Resource Management”). NOAA and the National Fish and Wildlife Foundation performed a coastal resilience assessment using combined spatial data related to land use, protected areas, human community assets, flooding threats, and natural resources to identify resilience hubs (large areas of natural habitat where there is potential for conservation and restoration to the benefit of human communities and natural ecosystems; Dobson et al. 2020). Park resource managers can use the assessment (coastal resilience evaluation and siting tool [CREST]) to help make informed decisions about the potential of restoration, conservation, or resilience projects to achieve dual benefits for both human and fish and wildlife communities (see “Guidance for Resource Management”; Dobson et al. 2020). The CREST layers geologic information, such as impermeable soils, soil erodibility, flood-prone areas, sea level rise, wave-driven flooding, and areas of low slope (National Fish and Wildlife Foundation 2020).

The park’s coastal and offshore areas rank high as resilience hubs—areas where resilience projects may have the greatest potential to benefit both human communities and wildlife (Dobson et al. 2020).

Coastal Engineering and Restoration Projects

The dynamic shoreline at the park requires monitoring and occasional maintenance, especially where infrastructure is undermined. Several coastal engineering and restoration projects are ongoing at the park, including a seawall repair project (Timothy Clark, marine ecologist, American Memorial Park, written communication 24 October 2023). The sea walls associated with the marina roads are among those being restored (Figure 30; Brooke Nevitt, lead ranger, American Memorial Park, conference call, 18 November 2021). The need for these projects is to stop the chronic shoreline erosion that could eventually destroy two access roads (Marina Drive and Basin Place) in the Smiling Cove and Outer Cove Marina complex (see Figure 5 and Figure 30; GHD 2020; American Memorial Park 2021). The engineering project encompasses replacing an approximate 220-m (720-ft) section of an existing, dilapidated (~30-years-old) concrete mattress and boulder revetement structure with new boulder revetment. A concrete mattress provides a durable, erosion-resistant surface. Revetments are sloping, (usually) permeable stone structures used to stabilize a shoreline. The new revetment is for the east side of the Smiling Cove Marina entrance channel.

A second project includes constructing a new 38-m (124-ft) shoreline boulder revetment structure along the shoreline at Outer Cove Marina (American Memorial Park 2021). For these projects, material will be demolished and removed, and new material will be brought in. When considering the ecological impacts, the dredge footprint of the projects was previously and permanently impacted during the construction of the original concrete mattress (American Memorial Park 2021). These projects are consistent with the Division of Coastal Resources Management because the projects would have a “reasonably foreseeable effect’ on land and water use or natural resources of the coastal zone, modify already modified land, and improve coastal water quality through control of erosion, among other policies (American Memorial Park 2021). For short-term, emergency repairs to try while other options and/or funding are being explored, concrete flexmat (a sheet of sturdy geotextile fabric with concrete blocks casted onto it), gabion baskets (metal mesh filled with rocks), rock placement, geotextile sandbags, and concrete grouting may be considered (GHD 2020).

Figure 30. Photographs showing the restoration sites along Basin Place and Marina Drive. These roads are used to access Outer Cove and Smiling Cove marina areas. Shoreline erosion has undercut the concrete mattresses, revetments, and roadways and are now targets for restoration projects at the park. Red stars denote project areas (top photograph). Photographs are (A) photo 4, (B) photo 20, (C) photo 3, and (D) photo 26 from GHD (2020), composition and annotation by Trista L. Thornberry-Ehrlich (Colorado State University).

Coral Reef Protection

The fringing coral reef off the coast of Saipan is a vital natural resource that is beyond the park boundaries but is a topic of great interest and concern. Functioning like low-crested breakwaters, coral reefs can dissipate as much as 97% of incident wave energy, thus reducing coastal flooding and erosion (Ferrario et al. 2014; Storlazzi et al. 2019). For this reason, sea level rise poses a major threat to the ability of the reef to buffer the shoreline at all. If the sea rises too far above the reef, its buffering ability is severely reduced. The USGS produced an open-file report addressing the role of coral reefs in coastal hazard risk reduction that has strong ties to the protective reef at Saipan (Storlazzi et al. 2019). The impacts of the coral reefs at Saipan are quantifiable in a similar way to those of artificial defenses such as seawalls (Storlazzi et al. 2019).

Terrestrial Erosion

Terrestrial erosion is a weathering process occurring inland from the coast. Most of Saipan's surficial geology is highly permeable limestone. This limits the amount of terrestrial erosion because surface water flows are quickly diverted underground (Rutherford and Kaye 2006). Problems with terrestrial erosion typically occur during storm events wherein erosion carries away soil resources, reduces soil fertility, and produces thousands of tons of sediment that degrades water quality. Similarly, the sediment may convey pesticides, harmful bacteria and toxins, and excess nutrients into the surface-water and groundwater systems (Rutherford and Kaye 2006). At the park, places where sediment accumulates (e.g., lagoons and wetlands) are most at risk from erosion-supplied sedimentation. Sediment deltas form around stormwater discharge outlets (see "Stormwater Contamination and Karst Permeability"; Division of Coastal Resources Management 2014). Using the CREST, the park's inland areas rank high on the community exposure index—areas where community assets are potentially exposed to impacts from flooding or severe storm events. This index takes into account factors such as soil erodibility, impermeable soils, areas of low slope, and flood-prone areas as local threats (Dobson et al. 2020).

Wetland Preservation

At the park, wetland preservation is a high-priority issue. The condition of wetlands and mangrove forests in the park was listed as moderate, with an unknown trend of change in the park's natural resource condition assessment (Greene et al. 2019). This environment provides critical habitat for flora and fauna, is important for curbing erosion, and contributes to flood control. At the park, wetlands play a critical role in reducing the impacts of flooding and stormwater runoff (Dobson et al. 2020). Also, the wetlands' influence extends to the fringing reef as well because wetlands act as "sponges" to absorb contaminants (Brooke Nevitt, lead ranger, American Memorial Park, conference call, 18 November 2021). By mitigating erosion and flooding, the wetlands provide for the protection of nearshore areas from upland-source pollution and excess sedimentation. The wetlands in the park include the only remaining mangrove forests on Saipan, which is one of only three in the entire Commonwealth of the Northern Mariana Islands (Rutherford and Kaye 2006; Greene et al. 2019; Dobson et al. 2020). Water sampling has revealed an increase in wetland salinity (Pacific Island Network et al. 2019). A drainage culvert under the park road is commonly blocked, causing local backups and contamination with stormwater runoff (Brooke Nevitt, lead ranger, American Memorial Park, conference call, 18 November 2021). Areas of the wetlands are in compromised condition

(Greene and Skeele 2014; Dobson et al. 2020). Altered hydrology and invasive species such as water hyacinth and pond apple reduce open water habitat and hinder the ability of man-made wetlands to store and convey water. Because of this, roads and properties adjacent to the wetlands frequently flood during heavy rain events (Dobson et al. 2020).

Resource managers at the park are currently (ca. 2022) writing a project to acquire funding for wetland projects; this would include planting more mangroves in addition to those already planted along the drainage from the man-made wetland. Planting mangroves and restoring wetlands along the coastline of Saipan both within the park and adjacent Garapan will help protect the coast and support wetland habitats (Dobson et al. 2020; Brooke Nevitt, lead ranger, American Memorial Park, conference call, 18 November 2021). The park is also part of a multi-agency effort (NOAA, Division of Coastal Resources Management, National Fish and Wildlife Foundation, and others) to encourage better upland construction practices to reduce damaging runoff and contamination in the wetland areas (Brooke Nevitt, lead ranger, American Memorial Park, conference call, 18 November 2021). Restoring the park and Garapan wetlands can provide important water quality benefits to adjacent coral reefs by reducing sediment and nutrient pollution (Dobson et al. 2020). Wetlands management (potential wetland mitigation, restoration, and/or migration) needs an examination of historic trends as well as projections of future conditions based on multiple climate scenarios. Additional wetland coring would help determine historic extent and identify rates of elevation change for wetlands and mangrove forests (Greene et al. 2019). The data that fill these knowledge gaps will be necessary to support the adaptive management that is required on Saipan, an island characterized by rapid change (Greene et al. 2019).

Stormwater Contamination and Karst Permeability

The threats posed to the park by stormwater runoff are multifaceted. Stormwater carries excess sediment, contaminants, and flood risk. The adjacent Garapan community is low-lying and subject to flooding exacerbated by stormwater and urban runoff (Department of Homeland Security 2021). Potential sources for contamination on Saipan include (1) quarries used for the extraction of limestone building materials; (2) an old solid-waste dump site near Puerto Rico; (3) small-scale sewage-waste systems of residences and businesses located away from the sewer-treatment distribution system; (4) commercial fuel-storage facilities; and (5) businesses such as gasoline stations, dry cleaners, and automotive repair and painting facilities (Carruth 2003). Impervious surfaces such as roads, parking lots, and roofs cause even more excessive runoff and less natural infiltration and groundwater recharge (Horsley Witten Group 2004). The park's watershed (West Takpochau watershed) contains more impervious surfaces than any of the island's 11 watersheds (Figure 31; Greene et al. 2019). Throughout much of the island's development history, stormwater was viewed as a drainage issue and was routed to the nearest discharge location—commonly, the ocean (Horsley Witten Group 2004). The park is one of the only natural parcels within the watershed that retains the ability, with its wetlands, mangrove forests, and other vegetated areas, to mitigate stormwater impacts via ponding and retention (Greene et al. 2019).

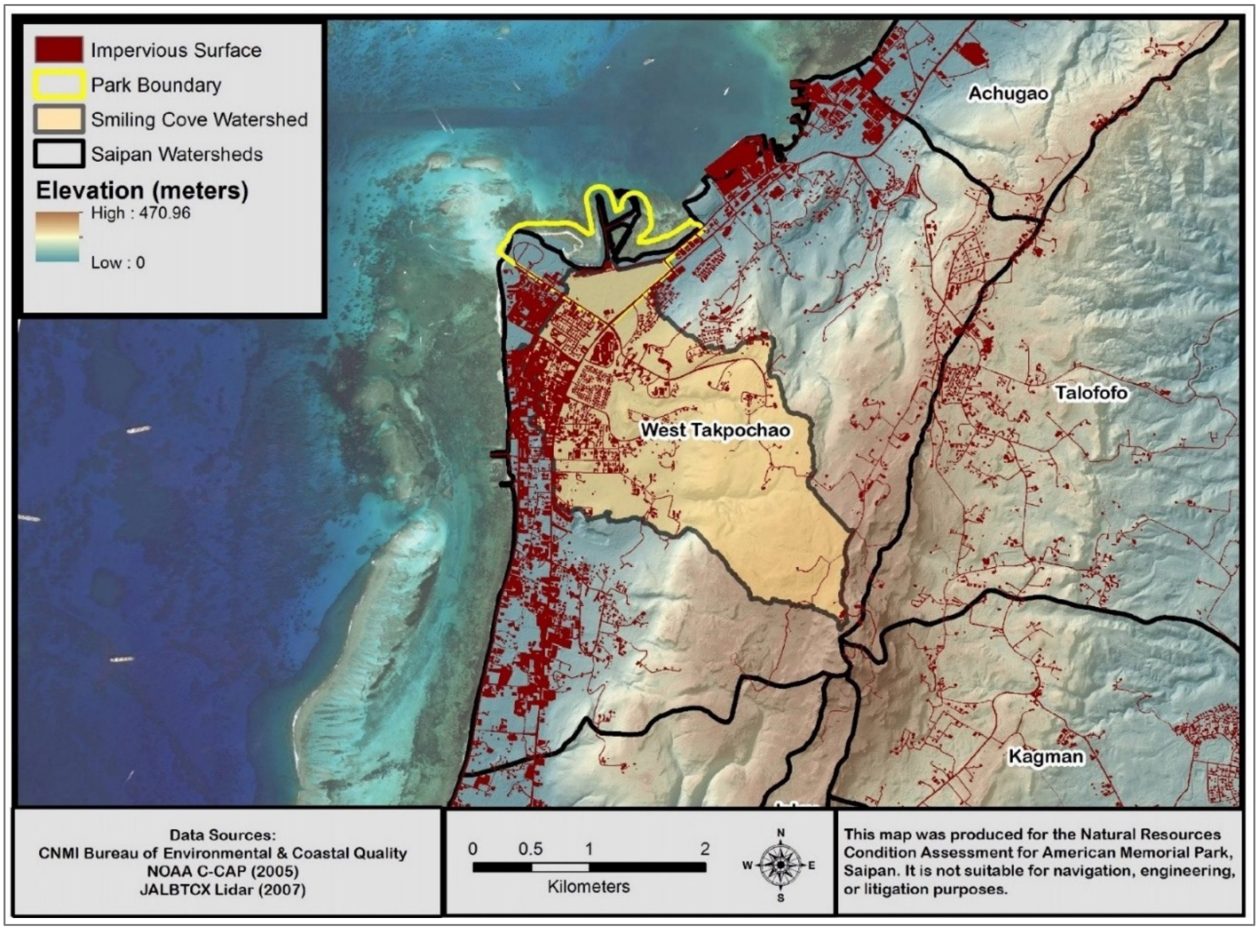


Figure 31. Map of the West Takpochao watershed and impervious surfaces. The area of impervious surface is high in the park's watershed, the West Takpochao watershed. The stormwater drainage system in the park is frequently overwhelmed during heavy rainfall. This is causing extreme stormwater drainage issues, including contamination, sedimentation, and flooding. Graphic is figure 16 from Greene et al. (2019).

South of the park in Garapan, "odorous" stormwater flows directly into the lagoon, and sediment deltas and algal blooms form around stormwater drainage outlets (Division of Coastal Resources Management 2014). Northeast of the park boundary is the former Puerto Rico unlined landfill, which received all solid waste, including toxic materials, metals, and unexploded ordnances after World War II, until its closure in 2003; it is now the Peace Park (Carruth 2003; Greene et al. 2019). Seepage from this feature has not been confirmed but is suspected, and bad-smelling gas is emitted from installed vents (Brooke Nevitt, lead ranger, American Memorial Park, conference call, 18 November 2021). Smells emanate from the man-made wetland in the park (intended to filter storm runoff), which is aggravated by frequent leaks and overflows of raw sewage from the overwhelmed nearby utility system (Greene et al. 2019). Groundwater contamination stemming from land use and storm-event flushing is a risk at the park because so much of the discharge is diffuse flow at the coast (Rutherford and Kaye 2006), and the drainage system at the park is inadequate to accommodate runoff events (Tahzay Jones, regional coastal ecologist, National Park Service-Alaska, conference call 16 November 2021).

Saipan's natural karst drainages compound the potential hazards of stormwater. A major problem posed by the island's carbonate rocks and karst setting is their high permeability and infiltration rates. Because the conduits of a limestone karst aquifer are like roofed creek beds, almost no filtration of percolating groundwater occurs, and almost no contaminants are adsorbed by soils. Karst conduits dissolved in carbonate bedrock can quickly transport water and contaminants over great distances. Heavy rainfall may reach the water table within a few hours and then carry contaminated water to wetlands or diffuse into discharge points and submarine springs along the coasts (Mitchell et al. 2020). Groundwater issues originating miles away can thus impact streams and wetlands within the park, as well as the lagoon environment offshore. Measuring the volume and direction of stormwater flow from upslope areas would be a valuable dataset for resource managers at the park (Greene et al. 2019).

Groundwater expertise remains a resource management need at the park. Water quality is beyond the scope of this GRI report; however, information regarding the park's water resources is available from the NPS Water Resources Division. Davis (1959) provides a snapshot of the groundwater resources on Saipan following World War II. The Pacific Islands Inventory and Monitoring Network monitors landscape dynamics and water quality at the park. The USGS maintains the Pacific Islands Water Science Center. Mitchell et al. (2020) inventoried groundwater conditions and trends for Saipan from 2009–2019 with suggestions for future data needs. Mink (1987) provided a snapshot of the hydrological characteristics of the groundwater resources prior to a population surge on the island. Stormwater management criteria provided by Horsley Witten Group (2004) detail a framework to ensure the effective implementation of stormwater management practices to protect vital water resources. The US Geological Survey (2003) identified information needs and deficiencies to address the issue of long-term groundwater availability on Saipan. Stormwater studies are underway (ca. 2021), but flood mitigation decisions are needed to improve the stormwater system (Department of Homeland Security 2021).

Groundwater Withdrawal

The volcanic core of Saipan is relatively impermeable to groundwater flow. The overlying, fragmental limestone aquifers are the principal source of the island's groundwater, pumped from shallow wells (Carruth 2003). The freshwater-saltwater coastal aquifer system, where most of the available fresh groundwater is on Saipan, forms a lens-shaped body of fresh and brackish water that floats on denser saltwater (Carruth 2003). Typical groundwater discharge is either below the current sea level via submarine springs or distributed along the coast as diffuse flow. Direct runoff only occurs during large storms; rainy season streams occur on Saipan but not in the park (Davis 1959; Carruth 2003; Rutherford and Kaye 2006; Brooke Nevitt, lead ranger, American Memorial Park, conference call, 18 November 2021).

Freshwater production is a resource management concern for Saipan, with direct potential impacts on park resources. Increasing impervious surfaces, less infiltration and recharge, and increasing demand (pumping) result in lower water tables, thinning freshwater lenses in the coastal aquifer, and ultimately increasing saltwater intrusion into low-lying aquifers and wells (Carruth 2003; Horsley

Witten Group 2004). In the park, over-pumping of groundwater and accompanying saltwater intrusion degrade the low-lying wetlands and mangrove forests (Greene et al. 2019).

Potable water within the coastal aquifer does not reach the park; the park's groundwater is in the brackish mixing zone (Greene et al. 2019). Developing freshwater from a thin, coastal aquifer lens requires widely spaced wells near the water table where the freshwater lens is thickest and to maintain low, uniform pumping rates at each well. Saltwater up-coning, or the upward movement of saltwater toward a pumped well, can inundate wells if the freshwater lens is too thin, if wells are too deep (too close to the transition zone), or if too much water is withdrawn from a small area (Figure 32). In wells near the coast, such as those in the park, daily ocean tides cause water level fluctuations as high as 0.08 m (0.25 ft). Precipitation also has an influence on well salinity. Dry weather conditions can cause the freshwater lens to shrink and contribute to increased salinity in wells (Carruth 2003). The constraints imposed by potential saltwater intrusion can be minimized by (1) drilling wells where the potable part of the freshwater lens is thicker; (2) ensuring that wells do not penetrate to depths near the freshwater-saltwater transition zone; and (3) determining pumping rates that can be maintained without causing the intrusion of saltwater into the well (Carruth 2003).

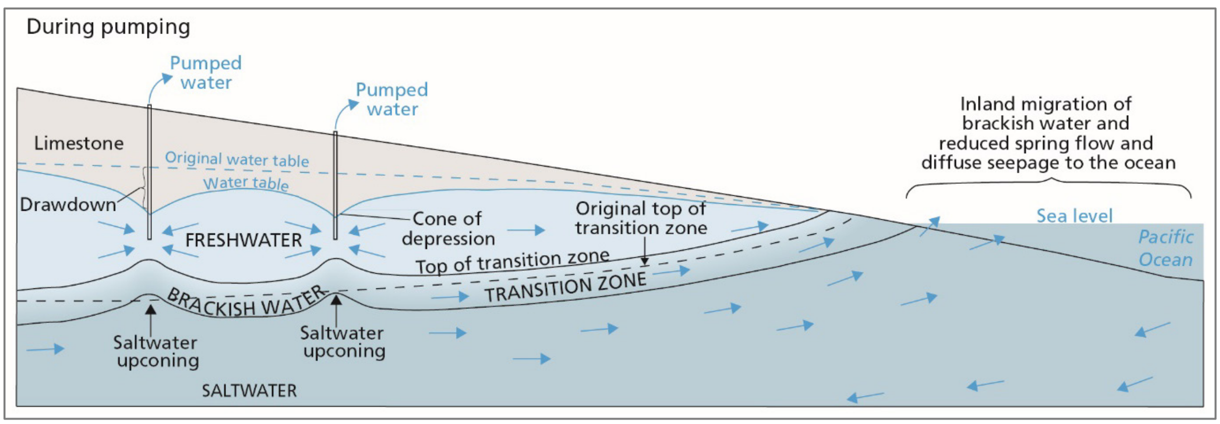


Figure 32. Diagram showing impacts of pumping on groundwater conditions. Pumping from the thin freshwater lens of the coastal aquifer causes not only a localized cone of depression at the water table around the well but may induce up-coning of saltwater from below up into the well. Too much pumping and freshwater withdrawal causes an inland migration of brackish water and reduced spring flow and diffuse seepage to the ocean. Graphic is by Mitchell et al. (2020) with modifications by Trista L. Thornberry (Colorado State University).

Knowledge of island wells and how groundwater is moving around remains a high priority; surface ecology depends on it (Greene et al. 2019; Brooke Nevitt, lead ranger, American Memorial Park, conference call, 18 November 2021). The extent of the freshwater lens in the park area is undefined and remains a data need (Greene et al. 2019). Generalized groundwater flow maps indicate the source of the park's groundwater flow in the Tagpochau neighborhood, just north of the peak of Okso Takpochao (Carruth 2003). Spatial variability due to faulting and karst development is substantial and can impact groundwater movement. The effects of the Matansa and other faults on groundwater flow are not well understood and remain a data need (Greene et al. 2019). The Pacific Islands

Inventory and Monitoring Network's website states that groundwater dynamics and water quality are being monitored at the park (https://www.nps.gov/im/pacn/index.htm). Groundwater monitoring was occurring at two wells within the park, but storm flooding forced this to stop (see Figure 4; Tahzay Jones, regional coastal ecologist, National Park Service-Alaska, conference call 16 November 2021; Brooke Nevitt, lead ranger, American Memorial Park, conference call, 18 November 2021). The groundwater wells in the park are flooded during storms, rendering them unsuitable (Tahzay Jones, regional coastal ecologist, National Park Service-Alaska, conference call, 16 November 2021).

Water quality is beyond the scope of this GRI report; however, information regarding the park's water resources is available from the NPS Water Resources Division. The Garapan Conservation Action Plan (CAP) contains an analysis of the threats and issues facing the West Takpochau watershed, including the park (Mattos 2013; Greene et al. 2019). Water quality was identified as one of the conservation targets. This CAP report contains a literature review of relevant material, threats, and stressors, as well as geologic, biologic, cultural, and socioeconomic features of the watershed (Greene et al. 2019).

Earthquakes, Tsunami, and Volcanic Hazards

Earthquake Hazards

Due to their setting on a convergent tectonic plate boundary (Pacific and Philippine Sea plates, and notably at the Mariana Trench), the Northern Marianas Islands are seismically active (Figure 33). Mapped fault segments in the GRI GIS data add up to more than 165 km (100 mi) of fault traces crisscrossing Saipan. Most of these fault segments could be active at any time; even the youngest geologic map units on the island show offsets (Cloud et al. 1956; Weary and Burton 2011). Earthquakes within this area are characterized by deep and shallow activity that has historically produced some strong ground motion in the 20th and early 21st centuries. Notable events in the last 100+ years achieved Mw 7.4 or greater. According to earthquake profiles in the park area, earthquakes occur at various depths in Earth's crust (see Figure 18; Smoczyk et al. 2013). The seismic hazard assessment for Saipan indicates the most damaging earthquakes occur at a depth of 40–160 km (25–100 mi; Mueller et al. 2012). Subduction at the Marianas Trench might be capable of producing megathrust type earthquakes. A megathrust is an extremely large thrust fault, typically formed at the plate interface along a subduction zone. Examples of megathrust quakes include the highly destructive 2004 Sumatra-Andaman and 2011 Tohoku-Oki earthquakes. However, probabilistic modeling indicates that these quakes are on a 3,000-to-4,000-year occurrence interval. The evidence of prior strong earthquakes from the trench is insufficient to better gauge their probability at this time (Jack Wood, geologist, NPS Geologic Resources Division, written communication, 27 February 2023).

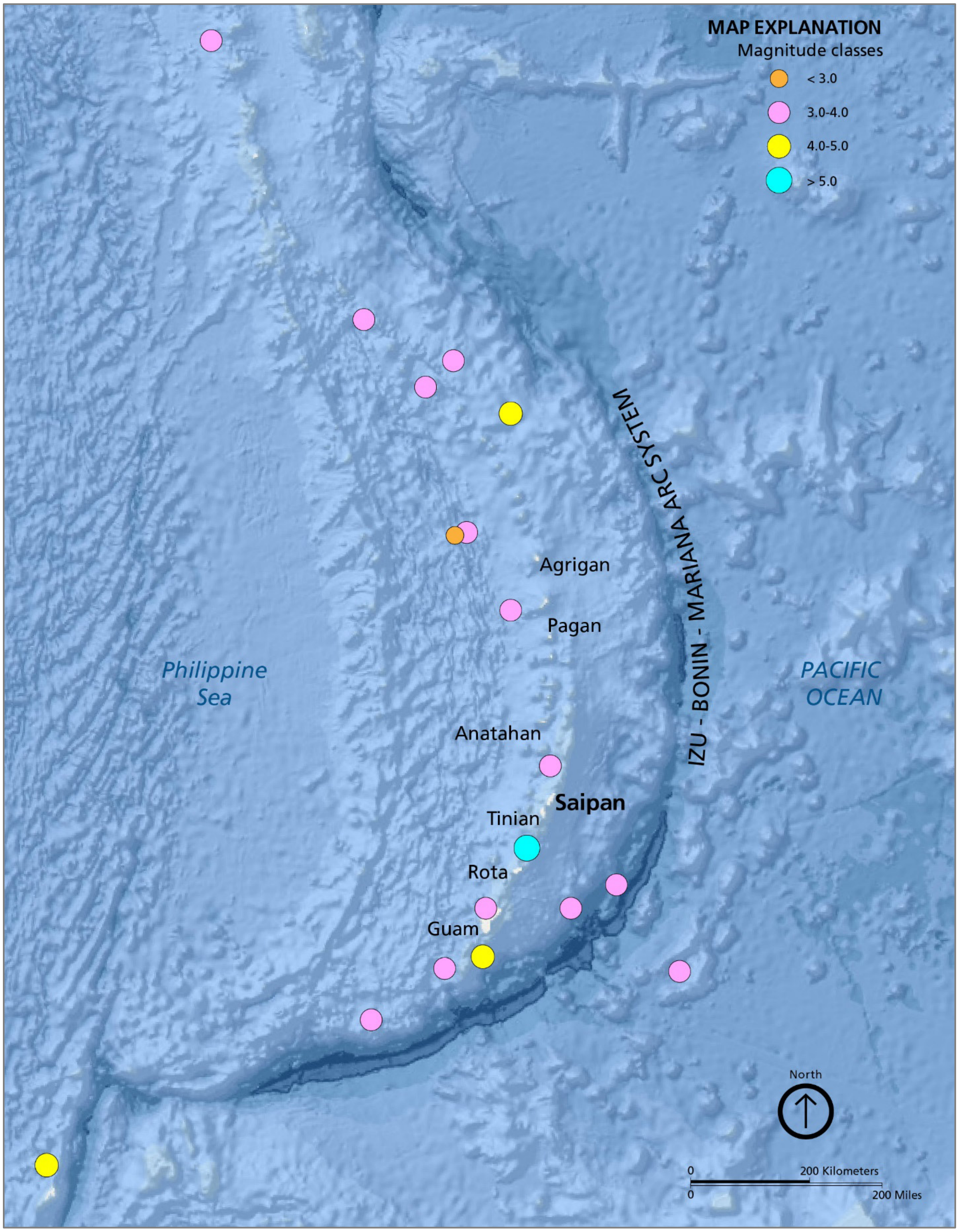


Figure 33. Map of Northern Mariana Islands showing earthquake epicenters for a 30-day period. The islands' setting near an active tectonic plate boundary makes seismicity common. Chosen 30-day period was October 2021. A magnitude 5.0 earthquake happened near Saipan during that time. Graphic modified from the USGS earthquake viewer (https://earthquake.usgs.gov/earthquakes/map/?extent=11.02747,-221.34155&extent=20.72529,-203.76343) by Trista L. Thornberry-Ehrlich (Colorado State University).

Ground shaking can damage buildings and infrastructure at the park; however, very little detail exists regarding the actual behavior of the nearby Matansa and other faults or whether the park's geologic map units of marsh deposits (**Qm**), artificial fill (**Qaf**), and emergent carbonate sands (**Qrl**) would experience liquefaction in a large earthquake (Greene et al. 2019). Liquefaction is a process by which unconsolidated deposits such as those at the park may become "liquified," lose cohesion, and behave fluidly during an earthquake. Given the tectonically active setting, potential earthquake effects remain a research need for the park (Greene et al. 2019).

On Saipan, the Emergency Management Office (EMO) of the Northern Mariana Islands maintains a seismic monitoring network whose function is to monitor, record local earthquakes, keep logs, and report significant seismic events daily (see Figure 18; Moore et al. 1991; Marso et al. 2003; Rutherford and Kaye 2006). A seismometer (SAP2), operated by the US Geological Survey and EMO, is located in the middle of the island, just east of the park, constantly measuring the earthquake situation. Braile (2009) suggested "vital signs" and methods for monitoring seismic activity, utilizing the following: earthquake activity monitoring, analysis and statistics of earthquake activity, analysis of historical and prehistoric earthquake activity, earthquake risk estimation, geodetic monitoring and ground deformation, and geomorphic and geologic indications of active tectonics.

Tsunami Hazards

Low-lying areas such as beaches, bays, lagoons, and harbors (i.e., the setting at the park) are the most vulnerable to damage by tsunami (Figure 34). Tsunami that push over 1 m (3 ft) of water ashore are the most dangerous to people and property, with impacts including coastal flooding, shoreline erosion, floating debris, damage or destruction of structures, and subsequent fire or release of hazardous materials. After the initial wave or waves, water can return rapidly seaward and suck debris back out to sea. Smaller tsunami can also be dangerous because strong currents can injure and drown swimmers and damage and destroy boats and infrastructure in harbors (NOAA 2022). Saltwater inundation or post-tsunami sedimentation can also impact freshwater ecosystems and freshwater infrastructure. If the tsunami is triggered by a local (near Saipan) earthquake, there may also be coastal subsidence, which increases flood extent into areas that were not previously considered at risk of coastal flooding.

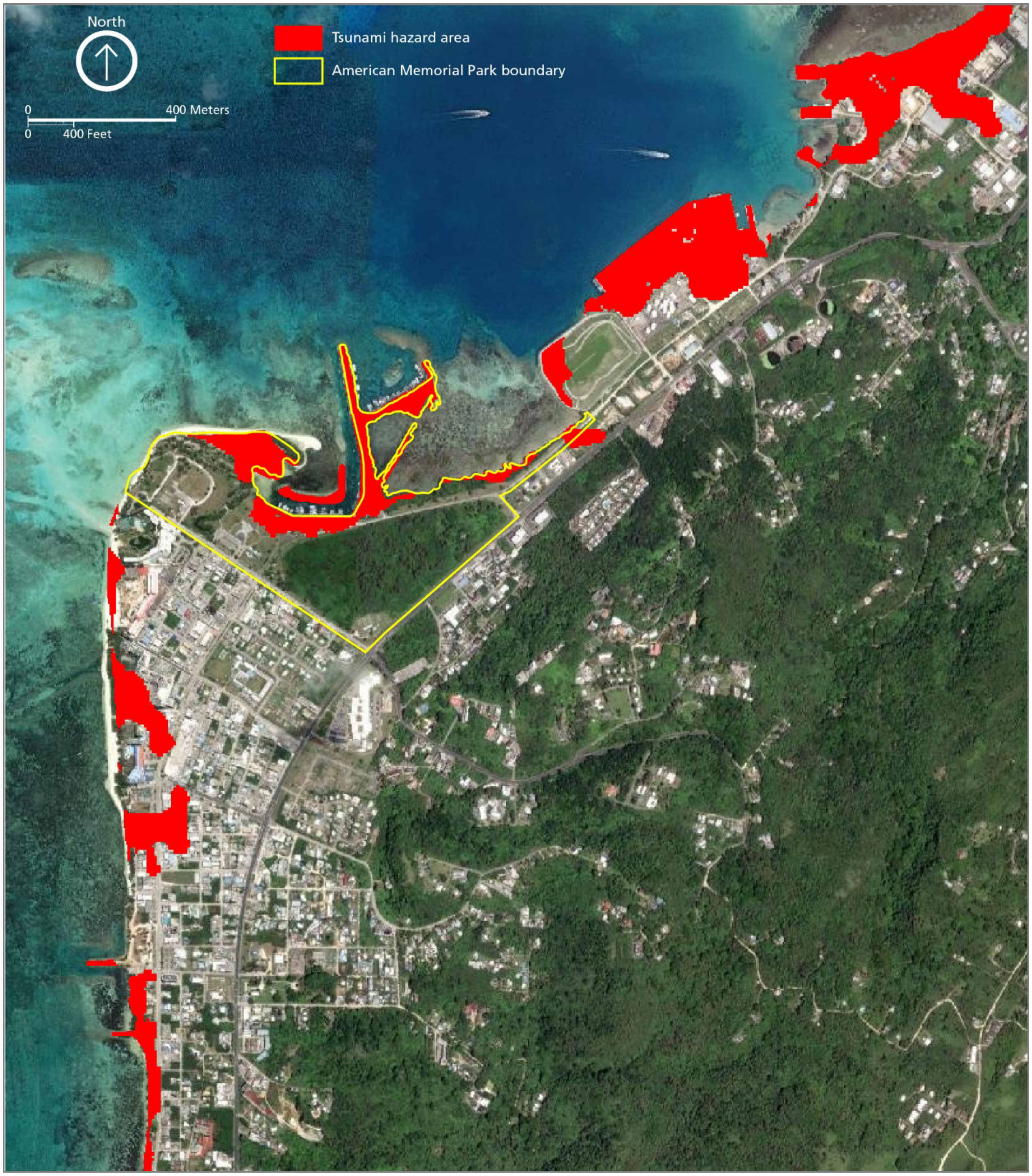


Figure 34. Aerial image of tsunami runup areas within and surrounding the park. Most of the coastline at the park is part of a tsunami hazard area (red shaded areas). The yellow outline denotes the park boundary. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) using the Coastal Flood Exposure Mapper from NOAA (https://coast.noaa.gov/digitalcoast/tools/flood-exposure.html, accessed 2 May 2023) with data coming from the National Tsunami Hazard Mitigation Program.

Tsunami modeling has indicated that the Commonwealth of the Northern Mariana Islands is at greater risk from other earthquake-prone parts of the Pacific. Japanese seismologists are modeling that an 8.5–9.0 magnitude earthquake is expected to occur in the Nankai Trough subduction zone of southeast Japan. Such an event would be expected to generate a large tsunami oriented directly toward Saipan and the rest of the commonwealth (Southern California Earthquake Center (2023). A comprehensive tsunami hazard assessment for the Commonwealth of the Northern Mariana Islands shows that a total of 26 potential earthquake scenarios pose a tsunami threat (Uslu et al. 2013). Specifically for Saipan, a Mw 9.0 earthquake originating from a source south of Japan could result in wave amplitudes exceeding 11 m (36 ft), and a Mw 9.0 earthquake occurring in the East Philippines could trigger tsunami wave amplitudes 4 m (Uslu et al. 2013). The greatest expected impact, islandwide, is predicted along the southwest coast of the island, where wave height and speeds are predicted to be at their maximums (Uslu et al. 2013). The coral barrier reef offshore Garapan, with an extended shallow shelf, appears to have a damping effect that reduces tsunami wave amplitudes by as much as 48% (Uslu et al. 2013). However, the natural hole in the reef offshore from the park complicates this effect. Any large waves would overwhelm the low-lying park, with the potential to destroy many park resources in its wake.

The US Tsunami Warning System (headed by NOAA and the National Weather Service Pacific Tsunami Warner Center (NWS PTWC in Hawaiʻi) provides warnings for earthquakes and tsunami across the Pacific Ocean basin as part of an international warning system. Seismic waves travel about 100 times faster than tsunami, so information about an earthquake is usually available in advance of any tsunami that may have been generated (NOAA 2022). Preliminary seismic data (magnitude, location, and depth) are used to determine if an earthquake could have generated a tsunami and if an initial tsunami message is warranted. From strongest to weakest, the tsunami alert levels are warning, advisory, watch, and information statement (no threat and potential threat) (Figure 35; NOAA and NWS PTWC 2014). NOAA warning center scientists are typically able to issue initial messages within five minutes of an earthquake, preliminary information about the earthquake, and an evaluation of the tsunami threat (NOAA 2022). According to a comprehensive tsunami hazard assessment for Saipan, education, planning, and preparedness are fundamentally necessary (Uslu et al. 2013).

Figure 35. Tsunami alert levels. Descriptions of the impacts and advice for each level are produced for every seismic event and distributed to the area in question. Graphic is from NOAA (2022).

An official tsunami warning means that sea level is expected to repeatedly rise and fall above and below the tide level by at least 1 m (3.3 ft) in cycles that may take from five minutes to an hour (NOAA and NWS PTWC 2014). These sea level changes are accompanied by repeated flooding and draining of land near the coast, such as that in the park, accompanied by damage to or destruction of coastal structures and park infrastructure. This warning denotes impacts that pose a hazard to all people in coastal areas of tsunami inundation zones (NOAA and NWS PTWC 2014). Park staff and emergency managers should take appropriate actions for a tsunami warning to inform and instruct the public and others at risk to evacuate the coast, move inland to higher ground away from the tsunami hazard zone (see Figure 34), and take other appropriate actions in order to protect lives and property (NOAA and NWS PTWC 2014). The Commonwealth of the Northern Mariana Islands Office of Homeland Security and Emergency Management is taking steps through community outreach, the installation of tsunami evacuation signage and alert sirens, and the production of inundation and evacuation maps (Southern California Earthquake Center 2023).

Volcanic Hazards

Saipan's central highland is Eocene and Oligocene volcanic and volcanic-derived sedimentary rocks more than 23 million years old. No evidence exists of recent volcanic activity on Saipan. However, 19 volcanoes (considered active) are listed in the USGS Volcano Hazards Program for the Mariana Islands region. The Commonwealth of the Northern Mariana Islands contains nine volcanic islands and about 60 submarine volcanoes (seamounts). Six volcanoes and six submarine volcanoes have had confirmed eruptions since the 1800s (Tepp et al. 2019). The closest active volcanoes to Saipan are submarine volcanoes Ruby and Esmeralda Bank. The Ruby Seamount is located 40 km (25 mi) northwest of Saipan and 60 m (200 ft) below sea level. The last known eruption occurred in 1995 (Rutherford and Kaye 2006). The larger Esmeralda Bank, 38 km (24 mi) west of the island of Tinian, rises to within 30 m (100 ft) of sea level (Stern and Bibee 1984). Six possible eruptions have been recorded at Esmeralda Bank since 1944. In the early part of the 20th century, the banks were noted to be above sea level but have since subsided because of ongoing earthquakes causing down dropping and erosion (Stern and Bibee 1984; Rutherford and Kaye 2006). According to the USGS Volcano Hazards Program, both Ruby Seamount and Esmeralda Bank are considered to have low to very low threat potential. Anatahan is the closest active volcano above sea level, 129 km (80 mi) from Saipan. An explosive eruption at Anatahan started on 6 April 2005 when 50 million m^3 of ash were blasted up to 15 km (9 mi) into the atmosphere (Figure 36; Earth Observatory 2005). According to the USGS Volcano Hazards Program, Anatahan is considered to have moderate threat potential.

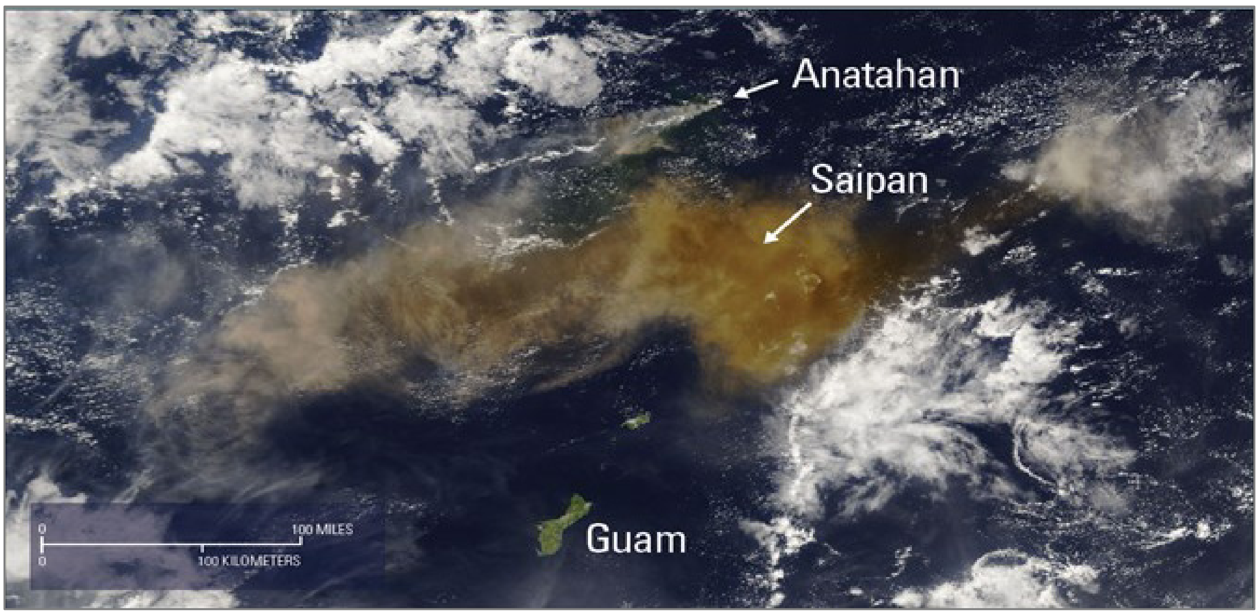


Figure 36. Ash plume over Saipan. This satellite image shows the brown ash from the 6 April 2005 Anatahan Island eruption which rose to about 15 km (49,000 ft). Eight hours after the eruption began, the ash plume had spread, covering Saipan Island, and demonstrating the far-reaching hazards of volcanoes. Image is an unnumbered figure from Tepp et al. (2019) originally from the National Aeronautics and Space Administration Moderate Resolution Imagery Spectroradiometer Rapid Response image gallery.

The primary volcanic hazards to Saipan are ash fall, earthquakes, and tsunami from eruptions in the northern islands (Rutherford and Kaye 2006; Tepp et al. 2019). Ash may interfere with aircraft and be deposited on the airport of Saipan, and ash decreases air quality and exacerbates health issues. In general, wind direction favors Saipan blowing from west to east; however, wind direction changes are possible and could bring in hazardous ash fall. In 2006, vog (potentially dangerous smog or haze containing volcanic dust and gases) could be smelled on Saipan from Anatahan and caused eye and respiratory irritation for several days (Dave Weary, geologist, US Geological Survey, written communication, 28 August 2023). An interagency task force has prepared an operating plan for volcanic-ash hazards to aviation in the Commonwealth of the Northern Mariana Islands, which includes aviation color codes for volcanic activity and courses of action for each entity for each code (US Geological Survey 2009).

Volcanic activity, updates, and hazards for the Northern Mariana Islands are updated by USGS Volcano Hazards Program. Warnings and restrictions related to eruptions are issued by the Federal Aviation Administration for flight restrictions if an ash plume is present or expected. The National Weather Service and NOAA may issue warnings about air quality and potential marine hazards, including tsunami. The Washington D.C. Volcanic Ash Advisory Center (VAAC), operated by the National Weather Service, issues ash-related notices for local airspace (Tepp et al. 2019). Smith et al. (2009) have suggested "vital signs" and monitoring methodologies for volcanoes utilizing earthquake activity, ground deformation, emission at ground level, emission of gas plume and ash clouds, hydrologic activity, and slope instability. Many of the examples used by Smith et al. (2009) come from the USGS Hawaiian Volcano Observatory's monitoring of volcanoes in Hawai‘i Volcanoes National Park.

Climate Change and Sea Level Rise

Although climate change planning is beyond the scope of this GRI report, a discussion of climate change is included because of the potential impacts it may cause to the park's geologic features and processes, including low-lying geologic resources. Island ecosystems are particularly vulnerable to climate variability and change (Schlappa et al. 2011; Greene and Skeele 2014). The park is vulnerable to flooding, erosion, storm damage, and saltwater intrusion—all likely results of climate change and sea level rise (Greene and Skeele 2014; National Park Service 2022). The peoples of the Pacific were among the first to observe and experience the effects of global climatic changes, such as changes to ocean chemistry, wind and waves, habitats and species distributions, and decreases in baseflow in streams (Helweg et al. 2014). In particular, park managers are concerned about changes in frequency or intensity of storm and typhoon events, as well as impacts from predicted sea-level rise (National Park Service 2017). On average, 31 tropical storms develop in the western north Pacific every year, and commonly, one or more of these impacts Saipan, with more frequency predicted as part of climate change (Whistler 2009; Greene and Skeele 2014). In August 2015, super typhoon Soudelor devastated the island of Saipan, taking out electricity, water, sewer, and communications services. Approximately 90% of the trees in the park were uprooted or snapped, and the main park waterline and other park facilities were damaged (National Park Service 2017). During some of these storms, wind-driven waves are coming from the west instead of the usual trade wind pattern. This focuses that energy on the lagoon and semi-exposed west coast. Shifts in climate that favor the western Pacific's rainy season conditions (prone to typhoons) will contribute to increased erosion and beach loss (Greene and Skeele 2014).

Sea level rise will impact the entire park (Figure 37) and is already well underway. At the tide gauge in Guam (the closest available to the park), sea level has risen by approximately 13 cm (5 in) since 1994 (National Park Service 2022). A walkway along the shore collapsed due to rising seas eroding the surrounding soil (National Park Service 2022). Sea level could rise another 1.65 m (5.41 ft) by 2100 (National Park Service 2022, NOAA 2022). Models predict local sea level rise to exceed global rates (Greene et al. 2019). Rising sea levels may cause existing coastal wetlands and mangrove areas to become more saline with time (Helweg et al. 2014). Sea level rise may cause the mangrove forests (which cannot migrate landward) and salt marshes in the park to "drown," causing the decline of critical fish nursery habitat and converting vegetated habitat to open water, respectively (National Park Service 2022).

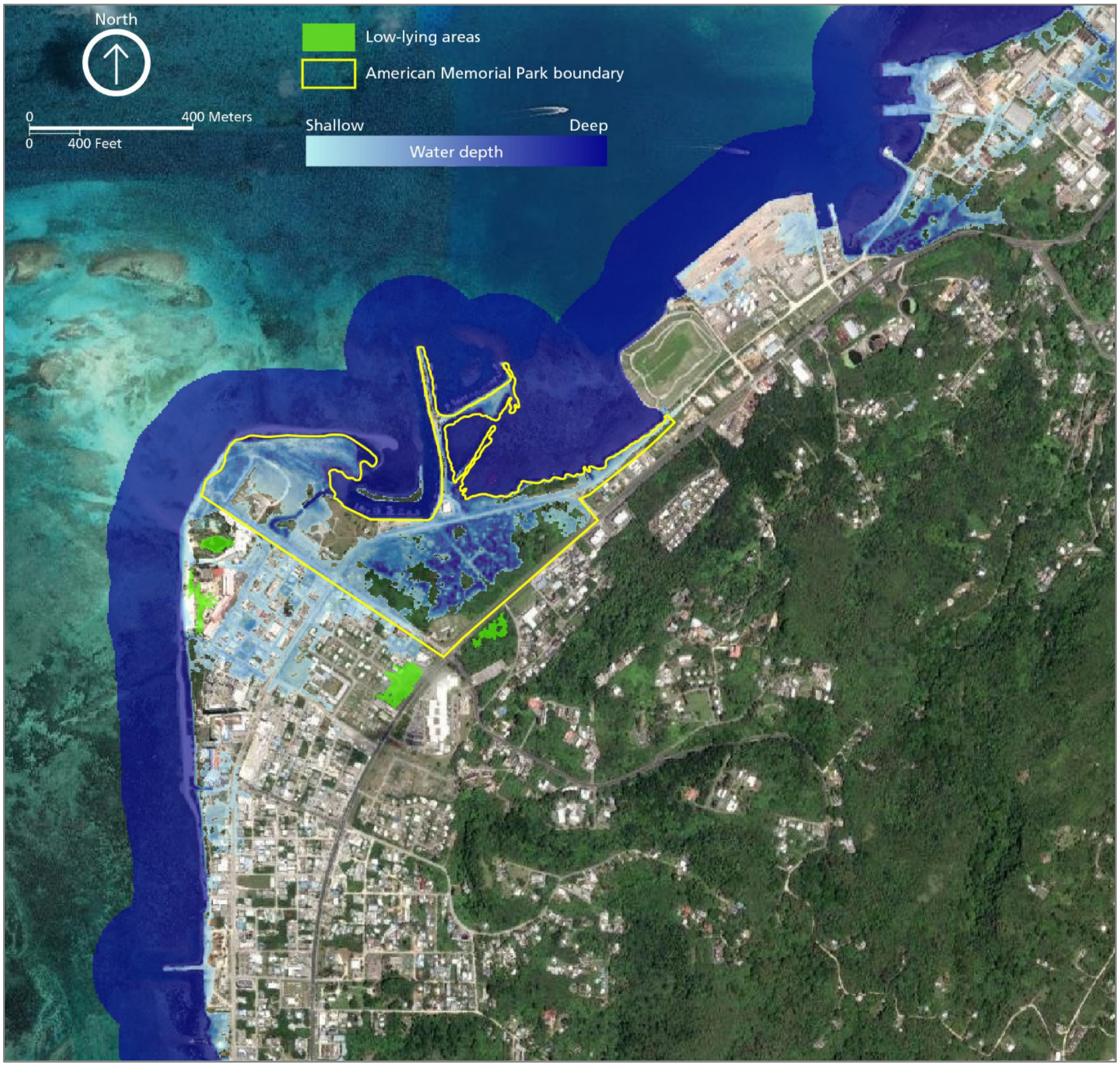


Figure 37. Predicted sea level rise within and surrounding the park. Most of the area within the park is low-lying. By the year 2100, predicted sea level rise is over 1.5 m (5 ft) for Saipan. This image models a 1.5 m (5 ft) sea level rise. Most of the park area is underwater. The yellow outline denotes the park boundary. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) using the Coastal Flood Exposure Mapper from NOAA (https://coast.noaa.gov/digitalcoast/tools/flood-exposure.html, accessed 2 May 2023) with data coming from the National Tsunami Hazard Mitigation Program.

Coral reefs are deteriorating due to sea level rise, ocean temperature increases, and chemistry changes. These effects are compounded by land-based sources of pollution, sedimentation, coastal development, and invasive species (US Geological Survey 2003; Helweg et al. 2014). Given the park's ridge-to-reef setting, reef health is of vital importance. Rising seas also reduce the reef's ability to buffer wave energy during storms. Modeling of projected sea inundation and resource management actions was identified as a medium priority data need for the park (National Park Service 2017). Already, the park is moving visitor facilities inland and working with local agencies to plant mangroves and restore habitats (National Park Service 2022). The park should continue to collaborate and cooperate with multi-agency climate change working groups to develop strategies to adapt to climate change impacts (Greene and Skeele 2012). The National Park Service completed the coastal hazards/sea level rise asset vulnerability protocol to understand the degree to which resources and assets are susceptible to harm from direct and indirect effects of climate change, including variability and weather extremes (Peek et al. 2022). A park-specific report has not yet been completed, but one for War in the Pacific National Historical Park on Guam is available for reference (Peek et al. 2017).

Artificial Fill Concerns

Much of the land within the park was modified by humans (e.g., map unit **Qaf**), particularly during World War II (see "Disturbed Lands" section). Among the resource management concerns related to this are buried explosives. Any excavation project also has the potential to unearth cultural resources (e.g., human remains dating from pre-contact to the World War II era). Much of the fill is broken coral and landfill waste, but metal pieces are omnipresent, as is other debris related to military housing waste (Tahzay Jones, regional coastal ecologist, National Park Service-Alaska, conference call, 16 November 2021).

Paleontological Resource Inventory, Monitoring, and Protection

All paleontological resources are non-renewable and subject to science-informed inventory, monitoring, protection, and interpretation as outlined by the 2009 Paleontological Resources Preservation Act. Fossils in NPS areas occur in situ in rocks or unconsolidated deposits, in museum collections, and in cultural contexts such as building stones or archeological resources. Paleontological resources have yet to be definitively identified at the park. A research-based baseline paleontological resources inventory indicates the potential for fossils to be part of the park's buildings, infrastructure, or monuments, as well as wash ashore and be part of wetland deposits (fossil pollen) (Hunt et al. 2007). In fact, researchers in 2009 found Holocene-age pollen in cores from the wetlands and mangrove forest in the park (Jarzen and Dilcher 2009; Greene et al. 2019). Anecdotal evidence suggests their ages may coincide roughly with the arrival of the first humans (Jarzen and Dilcher 2009). The precise ages of these cores remain uncertain; however, if old enough, they may qualify as paleontological material (Justin Tweet, paleontologist, National Park Service, written communication, 7 August 2023).

A field-based paleontological resource survey has not been completed for the park but could provide detailed, site-specific descriptions and resource management recommendations. Fieldwork could be accomplished by establishing a cooperative agreement with one or more of the local natural history museums with paleontological expertise or with local universities with geology departments. In the *Geological Monitoring* chapter about paleontological resources, Santucci et al. (2009) described five methods and vital signs for monitoring in situ paleontological resources: (1) erosion (geologic factors), (2) erosion (climatic factors), (3) catastrophic geohazards, (4) hydrology/bathymetry, and (5) human access/public use.

Guidance for Resource Management

This chapter provides information to assist resource managers in addressing geologic resource management issues and applying NPS policy. The compilation and use of natural resource information by park managers is called for in the 1998 National Parks Omnibus Management Act (§ 204), NPS 2006 Management Policies, and the Natural Resources Inventory and Monitoring Guideline (NPS-75).

Access to GRI Products

- GRI products (scoping summaries, GIS data, posters, and reports): http://go.nps.gov/gripubs
- GRI products are also available through the NPS Integrated Resource Management Applications (IRMA) DataStore portal: https://irma.nps.gov/DataStore/Search/Quick. Enter "GRI" as the search text and select a park from the unit list.
- GRI GIS data model: http://go.nps.gov/gridatamodel
- Additional information regarding the GRI, including contact information: https://www.nps.gov/subjects/geology/gri.htm

Three Ways to Receive Geologic Resource Management Assistance

- Contact the GRD (https://www.nps.gov/orgs/1088/contactus.htm). GRD staff members provide coordination, support, and guidance for geologic resource management issues in three emphasis areas: (1) geologic heritage, (2) active processes and hazards, and (3) energy and minerals management. GRD staff can provide technical assistance with resource inventories, assessments, and monitoring; impact mitigation, restoration, and adaptation; hazards risk management; laws, regulations, and compliance; resource management planning; and data and information management.
- Formally request assistance at the Solution for Technical Assistance Requests (STAR) webpage: https://irma.nps.gov/Star/ (available on the Department of the Interior [DOI] network only). NPS employees (from a park, region, or any other office outside of the Natural Resource Stewardship and Science [NRSS] Directorate) can submit a request for technical assistance from NRSS divisions and programs.
- Submit a proposal to receive geologic expertise through the Scientists in Parks program (SIP; see https://www.nps.gov/subjects/science/scientists-in-parks.htm). Formerly the Geoscientists-in-the-Parks program, the SIP program places scientists (typically undergraduate students) in parks to complete science-related projects that may address resource management issues. Proposals may be for assistance with research, interpretation and public education, inventory, and/or monitoring. The GRD can provide guidance and assistance with submitting a proposal. The Geological Society of America and Environmental Stewards are partners of the SIP program. Visit the internal SIP website to submit a proposal at https://doimspp.sharepoint.com/sites/nps-scientistsinparks (only available on DOI network computers).

Geological Monitoring

Geological Monitoring (Young and Norby 2009) provides guidance for monitoring vital signs (measurable parameters of the overall condition of natural resources). Each chapter covers a different geologic resource and includes detailed recommendations for resource managers, suggested methods of monitoring, and case studies. Chapters are available online at https://www.nps.gov/subjects/geology/geological-monitoring.htm.

Park-Specific Documents

The park's Foundation Document (National Park Service 2017) and Natural Resource Condition Assessment are primary sources of information for resource management within the park. Weary and Burton (2011) and Cloud et al. (1956) provide detailed geologic information for the island of Saipan.

NPS Natural Resource Management Guidance and Documents

- National Parks Omnibus Management Act of 1998: https://www.congress.gov/bill/105th-congress/senate-bill/1693
- NPS-75: Natural Resources Inventory and Monitoring guideline: https://irma.nps.gov/DataStore/Reference/Profile/622933
- NPS Management Policies 2006 (Chapter 4: Natural Resource Management): https://www.nps.gov/subjects/policy/management-policies.htm
- NPS Natural Resource Management Reference Manual #77: https://irma.nps.gov/DataStore/Reference/Profile/572379
- Resist-Accept-Direct (RAD)—A Framework for the 21st-century Natural Resource Manager: https://irma.nps.gov/DataStore/Reference/Profile/2283597

Identified Data and Resource Management Needs

Because of its active geologic setting, acreage at the park changes due to sand shifts caused by localized erosion and accretion. The park lacks accurate baseline data regarding land status, park boundaries, and total acreage (National Park Service 2017). Other planning and data needs recognized in the foundation document include land protection plans, general management plan update (to reflect the unique natural resources and climate change among other issues), cultural resources condition assessment, and a landscape vegetation recovery plan for Saipan after the damage inflicted by typhoons.

Geologic Resource Laws, Regulations, and Policies

The following sections, which were developed by the GRD, summarizes laws, regulations, and policies that specifically apply to NPS geologic resources, processes, and energy and minerals. The first section summarizes law and policy for geoheritage resources, which includes caves, paleontological resources, and geothermal resources. The energy and minerals section, includes abandoned mineral lands, mining, rock and mineral collection, and oil and gas operations. Active processes includes geologic hazards (e.g., landslides), coastal processes, soils, and upland and fluvial processes (e.g., erosion). Laws of general application (e.g., Endangered Species Act, Clean Water Act, Wilderness Act, NEPA, or the National Historic Preservation Act) are not included, but the NPS

Organic Act is listed when it serves as the main authority for protection of a particular resource or when other, more specific laws are not available.

Geoheritage Resource Laws, Regulations, and Policies

Caves and Karst Systems
Resource-specific laws:

- **Federal Cave Resources Protection Act of 1988, 16 USC §§ 4301 – 4309** requires Interior/Agriculture to identify "significant caves" on Federal lands, regulate/restrict use of those caves as appropriate, and include significant caves in land management planning efforts. Imposes civil and criminal penalties for harming a cave or cave resources. Authorizes Secretaries to withhold information about specific location of a significant cave from a Freedom of Information Act (FOIA) requester.
- **National Parks Omnibus Management Act of 1998, 54 USC § 100701** protects the confidentiality of the nature and specific location of cave and karst resources.
- **Lechuguilla Cave Protection Act of 1993, Public Law 103-169** created a cave protection zone (CPZ) around Lechuguilla Cave in Carlsbad Caverns National Park. Within the CPZ, access and the removal of cave resources may be limited or prohibited; existing leases may be cancelled with appropriate compensation; and lands are withdrawn from mineral entry.

Resource-specific regulations:

- **36 CFR § 2.1** prohibits possessing/ destroying/disturbing…cave resources…in park units.
- **43 CFR Part 37** states that all NPS caves are "significant" and sets forth procedures for determining/releasing confidential information about specific cave locations to a FOIA requester.

NPS Management Policies 2006:

- **Section 4.8.1.2** requires NPS to maintain karst integrity, minimize impacts.
- **Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity.
- **Section 4.8.2.2** requires NPS to protect caves, allow new development in or on caves if it will not impact cave environment, and to remove existing developments if they impair caves.
- **Section 6.3.11.2** explains how to manage caves in/adjacent to wilderness.

Geothermal
Resource-specific laws:

- **Geothermal Steam Act of 1970, 30 USC. § 1001** et seq. as amended in 1988, states:
    - No geothermal leasing is allowed in parks.

- “Significant” thermal features exist in 16 park units (the features listed by the NPS at 52 Fed. Reg. 28793-28800 (August 3, 1987), plus the thermal features in Crater Lake, Big Bend, and Lake Mead).
- NPS is required to monitor those features.
- Based on scientific evidence, Secretary of Interior must protect significant NPS thermal features from leasing effects.

- **Geothermal Steam Act Amendments of 1988, Public Law 100--443** prohibits geothermal leasing in the Island Park known geothermal resource area near Yellowstone and outside 16 designated NPS units if subsequent geothermal development would significantly adversely affect identified thermal features.

Resource-specific regulations:

- **43 CFR Part 3200** requires BLM to include stipulations when issuing, extending, renewing, or modifying leases or permits to protect significant thermal features in NPS-administered areas (see 43 CFR §3201.10), prohibit the bureau from issuing leases in areas where geothermal operations are reasonably likely to result in significant adverse effects on significant thermal features in NPS-administered areas (see 43 CFR §3201.11 and §3206.11), and prohibit BLM from issuing leases in park units.

NPS Management Policies 2006:

- **Section 4.8.2.3** requires NPS to:
    - Preserve/maintain integrity of all thermal resources in parks.
    - Work closely with outside agencies.
    - Monitor significant thermal features.

<u>Paleontological Resources</u>
Resource-specific laws:

- **Archaeological Resources Protection Act of 1979, 16 USC §§ 470aa – mm Section 3 (1)** Archaeological Resource—nonfossilized and fossilized paleontological specimens, or any portion or piece thereof, shall not be considered archaeological resources, under the regulations of this paragraph, unless found in an archaeological context. Therefore, fossils in an archaeological context are covered under this law.
- **Federal Cave Resources Protection Act of 1988, 16 USC §§ 4301 – 4309 Section 3 (5) Cave Resource**—the term “cave resource” includes any material or substance occurring naturally in caves on Federal lands, such as animal life, plant life, paleontological deposits, sediments, minerals, speleogens, and speleothems. Therefore, every reference to cave resource in the law applies to paleontological resources.
- **National Parks Omnibus Management Act of 1998, 54 USC § 100701** protects the confidentiality of the nature and specific location of paleontological resources and objects.

- **Paleontological Resources Preservation Act of 2009, 16 USC § 470aaa** et seq. provides for the management and protection of paleontological resources on federal lands.

Resource-specific regulations:

- **36 CFR § 2.1(a)(1)(iii)** prohibits destroying, injuring, defacing, removing, digging or disturbing paleontological specimens or parts thereof.
- **Prohibition in 36 CFR § 13.35** applies even in Alaska parks, where the surface collection of other geologic resources is permitted.
- **43 CFR Part 49** contains the DOI regulations implementing the Paleontological Resources Preservation Act, which apply to the NPS.

NPS Management Policies 2006:

- **Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity.
- **Section 4.8.2.1** emphasizes Inventory and Monitoring, encourages scientific research, directs parks to maintain confidentiality of paleontological information, and allows parks to buy fossils only in accordance with certain criteria.

Energy and Minerals Laws, Regulations, and Policies

Abandoned Mineral Lands and Orphaned Oil and Gas Wells
Resource-specific laws: The **Bipartisan Infrastructure Law**, **Inflation Reduction Act**, and **NPS Line Item** Construction program all provide funding for the reclamation of abandoned mineral lands and the plugging of orphaned oil and gas wells.

Resource-specific regulations: none applicable.

NPS Management Policies 2006: none applicable.

Coal
Resource-specific laws: **Surface Mining Control and Reclamation Act of 1977**, 30 USC § 1201 et. seq. prohibits surface coal mining operations on any lands within the boundaries of a NPS unit, subject to valid existing rights.

Resource-specific regulations: **SMCRA Regulations at 30 CFR Chapter VII** govern surface mining operations on Federal lands and Indian lands by requiring permits, bonding, insurance, reclamation, and employee protection. Part 7 of the regulations states that National Park System lands are unsuitable for surface mining.

NPS Management Policies 2006: none applicable.

Common Variety Mineral Materials (Sand, Gravel, Pumice, etc.)
Resource-specific laws:

- **Materials Act of 1947, 30 USC § 601** does not authorize the NPS to dispose of mineral materials outside of park units.
- **Reclamation Act of 1939, 43 USC §387**, authorizes removal of common variety mineral materials from federal lands in federal reclamation projects. This act is cited in the enabling statutes for Glen Canyon and Whiskeytown National Recreation Areas, which provide that the Secretary of the Interior may permit the removal of federally owned nonleasable minerals such as sand, gravel, and building materials from the NRAs under appropriate regulations. Because regulations have not yet been promulgated, the National Park Service may not permit removal of these materials from these National Recreation Areas.
- **16 USC §90c-1(b)** authorizes sand, rock and gravel to be available for sale to the residents of Stehekin from the non-wilderness portion of Lake Chelan National Recreation Area, for local use as long as the sale and disposal does not have significant adverse effects on the administration of the national recreation area.

Resource-specific regulations: none applicable.

NPS Management Policies 2006: **Section 9.1.3.3** clarifies that only the NPS or its agent can extract park-owned common variety minerals (e.g., sand and gravel), and:

- Only for park administrative uses;
- After compliance with NEPA and other federal, state, and local laws, and a finding of non-impairment;
- After finding the use is park's most reasonable alternative based on environment and economics;
- Parks should use existing pits and create new pits only in accordance with park-wide borrow management plan;
- Spoil areas must comply with Part 6 standards; and
- NPS must evaluate use of external quarries.

Any deviation from this policy requires a written waiver from the Secretary, Assistant Secretary, or Director.

<u>Federal Mineral Leasing (Oil, Gas, and Solid Minerals)</u>
Resource-specific laws:

- **The Mineral Leasing Act, 30 USC § 181** et seq., and the Mineral Leasing Act for Acquired Lands, 30 USC § 351 et seq. do not authorize the BLM to lease federally owned minerals in NPS units.
- **Combined Hydrocarbon Leasing Act, 30 USC §181**, allowed owners of oil and gas leases or placer oil claims in Special Tar Sand Areas (STSA) to convert those leases or claims to combined hydrocarbon leases, and allowed for competitive tar sands leasing. This act did not

modify the general prohibition on leasing in park units but did allow for lease conversion in GLCA, which is the only park unit that contains a STSA.

- **Exceptions:** Glen Canyon NRA (16 USC § 460dd et seq.), Lake Mead NRA (16 USC § 460n et seq.), and Whiskeytown-Shasta-Trinity NRA (16 USC § 460q et seq.) authorizes the BLM to issue federal mineral leases in these units provided that the BLM obtains NPS consent. Such consent must be predicated on an NPS finding of no significant adverse effect on park resources and/or administration.
- **American Indian Lands** Within NPS Boundaries Under the Indian Allottee Leasing Act of 1909, 25 USC §396, and the Indian Leasing Act of 1938, 25 USC §396a, §398 and §399, and Indian Mineral Development Act of 1982, 25 USCS §§2101-2108, all minerals on American Indian trust lands within NPS units are subject to leasing.
- **Federal Coal Leasing Amendments Act of 1975, 30 USC § 201** prohibits coal leasing in National Park System units.

Resource-specific regulations:

- **36 CFR § 5.14** states prospecting, mining, and…leasing under the mineral leasing laws [is] prohibited in park areas except as authorized by law.
- **BLM regulations at 43 CFR Parts 3100, 3400, and 3500** govern Federal mineral leasing.
- Regulations re: Native American Lands within NPS Units:
    - **25 CFR Part 211** governs leasing of tribal lands for mineral development.
    - **25 CFR Part 212** governs leasing of allotted lands for mineral development.
    - **25 CFR Part 216** governs surface exploration, mining, and reclamation of lands during mineral development.
    - **25 CFR Part 224** governs tribal energy resource agreements.
    - **25 CFR Part 225** governs mineral agreements for the development of Indian-owned minerals entered into pursuant to the Indian Mineral Development Act of 1982, Pub. L. No. 97-382, 96 Stat. 1938 (codified at 25 USC §§ 2101-2108).
    - **30 CFR §§ 1202.100-1202.101** governs royalties on oil produced from Indian leases.
    - **30 CFR §§ 1202.550-1202.558** governs royalties on gas production from Indian leases.
    - **30 CFR §§ 1206.50-1206.62 and §§ 1206.170-1206.176** governs product valuation for mineral resources produced from Indian oil and gas leases.
    - **30 CFR § 1206.450** governs the valuation coal from Indian Tribal and Allotted leases.
    - **43 CFR Part 3160** governs onshore oil and gas operations, which are overseen by the BLM.

NPS Management Policies 2006: **Section 8.7.2** states that all NPS units are closed to new federal mineral leasing except Glen Canyon, Lake Mead and Whiskeytown-Shasta-Trinity NRAs.

Mining Claims (Locatable Minerals)
Resource-specific laws:

- **Mining in the Parks Act of 1976, 54 USC § 100731** et seq. authorizes NPS to regulate all activities resulting from exercise of mineral rights, on patented and unpatented mining claims in all areas of the System, in order to preserve and manage those areas.
- **General Mining Law of 1872, 30 USC § 21** et seq. allows US citizens to locate mining claims on Federal lands. Imposes administrative and economic validity requirements for "unpatented" claims (the right to extract Federally-owned locatable minerals). Imposes additional requirements for the processing of "patenting" claims (claimant owns surface and subsurface). Use of patented mining claims may be limited in Wild and Scenic Rivers and OLYM, GLBA, CORO, ORPI, and DEVA.
- **Surface Uses Resources Act of 1955, 30 USC § 612** restricts surface use of unpatented mining claims to mineral activities.

Resource-specific regulations:

- **36 CFR § 5.14** prohibits prospecting, mining, and the location of mining claims under the general mining laws in park areas except as authorized by law.
- **36 CFR Part 6** regulates solid waste disposal sites in park units.
- **36 CFR Part 9**, Subpart A requires the owners/operators of mining claims to demonstrate bona fide title to mining claim; submit a plan of operations to NPS describing where, when, and how; prepare/submit a reclamation plan; and submit a bond to cover reclamation and potential liability.
- **43 CFR Part 36** governs access to mining claims located in, or adjacent to, National Park System units in Alaska

NPS Management Policies 2006:

- **Section 6.4.9** requires NPS to seek to remove or extinguish valid mining claims in wilderness through authorized processes, including purchasing valid rights. Where rights are left outstanding, NPS policy is to manage mineral-related activities in NPS wilderness in accordance with the regulations at 36 CFR Parts 6 and 9A.
- **Section 8.7.1** prohibits location of new mining claims in parks; requires validity examination prior to operations on unpatented claims; and confines operations to claim boundaries.

Nonfederal Minerals other than Oil and Gas
Resource-specific laws: NPS Organic Act, 54 USC §§ 100101 and 100751

Resource-specific regulations: **NPS regulations at 36 CFR Parts 1, 5, and 6** require the owners/operators of other types of mineral rights to obtain a special use permit from the NPS as a §

5.3 business operation, and § 5.7 – Construction of buildings or other facilities, and to comply with the solid waste regulations at Part 6.

NPS Management Policies 2006: **Section 8.7.3** states that operators exercising rights in a park unit must comply with 36 CFR Parts 1 and 5.

<u>Nonfederal Oil and Gas</u>
Resource-specific laws:

- **NPS Organic Act, 54 USC § 100751** et seq. authorizes the NPS to promulgate regulations to protect park resources and values (from, for example, the exercise of mining and mineral rights).
- Individual Park Enabling Statutes:
    - 16 USC § 230a (Jean Lafitte NHP & Pres.)
    - 16 USC §450kk (Fort Union NM)
    - 16 USC § 459d-3 (Padre Island NS)
    - 16 USC § 459h-3 (Gulf Islands NS)
    - 16 USC § 460ee (Big South Fork NRRA)
    - 16 USC § 460cc-2(i) (Gateway NRA)
    - 16 USC § 460m (Ozark NSR)
    - 16 USC§698c (Big Thicket N Pres.)
    - 16 USC §698f (Big Cypress N Pres.)

Resource-specific regulations:

- **36 CFR Part 6** regulates solid waste disposal sites in park units.
- **36 CFR Part 9, Subpart B** requires the owners/operators of nonfederally owned oil and gas rights in parks outside of Alaska to:
    - Demonstrate valid right to develop mineral rights;
    - Submit an Operations Permit Application to NPS describing where, when, how they intend to conduct operations;
    - Prepare/submit a reclamation plan; and
    - Submit financial assurance to cover reclamation and potential liability.
- **43 CFR Part 36** governs access to nonfederal oil and gas rights located in, or adjacent to, National Park System units in Alaska.

NPS Management Policies 2006: **Section 8.7.3** requires operators to comply with 9B regulations.

<u>Recreational Collection of Rocks and Minerals</u>
Resource-specific laws:

- **NPS Organic Act, 54 USC. § 100101** et seq. directs the NPS to conserve all resources in parks (which includes rock and mineral resources) unless otherwise authorized by law.
- **Exception: 16 USC. § 445c (c)** – Pipestone National Monument enabling statute. Authorizes American Indian collection of catlinite (red pipestone).

Resource-specific regulations:

- **36 C.F.R. § 2.1** prohibits possessing, destroying, disturbing mineral resources…in park units.
- **Exception: 36 C.F.R. § 7.91** allows limited gold panning in Whiskeytown.
- **Exception: 36 C.F.R. § 13.35** allows some surface collection of rocks and minerals in some Alaska parks (not Klondike Gold Rush, Sitka, Denali, Glacier Bay, and Katmai) by non-disturbing methods (e.g., no pickaxes), which can be stopped by superintendent if collection causes significant adverse effects on park resources and visitor enjoyment.

NPS Management Policies 2006: **Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity.

<u>Transpark Petroleum Product Pipelines</u>
Resource-specific laws:

- The **Mineral Leasing Act, 30 USC § 181** et seq., and the **Mineral Leasing Act for Acquired Lands, 30 USC § 351** et seq. authorize new rights of way across some federal lands for pipelines, excluding NPS areas.
- The only parks with the legal authority to grant new rights of way for petroleum product pipelines are:
    - Natchez Trace Parkway (16 USC §460a)
    - Blue Ridge Parkway (16 USC §460a-8)
    - Great Smoky Mountains National Park (P.L. 107-223 – 16 U.S.C. §403 notes)
    - Klondike Gold Rush (16 USC §410bb(c) (limited authority for the White Pass Trail unit)
    - Gulf Islands National Seashore - enabling act authorizes rights-of-way for pipelines for oil and gas transported across the seashore from outside the unit (16 USC §459h-3)
    - Gateway National Recreation Area - enabling act authorizes rights-of-way for gas pipelines in connection with the development of methane gas owned by the City of New York within the unit (16 USC §460cc-2(i))
    - Denali National Park – 2013 legislation allows for issuance of right-of-way permits for a natural gas pipeline within, along, or near the approximately 7-mile segment of the George Parks Highway that runs through the park (Public Law 113–33)

Resource-specific regulations: **NPS regulations at 36 CFR Part 14 Rights of Way**

NPS Management Policies 2006: **Section 8.6.4** states that new rights of way through, under, and across NPS units may be issued only if there is specific statutory authority and there is no practicable alternative.

<u>Uranium</u>
Resource-specific laws: **Atomic Energy Act of 1954** allows Secretary of Energy to issue leases or permits for uranium on BLM lands; may issue leases or permits in NPS areas only if president declares a national emergency.

Resource-specific regulations: none applicable.

NPS Management Policies 2006: none applicable.

Active Processes and Geohazards Laws, Regulations, and Policies

<u>Coastal Features and Processes</u>
Resource-specific laws:

- **NPS Organic Act, 54 USC § 100751** et. seq. authorizes the NPS to promulgate regulations to protect park resources and values (from, for example, the exercise of mining and mineral rights).
- **Coastal Zone Management Act, 16 USC § 1451** et. seq. requires Federal agencies to prepare a consistency determination for every Federal agency activity in or outside of the coastal zone that affects land or water use of the coastal zone.
- **Clean Water Act, 33 USC § 1342/Rivers and Harbors Act, 33 USC 403** require that dredge and fill actions comply with a Corps of Engineers Section 404 permit.
- **Executive Order 13089** (coral reefs) (1998) calls for reduction of impacts to coral reefs.
- **Executive Order 13158** (marine protected areas) (2000) requires every federal agency, to the extent permitted by law and the maximum extent practicable, to avoid harming marine protected areas.

Resource-specific regulations:

- **36 CFR § 1.2(a)(3)** applies NPS regulations to activities occurring within waters subject to the jurisdiction of the US located within the boundaries of a unit, including navigable water and areas within their ordinary reach, below the mean high water mark (or OHW line) without regard to ownership of submerged lands, tidelands, or lowlands.
- **36 CFR § 5.7** requires NPS authorization prior to constructing a building or other structure (including boat docks) upon, across, over, through, or under any park area.

NPS Management Policies 2006:

- **Section 4.1.5** directs the NPS to re-establish natural functions and processes in human-disturbed components of natural systems in parks unless directed otherwise by Congress.

- **Section 4.4.2.4** directs the NPS to allow natural recovery of landscapes disturbed by natural phenomena, unless manipulation of the landscape is necessary to protect park development or human safety.
- **Section 4.8.1** requires NPS to allow natural geologic processes to proceed unimpeded. NPS can intervene in these processes only when required by Congress, when necessary for saving human lives, or when there is no other feasible way to protect other natural resources/ park facilities/historic properties.
- **Section 4.8.1.1** requires NPS to:
    - Allow natural processes to continue without interference,
    - Investigate alternatives for mitigating the effects of human alterations of natural processes and restoring natural conditions,
    - Study impacts of cultural resource protection proposals on natural resources,
    - Use the most effective and natural-looking erosion control methods available, and
    - Avoid putting new developments in areas subject to natural shoreline processes unless certain factors are present.

<u>Geologic Hazards</u>
Resource-specific laws: **National Landslide Preparedness Act, 43 USC §§ 3101–3104** strengthens the mandate to identify landslide hazards and reduce losses from landslides. Established the National Landslide Hazards Reduction Program. "…the United States Geological Survey and other Federal agencies, shall – identify, map, assess, and research landslide hazards;" Reduce landslide losses, respond to landslide events

Resource-specific regulations: none applicable.

NPS Management Policies 2006:

- **Section 4.8.1.3**, Geologic Hazards
- **Section 9.1.1.5**, Siting Facilities to Avoid Natural Hazards
- **Section 8.2.5.1**, Visitor Safety
- **Policy Memo 15-01** (Climate Change and Natural Hazards for Facilities) (2015) provides guidance on the design of facilities to incorporate impacts of climate change adaptation and natural hazards when making decisions in national parks.

<u>Soils</u>
Resource-specific laws:

- **Soil and Water Resources Conservation Act, 16 USC §§ 2011–2009** provides for the collection and analysis of soil and related resource data and the appraisal of the status, condition, and trends for these resources.

- **Farmland Protection Policy Act, 7 USC § 4201** et. seq. requires NPS to identify and take into account the adverse effects of Federal programs on the preservation of farmland; consider alternative actions, and assure that such Federal programs are compatible with State, unit of local government, and private programs and policies to protect farmland. NPS actions are subject to the FPPA if they may irreversibly convert farmland (directly or indirectly) to nonagricultural use and are completed by a Federal agency or with assistance from a Federal agency. Applicable projects require coordination with the Department of Agriculture's Natural Resources Conservation Service (NRCS).

Resource-specific regulations: **7 CFR Parts 610 and 611** are the US Department of Agriculture regulations for the Natural Resources Conservation Service. Part 610 governs the NRCS technical assistance program, soil erosion predictions, and the conservation of private grazing land. Part 611 governs soil surveys and cartographic operations. The NRCS works with the NPS through cooperative arrangements.

NPS Management Policies 2006: **Section 4.8.2.4** requires NPS to (1) prevent unnatural erosion, removal, and contamination; (2) conduct soil surveys; (3) minimize unavoidable excavation; and (4) develop/follow written prescriptions (instructions).

<u>Upland and Fluvial Processes</u>
Resource-specific laws:

- **Rivers and Harbors Appropriation Act of 1899, 33 USC § 403** prohibits the construction of any obstruction on the waters of the United States not authorized by congress or approved by the USACE.
- **Clean Water Act 33 USC § 1342** requires a permit from the USACE prior to any discharge of dredged or fill material into navigable waters (waters of the US [including streams]).
- **Executive Order 11988** requires federal agencies to avoid adverse impacts to floodplains. (see also **D.O. 77-2**).
- **Executive Order 11990** requires plans for potentially affected wetlands (including riparian wetlands). (see also **D.O. 77-1**).

Resource-specific regulations: none applicable.

NPS Management Policies 2006:

- **Section 4.1** requires NPS to manage natural resources to preserve fundamental physical and biological processes, as well as individual species, features, and plant and animal communities; maintain all components and processes of naturally evolving park ecosystems.
- **Section 4.1.5** directs the NPS to re-establish natural functions and processes in human-disturbed components of natural systems in parks, unless directed otherwise by Congress.
- **Section 4.4.2.4** directs the NPS to allow natural recovery of landscapes disturbed by natural phenomena, unless manipulation of the landscape is necessary to protect park development or human safety.

- **Section 4.6.4** directs the NPS to (1) manage for the preservation of floodplain values; [and] (2) minimize potentially hazardous conditions associated with flooding.
- **Section 4.6.6** directs the NPS to manage watersheds as complete hydrologic systems and minimize human-caused disturbance to the natural upland processes that deliver water, sediment, and woody debris to streams.
- **Section 4.8.1** directs the NPS to allow natural geologic processes to proceed unimpeded. Geologic processes…include…erosion and sedimentation…processes.
- **Section 4.8.2** directs the NPS to protect geologic features from the unacceptable impacts of human activity while allowing natural processes to continue.

Additional References, Resources, and Websites

Marianas (Saipan) Geology

- Natural Resource Condition Assessment: Green et al. (2019)
- Geology of Saipan Mariana Islands: https://pubs.usgs.gov/pp/0280b-d/report.pdf
- Mariana Islands Water Operator Association: https://www.marianasoperators.org/marianas-geology.html
- Mindat mineralogical information: https://www.mindat.org/loc-214443.html
- Geologic map of Saipan: https://pubs.er.usgs.gov/publication/ofr20111234
- Paleontological resources of Saipan: https://pubs.er.usgs.gov/publication/pp280EJ
- Military geology of Saipan: https://irma.nps.gov/DataStore/Reference/Profile/551947

Wetland Loss

- Saipan's Watershed Working Group, part of the Division of Coastal Resources Management: https://dcrm.gov.mp/our-programs/water-quality-and-watershed-management/watershed-working-group/. This includes a watershed map viewer that contains GIS data
- NPS Water Resources Division https://home.nps.gov/orgs/1439/index.htm
- NPS Wetlands Program https://home.nps.gov/orgs/1439/wetlands.htm. This program offers wetland protection policies and procedures.
- Division of Coastal Resources Management wetlands, streams, and mangroves publication datastore: https://dcrm.gov.mp/resources-publications/wetlands-streams-and-mangroves-publications/

Saipan Coastal and Lagoon Management

- Saipan Lagoon Use Management Planning: https://dcrm.gov.mp/current-projects/saipan-lagoon-use-management-planning/
- Saipan beach erosion: https://www.arcgis.com/apps/MapJournal/index.html?appid=77f8ffb6ab2d45fba4d388b5bbc43b56
- Division of Coastal Resources Management shoreline monitoring: https://dcrm.gov.mp/our-programs/coastal-resources-%20planning/shoreline-monitoring/
- Division of Coastal Resources Management living shorelines guidebook: https://dcrm.gov.mp/living-shorelines-and-nature-based-solutions-guidebook-accessible-aug2022/
- The Nature Conservancy's living shoreline applicability index: http://www.conservationgateway.org/ConservationPractices/Marine/crr/Documents/FINAL_Applicability_Index_7_12_2017_LOCKED.xlsx?Web=1

- Sea Engineering hydrodynamic study: https://dcrm.gov.mp/wp-content/uploads/crm/25582_Hydrodynamic-Study-of-Saipans-Western-Lagoon-02-25-19.pdf
- NOAA and National Fish and Wildlife Foundation coastal resilience assessment: https://www.nfwf.org/sites/default/files/2020-08/northern-mariana-islands-coastal-resilience-assessment.pdf
- NOAA and National Fish and Wildlife Foundation coastal resilience evaluation and siting tool (CREST): https://resilientcoasts.org/#Home

Climate Change Resources

- Commonwealth of the Northern Mariana Islands climate impact viewer: https://dcrm.maps.arcgis.com/apps/MapSeries/index.html?appid=3b8d1a4b46d64586b39047f5732621cd
- Division of Coastal Resources Management - Coastal Hazards, Climate, and Shoreline Change website: https://dcrm.gov.mp/resources-publications/coastal-hazards-climate-change-and-shoreline-change/
- Intergovernmental Panel on Climate Change: http://www.ipcc.ch/
- *Global and regional sea level rise scenarios for the Unites States* (Sweet et al. 2022): https://oceanservice.noaa.gov/hazards/sealevelrise/sealevelrise-tech-report.html.
- NPS Climate Change Response Strategy (2023 Update): https://www.nps.gov/subjects/climatechange/response-strategy.htm
- NPS Green Parks Plan: https://www.nps.gov/subjects/sustainability/green-parks.htm
- NPS National Climate Change Interpretation and Education Strategy: https://www.nps.gov/subjects/climatechange/nccies.htm
- NPS Policy Memorandum 12-02—Applying NPS Management Policies in the Context of Climate Change: https://npspolicy.nps.gov/PolMemos/policymemoranda.htm
- NPS Policy Memorandum 15-01—Addressing Climate Change and Natural Hazards for Facilities: https://npspolicy.nps.gov/PolMemos/policymemoranda.htm
- NPS Sea Level Change website: https://www.nps.gov/subjects/climatechange/sealevelchange.htm/index.htm
- *Sea level rise and storm surge projections for the National Park Service* (Caffrey et al. 2018): https://irma.nps.gov/DataStore/Reference/Profile/2253283
- U.S. Global Change Research Program: http://www.globalchange.gov/home
- Weather and climate monitoring protocol for Pacific Islands Network parks: Schlappa et al. (2011)

Coastal and Terrestrial Erosion

- The US Geological Survey (2003) identified sediment delivery to coral reefs as an information need and data deficiency. The amount of sediment that reaches the ocean in

Saipan is poorly known, as is the extent to which land-use practices contribute to erosion and sediment delivery to coastal waters.

- Bush (2009) and Bush and Young (2009) provide guidance for marine and coastal monitoring.
- Dallas et al. (2012) present plans and ideas to manage beach nourishment (the practice of adding sand or sediment to beaches to combat erosion and increase beach width) projects when beach nourishment has been determined to be consistent with NPS management policies.
- Department of Homeland Security risk map, assessment, and planning program: https://opd.gov.mp/library/reports/region-9-cnmi-discovery-report-risk-map-january-2021/region-9-cnmi-discovery-report-risk-map-january-2021.pdf

Days to Celebrate Geology

- Geologist Day—the first Sunday in April (marks the end of the winter and beginning of preparation for summer field work; formally celebrated in Ukraine, Kazakhstan, Belarus, Kyrgyzstan, and Russia)
- National Cave and Karst Day—6 June, also known as International Day of Caves and Subterranean World
- International Geodiversity Day—6 October: https://www.geodiversityday.org/
- Earth Science Week—typically the second full week of October: https://www.earthsciweek.org/
- National Fossil Day—the Wednesday of Earth Science Week: https://www.nps.gov/subjects/fossilday/index.htm

Earthquakes, Tsunami, and Volcanoes

- USGS Earthquake Hazards Program unified hazard tool: https://earthquake.usgs.gov/hazards/interactive/
- Commonwealth of the Northern Mariana Islands Homeland Security and Emergency Management: http://www.cnmihsem.gov.mp/
- The Commonwealth of the Northern Mariana Islands tsunami information: https://www.tsunamizone.org/cnmi/
- US Tsunami Warning System: www.tsunami.gov
- US Geological Survey Northern Mariana hazard notifications: https://volcanoes.usgs.gov/hans2/
- NOAA Coastal Flood Exposure mapper: https://coast.noaa.gov/digitalcoast/tools/flood-exposure.html
- National Tsunami Hazard Mitigation Program: https://nws.weather.gov/nthmp/
- Satellite information, Washington VAAC http://www.ssd.noaa.gov/VAAC/washington.html

- USGS Earthquake Map Viewer: https://earthquake.usgs.gov/earthquakes/map/
- USGS Earthquake Hazard Map explanation: https://www.usgs.gov/programs/earthquake-hazards/science/earthquake-hazards-201-technical-qa#:~:text=Peak%20acceleration%20is%20a%20measure,hazard%20for%20short%20stiff%20structures

Geologic Heritage

- NPS America's Geologic Heritage: https://www.nps.gov/subjects/geology/americas-geoheritage.htm
- NPS Geoheritage Sites - Examples on Public Lands, Natural Landmarks, Heritage Areas, and The National Register of Historic Places: https://www.nps.gov/subjects/geology/geoheritage-sites-listing-element.htm
- NPS Museum Collection (searchable online database): https://museum.nps.gov/ParkPList.aspx
- NPS National Natural Landmarks Program: https://www.nps.gov/subjects/nnlandmarks/index.htm
- NPS National Register of Historic Places: https://www.nps.gov/subjects/nationalregister/index.htm
- NPS Stratotype Inventory: https://www.nps.gov/subjects/geology/nps-stratotype-inventory.htm
- UNESCO Global Geoparks: https://en.unesco.org/global-geoparks

Geologic Maps

- American Geosciences Institute (provides information about geologic maps and their uses): http://www.americangeosciences.org/environment/publications/mapping
- *General Standards for Geologic Maps* (Evans 2016)
- USGS MapView by National Geologic Map Database: https://ngmdb.usgs.gov/mapview
- USGS National Geologic Map Database: https://ngmdb.usgs.gov/ngmdb/ngmdb_home.html

Geological Surveys and Societies

- American Geophysical Union: http://sites.agu.org/
- American Geosciences Institute: http://www.americangeosciences.org/
- Association of American State Geologists: http://www.stategeologists.org/
- Geological Society of America: http://www.geosociety.org/
- US Geological Survey: http://www.usgs.gov/

NPS Geology

- NPS America's Geologic Legacy: http://go.nps.gov/geology. This primary site for information about NPS geology includes a geologic tour, news, and other information about geology in the NPS, and resources for educators and park interpreters.
- NPS Geodiversity Atlas: https://www.nps.gov/articles/geodiversity-atlas-map.htm. The NPS Geodiversity Atlas is a collection of park-specific webpages containing information about the park's geology and links to additional resources.
- NPS Geologic Resources Inventory: http://go.nps.gov/gri

NPS Reference Tools

- NPS Technical Information Center (TIC; repository for technical documents and means to receive interlibrary loans): https://www.nps.gov/orgs/1804/dsctic.htm
- GeoRef. The GRI team collaborates with TIC to maintain an NPS subscription to GeoRef (the premier online geologic citation database) via the Denver Service Center Library interagency agreement with the Library of Congress. Multiple portals are available for NPS staff to access these records. Park staff can contact the GRI team or GRD for access.
- NPS Integrated Resource Management Applications (IRMA) DataStore portal: https://irma.nps.gov/DataStore/Search/Quick. *Note*: The GRI team uploads scoping summaries, maps, and reports to IRMA. Enter "GRI" as the search text and select a park from the unit list.

Relevancy, Diversity, and Inclusion

- NPS Office of Relevancy, Diversity, and Inclusion: https://www.nps.gov/orgs/1244/index.htm
- Changing the narrative in science & conservation: an interview with Sergio Avila (Sierra Club, Outdoor Program coordinator). Science Moab radio show/podcast: https://sciencemoab.org/changing-the-narrative/

Soils

- Web Soil Survey (WSS) provides soil data and information produced by the National Cooperative Soil Survey. It is operated by the USDA Natural Resources Conservation Service (NRCS): https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm
- WSS_four_steps (PDF/guide for how to use WSS): https://irma.nps.gov/DataStore/Reference/Profile/2190427. *Note*: The PDF is contained within SRI_Detailed_Soils.zip, which also contains an index map of parks where SRIs have been completed. Download and extract all files.

USGS Reference Tools

- Geographic Names Information System (GNIS; official listing of place names and geographic features): http://gnis.usgs.gov/

- Geologic Names Lexicon (Geolex; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex
- National Geologic Map Database (NGMDB): http://ngmdb.usgs.gov/ngmdb/ngmdb_home.html
- NGMDB Geochron Downloader: https://ngmdb.usgs.gov/geochron/
- Publications Warehouse: http://pubs.er.usgs.gov
- A Tapestry of Time and Terrain (descriptions of physiographic regions; Vigil et al. 2000): http://pubs.usgs.gov/imap/i2720/
- USGS Store (find maps by location or by purpose): http://store.usgs.gov

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