National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

War in the Pacific National Historical Park

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2012/573

ON THE COVER
View of Asan Beach within War in the Pacific National Historical Park. Asan Beach was the site of the U.S. Marine Corps landing on July 21, 1944.

THIS PAGE
The park's units range from costal marine areas to beaches to dissected uplands.

National Park Service photographs courtesy Daniel A. Brown (War in the Pacific NHP).

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National Park Service
Geologic Resources Division
PO Box 25287
Denver, CO 80225

September 2012

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

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Contents

List of Figures

List of Tables

Executive Summary

This report accompanies the digital geologic map data for War in the Pacific National Historical Park in Guam, produced by the Geologic Resources Division in collaboration with its partners. It contains information relevant to resource management and scientific research. This report was prepared using available published and unpublished geologic information. The Geologic Resources Division did not conduct any new fieldwork in association with this report.

The geologic framework of Guam set the stage for the dramatic World War II stories that War in the Pacific National Historical Park commemorates. Japanese forces invaded the island in December 1941 after their attack on Pearl Harbor, Hawaii. Guam's strategic position as the southernmost and largest of the volcanic Mariana Islands, within striking distance of the Philippines, made it an important asset for Japan. The United States, just entering the war, did not immediately recognize Guam's significance. Nearly three years would pass before American forces liberated the island.

Liberating Guam proved to be a great struggle. Japanese forces took advantage of natural caves, secure water sources, highland vantage points, and local slave labor, and were well-fortified and strategically positioned when American forces first landed on the Asan and Agat beaches in 1944. Other portions of the island are rimmed with precipitous limestone cliffs, undesirable for large-scale landings. After nearly two weeks of fighting, American forces liberated Guam. Recognizing the continued strategic importance of the island, the U.S. military began large-scale development on Guam, which led to many geologic studies of the island. The hydrogeologic system was of particular interest and geologic reports assessed its capacity to provide fresh groundwater. Military and other urban development had and continues to have significant impacts on the ecosystems of Guam.

Geology is the foundation of all ecosystems, and thus influences management of the scenic, natural, and cultural resources of the park. Anthropogenic alterations to the landscape within and adjacent to the park may exacerbate or create geologic issues. Geologic issues of particular significance for resource management at War in the Pacific National Historical Park were discussed during a 2003 scoping meeting and a 2011 follow-up conference call. They include:

- Terrestrial Erosion and Coastal Sedimentation. Land-disturbing activities cause increased upland erosion that, in turn, causes increased sedimentation on the park's lagoons and reefs. Increased sedimentation can degrade or destroy the park's unique coral reefs.
- Relative Sea-Level Rise and Coastal Vulnerability. Many of the park's natural and cultural features are within a few meters of sea level and will be impacted as sea level continues to rise. Certain stretches of the park's coastline are particularly vulnerable due to factors such as coastal slope, geomorphology, and wave height.
- Adjacent Development and Disturbed Areas. Guam's long history of military installments and increasing population have led to significant land-use impacts on the island, including waste disposal sites, sewer outfalls, exacerbated erosion, off-road vehicle (ORV) use, and unexploded ordnance.
- Groundwater Withdrawal and Contamination. Groundwater is a precious commodity for the isolated island and is present primarily as a floating lens of freshwater atop saline water. Knowledge of the hydrogeologic system contributes to proper management and protection of the quality and quantity of this limited resource.
- Seismicity and Tsunamis. Guam is located along the boundary of the Pacific tectonic plate, commonly called the "Ring of Fire." The Ring of Fire is a very active, dynamic geologic setting characterized by earthquakes and volcanoes. All along the Ring of Fire, oceanic crust of the Pacific Plate is plunging—subducting—beneath neighboring plates. Guam is near the Mariana Trench, one of the most active geologic boundaries on Earth. The island thus experiences frequent, strong earthquakes and, less frequently, earthquake-triggered tsunamis. Areas underlain by artificial fill or unconsolidated sediments are particularly vulnerable to damage during an earthquake.
- Mass Wasting. Guam's upland areas are characterized by steep slopes. In areas where vegetation has been removed or slope bases have been excavated, slumps and landslides threaten park lands.
- Storm Damage. Given its tropical location, Guam is frequently in the path of large typhoons. These large storms cause extensive wind and wave damage across the island, but particularly in coastal areas.
- Radon Potential. The radioactive gas radon is naturally present in the bedrock and overlying unconsolidated material that underlie buildings and other infrastructure within the park. Radon monitoring will alert park staff to potentially harmful radon accumulations.

Guam is one of the volcanic Mariana Islands, although it is not cored by a "volcano" *per se*. The Mariana Islands' volcanoes are fueled by a boundary where the Pacific

Plate plunges beneath the Mariana Microplate and Philippine Plate along the Mariana Trench—the deepest point on Earth. The volcanic rocks on the island attest to its early history as part of this still-active island arc. Today, the volcanoes near Guam are quiet and volcanism is focused on the northern Mariana Islands. The accumulation of limestones atop the volcanic rocks on Guam began even before the islands emerged from the sea. The presence of these marine rocks atop the highest peaks of Guam attest to a long history of uplift associated with their location on the forearc bulge (east of the subduction zone) created by the convergence of the Pacific and Marianna plates. Modern carbonate sediments—which may become limestones in the future—are currently accumulating off the island's coasts. Current uplift continues to expose newly formed rocks along the shorelines.

The limestones of Guam display classic carbonate island karst features such as caves, pinnacles, and blind valleys. The limestones also form the substrate for unique ecosystems such as limestone forests. Weathering and erosion are continuously shaping the landscape within War in the Pacific National Historical Park. Guam experiences abundant precipitation that washes sediments eroded in the uplands down to the beaches and out to sea.

As described in the Geologic Map Data section, geologic maps from the 1960s were used to produce digital geologic map (GIS) data for the park. Subsequent geologic mapping (Siegrist et al. 2007) provides updated geologic interpretations. The geologic map data provide a detailed base upon which to make science-based resource management decisions within the park. Knowledge of the physical properties of the different geologic units mapped at War in the Pacific National Historical Park is important to understanding their role in park ecosystems and managing natural and cultural resources. The Map Unit Properties Table includes links to the aforementioned geologic issues, features, and processes for each mapped geologic unit. A GoogleEarth-viewable version of the map data is included in the attached CD and available online (link in the Geologic Map Data section).

The glossary contains explanations of many technical terms used in this report, including terms used in the Map Unit Properties Table. A geologic timescale is included as figure 8.

Acknowledgements

The Geologic Resources Inventory (GRI) is one of 12 inventories funded by the National Park Service Inventory and Monitoring Program. The GRI is administered by the Geologic Resources Division of the Natural Resource Stewardship and Science Directorate.

The Geologic Resources Division relies heavily on partnerships with institutions such as the U.S. Geological Survey, Colorado State University, state geologic surveys, local museums, and universities in developing GRI products.

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Introduction

This section briefly describes the National Park Service Geologic Resources Inventory Program and the regional geologic and historic setting of War in the Pacific National Historical Park.

Geologic Resources Inventory Program

The Geologic Resources Inventory (GRI) is one of 12 baseline natural resource inventories funded by the National Park Service (NPS) Inventory and Monitoring Program. The Geologic Resources Division of the NPS Natural Resource Stewardship and Science Directorate administers the GRI.

The compilation and use of natural resource information by park managers is called for in the 1998 National Parks Omnibus Management Act (section 204), the 2006 NPS Management Policies, and in the Natural Resources Inventory and Monitoring Guideline (NPS-75). Refer to the "Additional References" section for links to these and other resource management documents.

The objectives of the GRI are to provide geologic map data and pertinent geologic information to support resource management and science-based decision making in more than 270 natural resource parks throughout the National Park System. To realize these objectives, the GRI team undertakes three tasks for each natural resource park: (1) conduct a scoping meeting and provide a scoping summary, (2) provide digital geologic map data in a geographic information system (GIS) format, and (3) provide a GRI report. These products are designed and written for nongeoscientists. Scoping meetings bring together park staff and geologic experts to review available geologic maps, develop a geologic mapping plan, and discuss geologic issues, features, and processes that should be included in the GRI report. Following the scoping meeting, the GRI map team converts the geologic maps identified in the mapping plan into digital geologic map data in accordance with their data model. Refer to the "Geologic Map Data" section for additional map information. After the map is completed, the GRI report team uses these data, as well as the scoping summary and additional research, to prepare the geologic report. This geologic report assists park managers in the use of the map, and provides an overview of the park geology, including geologic resource management issues, geologic features and process, and the geologic history leading to the park's present-day landscape.

For additional information regarding the GRI, including contact information, please refer to the Geologic Resources Inventory website (http://www.nature.nps.gov/geology/inventory/). The current status and projected completion dates for GRI products are available on the GRI status website (http://www.nature.nps.gov/geology/GRI_DB/Scoping/Quick_Status.aspx).

Park Setting

Park Establishment

War in the Pacific National Historical Park was authorized by an act of Congress on August 18, 1978. Spread over seven units (Asan Beach, Asan Inland, Fonte Plateau, Piti Guns, Mt. Chachao/Mt. Tenjo, Mt. Alifan, and Agat units) on the island of Guam (fig. 1), the park commemorates the sacrifices made by American forces trying to recapture the island from the Japanese during World War II. The Asan Beach and Agat units preserve two landing sites used by American forces to retake Guam. The Fonte Plateau Unit was the site of a former Japanese naval communications center. The Piti Guns Unit preserves a highland area with three Japanese coastal defense weapons that were not operational at the time of the battle. The Asan Inland, Mt. Chachao/Mt. Tenjo, and Mt. Alifan (former command post) units preserve upland defensive positions occupied by the Japanese. The park covers 824.34 ha (2,036.98 ac), of which 405 ha (1,002 ac) are offshore, protecting submerged cultural resources and coral reef ecosystems along 5.6 km (3.5 mi) of coastline.

Guam Geography and Physiology

Guam is located approximately 13 degrees north of the equator and 5,300 km (3,300 mi) southwest of Hawaii. To the west of Guam is the Philippine Sea; to the east is the Pacific Ocean. Guam is the largest and southernmost landmass in the Mariana Islands, which include Rota, Tinian, Saipan, and Pagan, as well as numerous smaller islands. Guam is about 49 km (30 mi) long and tapers in width from 14 km (9 mi) in the north to 7 km (4 mi) in the center, then broadens to a maximum width of 19 km (12 mi) in the south. The widest point stretches from Orote Point in the west to Ylig Bay on the eastern coast. The total land area of Guam is 550 km^2 (212 mi^2). Surveys in noted the presence of 12 small limestone islands surrounding the main island of Guam, the largest of which are Cocos and Cabras islands (Tracey et al. 1959).

The landforms of northern and southern Guam differ significantly (fig. 2). Southern Guam is oriented along a north–south axis and northern Guam along a northeast–southwest axis. They are divided by the narrow central stretch between Agana and Pago Bay containing the Asan Beach, Asan Inland, Piti Guns, and Fonte Plateau units of War in the Pacific National Historical Park. The northern half of Guam is a broad, gently undulating plateau bordered by steep cliffs up to 180 m (600 ft) high. The elevation of this limestone plateau changes from approximately 180 m (600 ft) above sea level in the north

Figure 1. Map of War in the Pacific National Historical Park showing the seven park units, Apra Harbor, major rivers, and roads across central Guam. National Park Service map.

to less than 30 m (100 ft) above sea level at the narrowest point in the center of the island. Three significant peaks (Mt. Santa Rosa, Mataguac Hill, and Barrigada Hill, for which geologic map unit Tbl was named) rise above the northern plateau, with elevations reaching nearly 275 m (900 ft). These peaks featured prominently in the military history of the island.

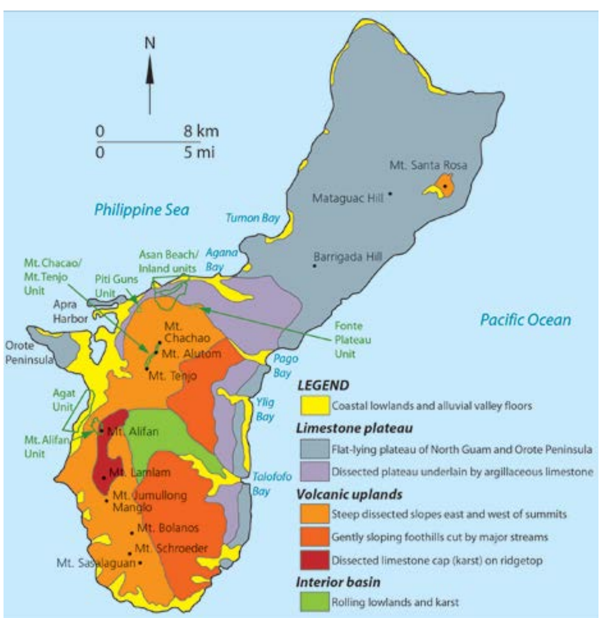

Figure 2. Map of the major physiographic regions of Guam and the seven units of War in the Pacific National Historical Park. Graphic adapted from Tracey et al. (1964a; fig. 31) by Trista L. Thornberry-Ehrlich (Colorado State University) modified by Philip Reiker (NPS Geologic Resources Division).

Southern Guam is a broad, dissected upland that has weathered and eroded into a rugged landscape of peaks, knobs, ridges, deep channels, and basin-like areas. The Agat, Mt. Alifan, and Mt. Chachao/Mt. Tenjo park units are in the northern portions of southern Guam. A nearly continuous ridge of volcanic rocks forms a spine of the island some 2–4 km (1–2 mi) inland of the western coast. This ridge stretches from the village of Piti to the southern tip of Guam. Principal peaks in southern Guam reach elevations of nearly 425 m (1,400 ft) and include, from north to south: Mt. Alutom (for which geologic map units Ta and Tam are named), Mt. Tenjo, Mt. Alifan (for which geologic map units Tal and Tt are named), Mt. Lamlam, Mt. Jumullong Manglo, Mt. Bolanos, Mt. Schroeder, and Mt. Sasalaguan. The dissected upland is bordered by a plain that rises from sea level to approximately 90 m (300 ft) on the western coast. Two prominent limestone masses, Cabras Island and Orote Peninsula, project from the plain at Apra Harbor. To the east, the upland gently slopes to a narrow limestone plateau ranging in elevation from 30 to 109 m (100–350 ft). This plateau fringes the east side of Guam from Pago Bay to Inarajan.

Within the seven units of War in the Pacific National Historical Park, elevations range from the summit of Mt. Tenjo at 315 m (1,033 ft) above sea level to the depths of offshore coral reefs at 40 m (132 ft) below sea level.

Geologic Setting

Guam is located just west of the western boundary of the Pacific tectonic plate, and is part of a feature commonly called the "Ring of Fire." The Ring of Fire is a very active, dynamic geologic setting. Earthquakes and volcanoes are common along the circumference of this ring, where the oceanic crust of the Pacific Plate is subducting beneath neighboring tectonic plates. Guam is near one of the most active geologic boundaries on Earth—the Mariana Trench. The Mariana Islands, of which Guam is a member, are an arc-shaped archipelago made up by the summits of at least 15 volcanic highs in the western Pacific Ocean on the Mariana Plate (figs. 3-5). Some of these highs are volcanoes and others are formed by uplifted volcanic oceanic crust. The very small Mariana Plate is located between the Philippine and Pacific plates. The Mariana Trough marks the divergent (spreading) western boundary with the Philippine Plate. The 2,550-km-long (1,580-mi-long) Mariana Trench marks the convergent (subducting) eastern boundary with the Pacific Plate (figs. 4, 5). The great depth of the Mariana Trench, nearly 11 km (7 mi) below the ocean's surface, makes it the lowest point on the surface of Earth's crust.

The Mariana Islands are divisible geographically, tectonically, and chronologically into an older, frontal arc (which includes Guam and the other larger, southern islands), and a younger arc of active seamounts and islands that lie to the west and north of the older arc (fig. 3) (Siegrist and Randall 1992, Barner 1995).

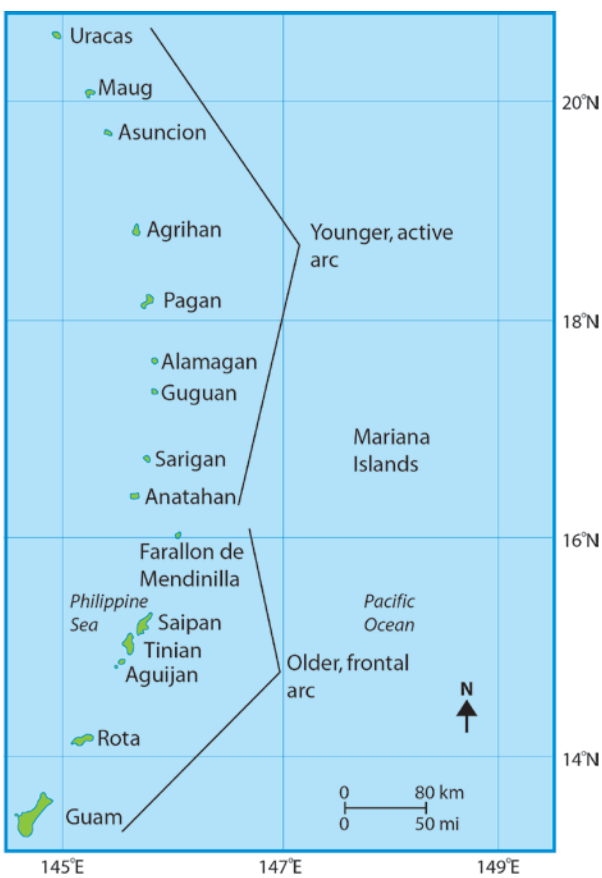

Figure 3. Map of the Mariana Islands arc in the South Pacific. Note that the younger arc is offset to the north and west relative to the older arc. Graphic adapted from Barner (1995; fig. 1) by Trista L. Thornberry-Ehrlich (Colorado State University).

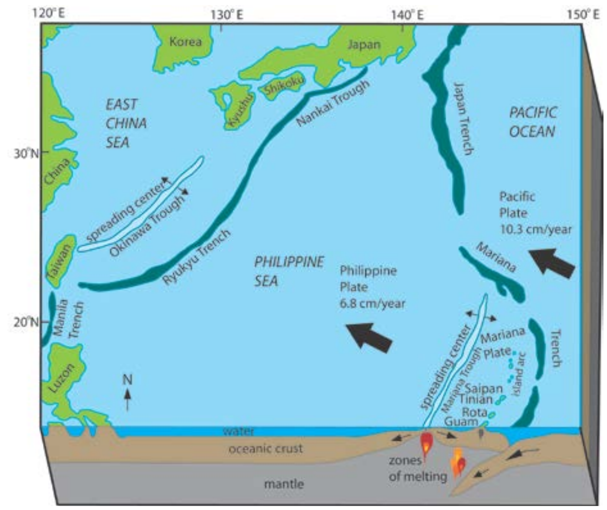

Figure 4. Map and cross-sectional view of the Mariana Trench and associated landforms in the western Pacific Ocean basin. Plate velocities are relative to the African Plate, which is assumed to be stationary. Note the location of the Mariana Microplate between the Pacific and Philippine plates. Some features have been omitted for clarity. Graphic adapted by Trista L. Thornberry-Ehrlich (Colorado State University) from Vahdani et al. (1994; fig. 1) with information from Comartin (1995).

Tracey et al. (1959, 1964a) described three principal provinces of Guam (northern, central, and southern) characterized by different geologic units, structures, and processes. The land surface within these three provinces is further divided into four principal categories: limestone plateau, dissected volcanic uplands, interior basin, and coastal lowland and valley floors (fig. 2). The Mt. Alifan, Piti Guns, Fonte Plateau, Asan Inland, and Mt. Chacao/Mt. Tenjo units of War in the Pacific National Historical Park are located within the volcanic uplands, whereas the Asan Beach and Agat units are within the coastal lowlands (Tracey et al. 1964a). Volcanic rocks and chemical sediments (limestone) are the principal rock types present on Guam. The volcanic rocks tend to be older and dominate the southern end of the island, whereas the limestones tend to be younger and reflect a marine depositional environment. Siegrist et al. (2007) provided updated stratigraphic interpretations and terminology for geologic units originally mapped by Tracey et al. (1964).

A broad limestone plateau, fringed by cliffs fronted by a narrow coastal platform, dominates the northern half of Guam. The undulating plateau tilts gently toward the southwest. According to Tracey et al. (1964b), the limestones of the Barrigada Limestone (geologic map unit Tbl) are exposed at the surface in the interior of northern Guam and grade laterally and upward into the Mariana Limestone (geologic map units beginning with QTm), which dominates the northern plateau. These limestones cover most of the older, volcanic basement rocks of northern Guam.

The central portion of the island contains volcanic rocks that have been deformed by folding and faulting (breakage with displacement along fractures). Most faults have normal offset, meaning that the hanging wall

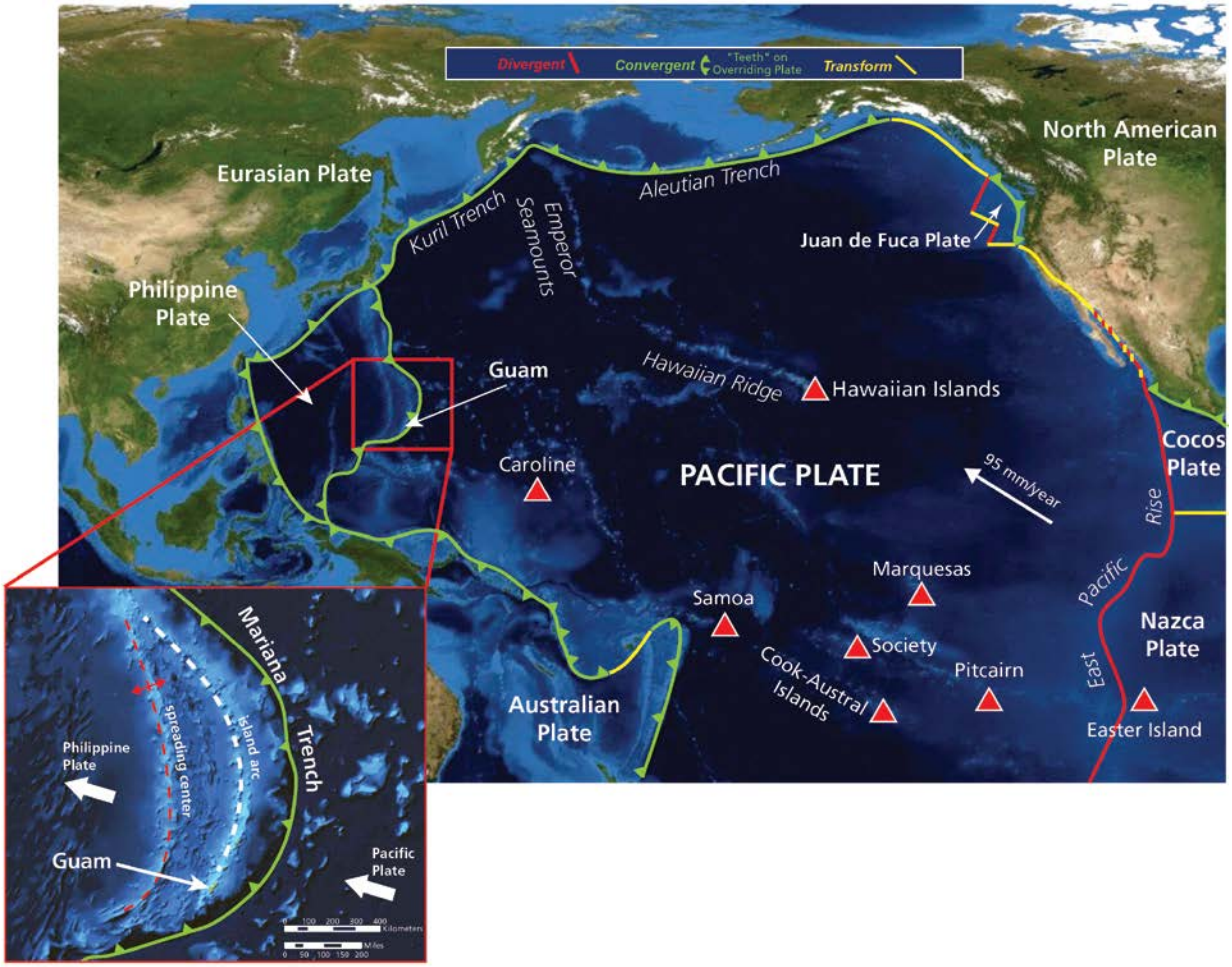

Figure 5. Tectonic setting of the Pacific Plate. This figure illustrates many of the features described in the Geologic History section. The volcanoes of the Pacific Ring of Fire are associated with subduction zones surrounding the Pacific Plate (green lines with "teeth"). Currently, the Pacific Plate is moving northwestward at a rate of about 95 mm (3.7 in) per year. The "kink" between the Emperor Seamounts and Hawaiian Islands chain shows how the direction of plate motion changed while the Hawaiian hotspot remained stationary. Selected hotspots across the Pacific Ocean are indicated by red triangles. Boundaries between plates are color coded. Plates pull apart at divergent boundaries (red), come together at convergent boundaries (green; green triangles indicate overriding plate at subduction zone), and slide past one another at transform boundaries (yellow). Compiled by Jason Kenworthy (NPS Geologic Resources Division) from ESRI Arc Image Service Imagery Prime World 2D, with information from Clouard and Bonneville (2001; fig. 2).

is displaced downward with respect to the footwall. This offset has resulted from varying degrees of uplift and crustal flexure since Guam's formation. The Pago-Adelup Fault (see fig. 23), in which the northern block is downthrown relative to the southern block, is the most prominent of these fractures.

The volcanic rocks of southern Guam show less deformation, with fewer through-going faults and fractures, than those of central Guam. This rugged highland comprises mixed volcanic and sedimentary rocks with occasional limestone units (the Maemong Limestone Member of the Umatac Formation, geologic map unit Tum); limestone outliers are found predominantly in coastal areas. Locally, the Bonya and Alifan limestones (geologic map units Tb and Tal) mantle the older, volcanic-rich rocks. Mariana Limestone exposures occur along the eastern coast of southern Guam, and minor outcrops of Janum and Merizo limestones (geologic map units Tj and Qrm) occur in several coastal areas.

Coastal areas of Guam are characterized by beaches and rocky cliffs. Rocky cliffs are common along the northern coast, with narrow fringing reefs at some cliff bases. In western Guam, shallow embayments contain beaches, reefs, reef-like volcanic platforms, and lagoonal areas (Randall 1979).

Cultural History

Guam has a rich history prior to the World War II stories commemorated by War in the Pacific National Historical Park. The earliest human inhabitants, ancestors of the Chamorro people, established an agrarian society on Guam between 3000 and 2000 B.C.E. (Before Common Era; preferred to "BC"), probably arriving from Southeast Asia. Pottery shards and other archaeological artifacts are found within the park (M. Gawel and J. Oelke, War in the Pacific National Historical Park staff, email communication, July 2, 2012). Following European discovery by Magellan in 1521 during the Pacific crossing, Guam was visited by a host of European explorers until the establishment of a Spanish colony in 1668 (Comartin 1995, Rogers 1996, National Park

Service 2011). Many of the Spanish-era homesteads were disrupted during World War II; however, it is ethnographically recorded that the Asan Beach area has been continually inhabited since the island was discovered by the original indigenous Chamorro settlers (M. Gawel and J. Oelke, email communication, July 2, 2012).

In 1892, Asan Beach was established as a settlement for sufferers of Hansen's disease (leprosy). Similar to the settlement for individuals with this disease at what is now Kalaupapa National Historical Park in Hawaii (Thornberry-Ehrlich 2010), the site was chosen for its warm climate and isolated location. The settlement was destroyed by a typhoon eight years later. The Treaty of Paris, which ended the Spanish-American War, granted Guam to the United States as a colony in 1899 (Tracey et al. 1959, Rogers 1996, National Park Service 2011). In 1901, the Asan Beach area became an American prison camp for exiled Filipino insurrectionists who believed that the United States should not take over the Philippines.

During World War I, the United States used Asan Point as a prisoner of war camp. After the war, the U.S. military continued to use Asan Point as a Marine Corps camp. However, the perception that the island was indefensible and of little strategic importance led to its demilitarization in 1931 (Rogers 1996, Rottman 2004, National Park Service 2011). Between the two world wars, Guam served as a commercial airline stop and the public infrastructure and services available on the island began to develop (Comartin 1995).

Although not appreciated by the U.S. military, the strategic importance of Guam as an access point to the Philippines and part of a vital sea route was not overlooked by the Japanese military. In December 1941, just after Japan attacked Pearl Harbor, Japanese troops quickly forced U.S. Marines and Chamorro military personnel to surrender the island (Rottman 2004, National Park Service 2011). The Japanese forced the Chamorro population into work camps to construct much of the island's military infrastructure and defenses. Airfields, roads, caves and modified caves, trenches (e.g. Mt. Alifan and Mt. Chachao/Mt. Tenjo units), pillboxes (dug-in concrete guard posts), gun emplacements (e.g. Piti Guns and Ga'an Point, Agat Beach units), and tank traps throughout the park attest to the military importance of the island to the Japanese (National Park Service 2011). The island was held by the Japanese for nearly three years, until June 1944. After initially bombing Asan and Agat beaches on June 16, 1944, the assault by U.S. armed forces to retake Guam was delayed until July 21, 1944 (fig. 6). Japanese coastal defenses were strong, consisting of obstacles and mines on the fringing reef, obstacles and tank traps on the beaches, and gun positions, pillboxes, heavy weapons, artillery, and coastal defense guns further inland. The high vantage points inherent to Guam's landscape, including strongholds at Adelup Point, Chorrito Cliff, Bundchu Ridge, Fonte Plateau, and Mt. Tenjo, allowed Japanese machine guns, heavy weapons, and artillery to fire upon the beaches below at Asan and Agat (Rottman 2004, National Park Service 2011). Fortunately for American troops, the guns at the heights of Piti were not operational at the time of the invasion (fig. 7).

The early goal for U.S. forces was to take possession of the inland high ground to ensure a safe beach below for the unloading of supplies and additional troops. U.S. Marines assaulted beaches, captured Orote Peninsula (important for its airfield and entrance to Apra Harbor as a supply port), and the land behind Asan Village, and established what the invasion commanders called the "Force Beachhead Line" from Adelup Point to Mt. Chachao/Mt. Tenjo. The U.S. Army troops fought in Agat Village, captured Mt. Alifan, and established their part of the Force Beachhead Line from Facpi Point to Mt. Tenjo, where it connected with the line established by the Marines (fig. 6). The Asan Beach area was secured by July 28, but predominantly northeastward movements did not succeed in eliminating organized Japanese resistance on the rest of Guam until August 10, 1944, when the island was declared "liberated."

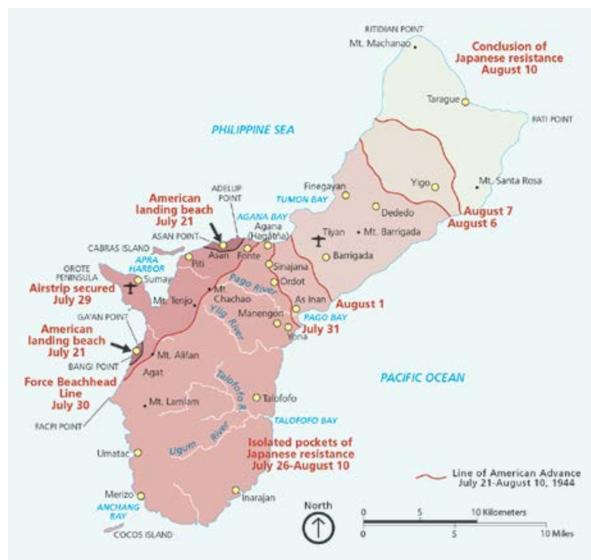

Figure 6. Map of Guam showing the progression of American forces in 1944. National Park Service map.

Of the approximately 55,000 U.S. Marine and Army soldiers who invaded Guam, an estimated 2,124 were killed in action or died of wounds sustained there (Rottman 2004, National Park Service 2011). More than 10,000 Japanese troops died on the island. Following the liberation of Guam, the U.S. Navy undertook reconstruction of much of the badly damaged infrastructure. Memorials at the Asan Beach and Asan Inland units tell the story of the battle sacrifices here. Guam also served as the staging ground for the final chapter of combat in the Pacific Theater. At U.S. headquarters on the hill above Agana, Admiral Chester W. Nimitz ordered the fateful bombing of Hiroshima and Nagasaki—the decisive blow to force Japan's surrender (Comartin 1995, Rogers 1996, Rottman 2004).

Figure 7. A Japanese gun at Piti Guns Unit perched above the landing beaches below as an example of defensive fortifications built by the Japanese. The guns were not operational at the time of the 1944 U.S. invasion of Guam. Note the steep slopes and pervasive vegetation surrounding the gun and visitor trail. National Park Service photograph by Deanna Greco (Grand Canyon NP), 2003.

The history commemorated at War in the Pacific National Historical Park does not end with World War II. Following the end of the war in 1945, Asan Beach became Camp Asan, the headquarters and barracks for U.S. Navy Seabees assigned to help reconstruct the island's infrastructure.

After 1948, it was used as a civil service camp until 1967, when the buildings were converted into a hospital annex for use during the Vietnam War. In 1975, this location served as a Vietnamese refugee camp, hosting as many as 111,000 people who were transferred through Guam by U.S. military cargo ships on their flight from Vietnam primarily to the refugee centers in the United States. In 1976, Supertyphoon Pamela destroyed the remaining buildings at Asan Beach, which was cleared by the U.S. Navy prior to its transfer to the NPS.

On July 21, 1950, Guam became an unincorporated territory of the United States. However, access to Guam was largely restricted for reasons of military security until 1962, when it was re-opened for commerce (Rogers 1996). The island's economy and population grew slowly but steadily until the Asian expansion of the 1980s brought economic investment. In addition to the continued and growing U.S. military presence on the island, tourism is a leading industry and the island receives over one million visitors per year (Mylroie et al. 2001). More than 482,000 people visited War in the Pacific National Historical Park in fiscal year 2011.

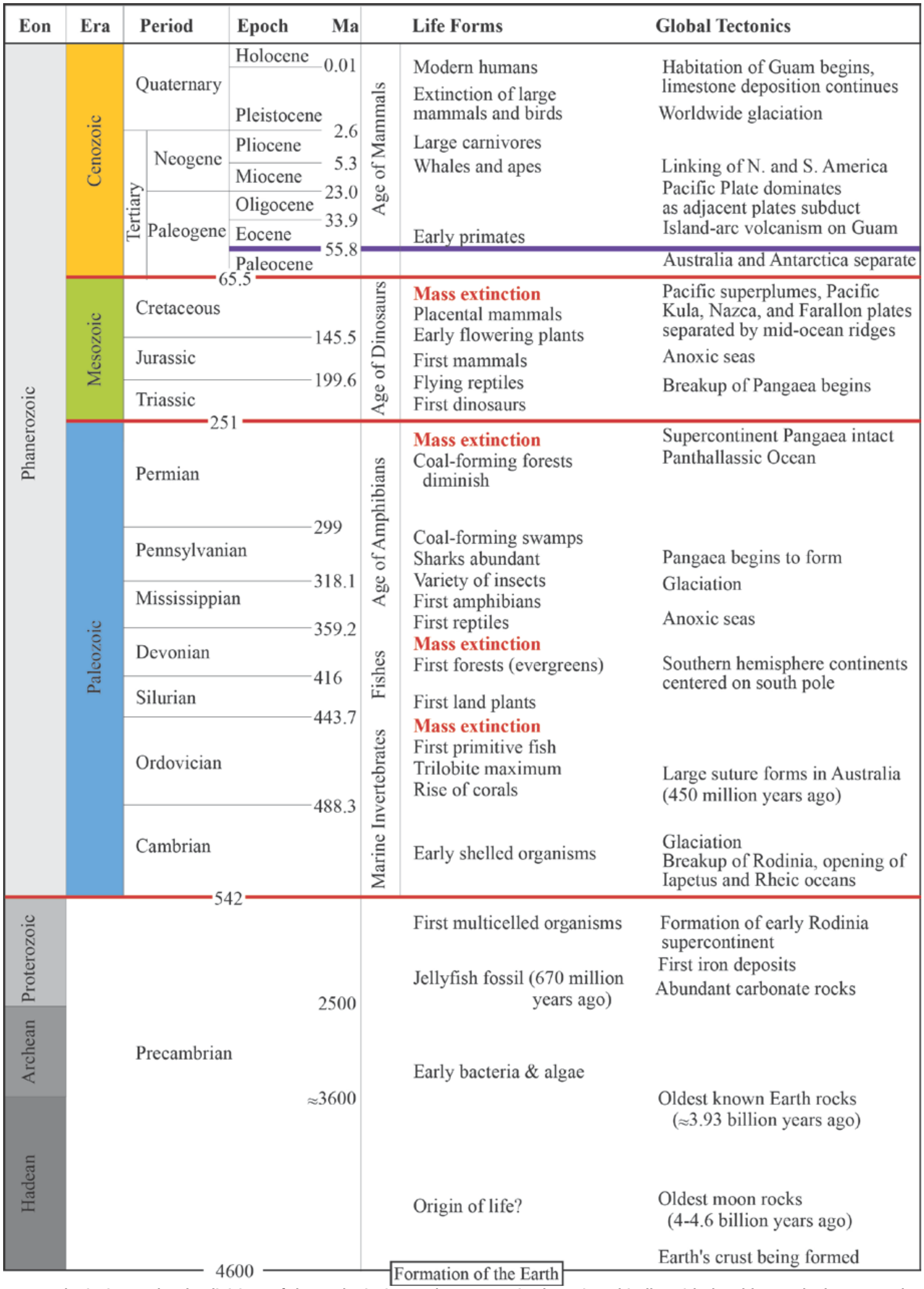

Figure 8. Geologic time scale. The divisions of the geologic time scale are organized stratigraphically, with the oldest at the bottom and youngest at the top. Boundary ages are in millions of years (Ma). Major life history and tectonic events occurring in the Pacific Basin continent are included. Purple line marks the inception of subduction and volcanism in the Guam region. Red lines indicate major boundaries between eras. Graphic design by Trista Thornberry-Ehrlich (Colorado State University), adapted from geologic time scales published by the U.S. Geological Survey (http://pubs.usgs.gov/fs/2010/3059/) and the International Commission on Stratigraphy (http://www.stratigraphy.org/ics%20chart/09_2010/StratChart2010.pdf) with additional information from Condie and Sloan (1998).

Geologic Issues

The Geologic Resources Division held a Geologic Resources Inventory scoping session for War in the Pacific National Historical Park on March 20–21, 2003, and a follow-up conference call on March 2, 2011, to discuss geologic resources, address the status of geologic mapping, and assess resource management issues and needs. This section synthesizes those discussions and highlights particular issues that may require attention from resource managers. Contact the Geologic Resources Division for technical assistance.

Resource managers at War in the Pacific National Historical Park face geologic issues stemming from natural and anthropogenic factors, including:

- terrestrial erosion and coastal sedimentation,
- relative sea-level rise and coastal vulnerability,
- adjacent development and disturbed areas,
- groundwater withdrawal and contamination,
- seismicity and tsunamis,
- mass wasting,
- storm damage,
- visitor center stability, and
- radon potential.

These issues were identified during the scoping meeting (March 20–21, 2003), a post-scoping follow-up conference call (March 2, 2011), and post-scoping research. Rutherford and Kaye (2006) have provided an overview of geologic issues facing all parks in the NPS Pacific Island Network, including War in the Pacific National Historical Park.

The NPS Geologic Resources Division initiated and funded the development of *Geological Monitoring* (Young and Norby 2009; http://nature.nps.gov/geology/monitoring/index.cfm) to provide guidance for resource managers seeking to establish the status and trends of geologic resources and processes within the National Park System, and to advance the understanding of how geologic processes impact ecosystem dynamics. The manual 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, including expertise, personnel, and equipment needed; approximate cost; and labor intensity.

Terrestrial Erosion and Coastal Sedimentation

Extrapolating from limited natural resource inventories, NPS personnel have estimated that more than 3,000 species of corals, reef fish, algae, and invertebrates thrive within War in the Pacific National Historical Park (National Park Service 2002; M. Gawel, Integrated Resources Manager, War in the Pacific NHP, email communication, April 11, 2011). Guam's coral reefs exhibit the highest biodiversity among reefs in the United States, and some species and marine habitats in Guam are found nowhere else within the United States and its territories (M. Gawel, email communication, April 11, 2011). Coral reefs on Guam are vulnerable to sea-level rise, storm damage, increased water temperatures, coral diseases, and surface runoff and sedimentation (Pendleton et al. 2005). Coastal vulnerability and relative sea-level rise, as well as storm damage, are further described in subsequent sections.

The coastal areas of War in the Pacific National Historical Park are not eroding considerably; however, steep slopes in other units, including Asan Inland, Mt. Alifan, Mt. Tenjo, and Fonte Plateau, are prone to erosion during heavy precipitation events (fig. 9). Slopes are particularly vulnerable to erosion when stabilizing vegetation is disturbed by fire (up to 20% of the forested terrain in the park is burned intentionally each year), grazing, and ORV use (Daniel 2006; M. Gawel and B. Alberti, Superintendent, War in the Pacific NHP, conference call, March 2, 2011).

Figure 9. Upland area at War in the Pacific National Historical Park. Note slumps and erosion marked by fresh exposures of orange soils (yellow arrows) and precipitously steep slopes. National Park Service photograph by Deanna Greco (Grand Canyon NP), 2003.

Coastal development and poor land-management practices (agriculture, feral grazing, forest clearing and burning) adjacent to park units have created a significant erosion problem, ultimately leading to high sedimentation on the park's reefs (National Park Service

2002, Storlazzi et al. 2009; M. Gawel and B. Alberti, conference call, March 2, 2011). Between June 2003 and May 2005, four fires burned approximately 9% of park lands and subsequent erosion from burned areas was nearly six fold higher than continuously vegetated savanna; sedimentation collection rates were among the highest on record (Minton 2006). Increased sedimentation will cause immediate death of corals by smothering or blocking light, or reduce biodiversity as some coral and algae species may grow faster than others to keep pace with sedimentation (National Park Service 2002). As of 2012, anticipated coral death strictly from sedimentation is not clear or recently measured (M. Gawel and J. Oelke, War in the Pacific NHP, email communication, July 2, 2012).

The U.S. Geological Survey measured coastal circulation and sediment dynamics in War in the Pacific National Historical Park to determine their influence on the health and sustainability of the coral reef ecosystem (Storlazzi et al. 2009). The survey found that reef morphology and resultant interactions with ocean currents dictate whether sediment is pushed off the reef or accumulated onto it in an eddy. After precipitation events, plumes of terrestrial sediment (often with nutrients, bacteria, and pesticides adsorbed to particles) flow out to sea and collect on the reef and forereef. This accumulation is particularly apparent where the Asan Watershed drains into the Asan Marine Unit (Minton et al. 2007; M. Gawel and B. Alberti, conference call, March 2, 2011). A large quantity of terrestrial sediment accumulates on the forereef, but sedimentation is not burying the elevated reef (Minton et al. 2007, Storlazzi et al. 2009). Currents within Asan Bay transport vast amounts of terrestrial sediment offshore, away from the reef and forereef; however, a particularly large sediment input followed by transient low-energy conditions could cause harmful build-up of sediment in the bay (Storlazzi et al. 2009).

In addition to increased terrestrial erosion, coastal shipping might also contribute to sedimentation and pollution, further threatening the island's coral reefs. Guam has been a major shipping center in Micronesia for approximately 400 years, but the potential pollution of Guam's coastal waters and sediments by harbor activities has been considered only in the past 20–30 years (Denton et al. 2005). Denton et al. (2005) performed a trace metal in sediment study in four harbors: Agana Boat Basin, Outer Apra Harbor, Agat Marina, and Merizo Pier. They found enrichment of many trace metals (e.g., silver, arsenic, cadmium, chromium, copper, mercury, nickel, lead, zinc, and tin) at some sites at Apra Harbor, Agana Boat Basin, and Merizo Pier, and relatively little enrichment at Agat Marina (Denton et al. 2005). Sediments circulating in this system could be accumulating on coral reefs or be further disturbed during high-energy events, such as typhoons.

In the marine monitoring chapter of *Geological Monitoring*, published by the Geological Society of America in cooperation with the NPS, Bush (2009) suggested five "vital signs"(or measurable parameters of the overall condition) for monitoring marine features and processes: 1) the general setting of the environment, of which water depth is the primary indicator; 2) the energy of the environment, waves, and currents; 3) barriers, including reefs and other offshore barriers, which block energy; 4) seafloor composition, or substrate; and 5) water column turbidity. That publication includes detailed recommendations and methodologies for resource managers. These kinds of data are important as development surrounding the park continues (see "Adjacent Development and Disturbed Areas" below).

Relative Sea-Level Rise and Coastal Vulnerability

Rising sea level is a major concern at War in the Pacific National Historical Park, where information is lacking about local sea-level changes in the Mariana Islands (M. Gawel and B. Alberti, conference call, March 2, 2011). Rising seas have the potential to increase shoreline erosion, cause saltwater intrusion into groundwater aquifers, inundate coastal wetlands and estuaries, and threaten the park's cultural resources and infrastructure (Pendleton et al. 2005). Global sea-level rise is related to climate change. Projections of sea-level rise associated with climate change vary widely depending on location and future emissions scenarios. Globally, at least 0.18–0.59 m (7 in. to 2 ft) of sea-level rise is projected by 2100 (IPCC 2007, Meehl et al. 2007). Because Guam is a tectonically active island, periods of uplift and subsidence create local, relative sea-level changes that overprint or may even run counter to global trends. Uplift can lower relative sea level around the island (Mylroie et al. 2001). According to unpublished information provided by the Water and Environmental Research Institute (WERI), University of Guam, sea level has risen more rapidly relative to the island of Guam than in the greater Pacific in the last 10 years (M. Gawel and B. Alberti, conference call, March 2, 2011). Glacioeustasy (change in global sea level due to storage or release of water in glacial ice) and tectonic uplift have produced cliffs with numerous exposed notches, caves, and cave remnants (Reece et al. 2000). As described in the "Geologic Features and Processes" section, the geologic units and karst features dissolved into the limestones of Guam record a history of sea-level change for the island.

The U.S. Geological Survey (Pendleton et al. 2005) created a map of relative vulnerability to future sea-level rise of more than 11 km (7 mi) of the coast within War in the Pacific National Historical Park using a coastal vulnerability index (CVI) (fig. 10). The CVI ranks the following geologic and physical process factors in terms of their contribution to sea-level rise–related coastal change: geomorphology, regional coastal slope, rate of relative sea-level rise, historical shoreline change rates, mean tidal range, and mean significant wave height. Within the park, the most influential variables in the CVI are geomorphology, regional coastal slope, and wave energy (Pendleton et al. 2005). The CVI and raw data used for the analysis emphasize regions where the impacts of sea-level rise might be the greatest, and provides an evaluation tool and baseline information for park resource managers (Pendleton et al. 2005). Within the park, areas of unconsolidated sediment where coastal

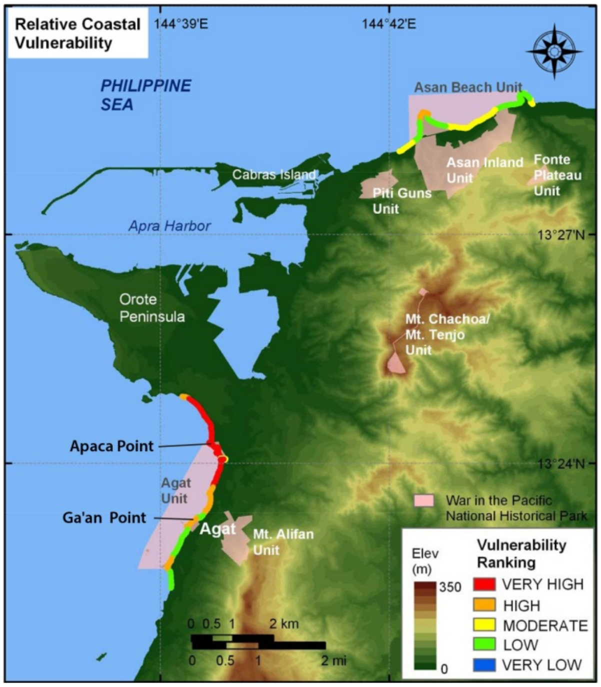

Figure 10. Map of relative coastal vulnerability for War in the Pacific National Historical Park. This map represents compiled vulnerability determined from six variables: geomorphology, shoreline change, regional coastal slope, relative sea-level rise, mean significant wave height, and mean tidal range. Maps for each of the variables are included in Pendleton et al. (2005). Note the area of very high vulnerability within the Agat Unit. U.S. Geological Survey graphic from Pendleton et al. (2005; fig. 11).

slope is low and wave energy is high, such as the sandy areas of the Agat Unit, are most vulnerable to sea-level rise. The beaches south of Apaca and Ga'an points exemplify the approximately 26% of shoreline considered to be very highly vulnerable to future sea-level rise. Apaca Point is an example of the 20% of shoreline classified as highly vulnerable. The remaining 54% of the park's shoreline was mapped as having moderate (20%) or low (34%) vulnerability.

Rubbly/rocky shorelines and sandy beaches, both with fringing reefs, are two shoreline geomorphologies that may be particularly vulnerable to rising seas. Both types of shoreline exist within the park. Measured shoreline change rates show some erosion along Asan Beach and in other sandy areas, but virtually no erosion in rocky (non-beach) portions of the coastline. The CVI for regional coastal slopes locally exceeded 14.7%, and the range of slopes within the park fell within the very low to very high vulnerability categories; steeper coastal slopes were generally less vulnerable to the negative impacts of sea-level rise (Pendleton et al. 2005). These types of studies provide guidance to target geographic areas for site-specific monitoring.

Among the monitoring targets related to climate change of interest to park managers are local sea-level rise, oceanic acidification, and vulnerability of coastal, cultural, and /or submerged resources (M. Gawel and B. Alberti, conference call, March 2, 2011). The Micronesian Area Research Center (MARC) of the University of Guam is conducting ongoing vulnerability assessments for coastal cultural resources and submerged resources at War in the Pacific National Historical Park and American Memorial Park on Saipan (as of 2012, contact Dr. John Peterson and Dr. Steve Acabado). This work is expected to become part of the park's GIS in 2012 (M. Gawel and B. Alberti, conference call, March 2, 2011). The park is currently awaiting the results of the University of Guam study, but has no plans for structural measures to curb sea level rise, preferring instead to plan new facilities set back from projected sea level inundation areas (M. Gawel and J. Oelke, email communication, July 2, 2012).

The NPS established the Climate Change Response Program (http://www.nature.nps.gov/climatechange/index.cfm) to facilitate scientific mitigation, adaptation, outreach, and education regarding climate change throughout the park system. War in the Pacific National Historical Park managers are currently collecting ideas for the Pacific Islands Climate Change Cooperative (PICCC)—an applied conservation science partnership located in Honolulu, Hawaii, and formed by the NPS, National Oceanographic and Atmospheric Administration, U.S. Fish and Wildlife Service, U.S. Geological Survey, and others to address climate change and other landscape-scale change events throughout U.S. territories in the Pacific. Schramm and Loehman (2011) have compiled talking points regarding climate change impacts to the Pacific Islands.

Adjacent Development and Disturbed Areas

The park boundary has not been accurately marked or surveyed, leading to development issues with adjacent landowners (M. Gawel and B. Alberti, conference call, March 2, 2011). Because of poorly planned and outdated zoning regulations on Guam, industrial, commercial, and residential developments are encroaching on park boundaries, and some have crossed onto park lands (Daniel 2006). Due to the lack of a Seashore Protection Plan and an updated Master Land Use Plan (current regulations are based on the 1966 Guam Land Use Plan), regulations overseeing development along the coast are incomplete. Marine Corps Drive runs only a few meters from the water's edge, and buildings have been constructed along the coast, many contacting the ocean on the seaward edge of seawalls. Ongoing development in the upland areas above the Asan and Agat beach units has taken advantage of weakly enforced anti-erosion regulations, and threatens water quality and offshore resources (Daniel 2006).

U.S. military plans call for the stationing of approximately 4,500 Marines in a new base to be created, in addition to the creation of a U.S. Army air and missile defense task force. Construction of new facilities to accommodate them, as well as a berth for aircraft carriers at Apra Harbor, will fuel much development across the island and adjacent to park areas (M. Gawel, email communication, April 11, 2011). U.S. military plans to restructure and increase installations on Guam may involve encroachment on park lands, given the lack of available land in some stretches to add road lanes, training areas, or stormwater management structures (Daniel 2006; M. Gawel and B. Alberti, conference call, March 2, 2011). The U.S. Navy created a website to provide information about the expansion and associated environmental impacts (http://www.guambuildupeis.us/). The following issues are not all tied to the military expansion, but may be exacerbated as Guam's population continues to increase. An accurately mapped and enforced park boundary, a robust seashore protection plan, and continuous cooperation and communication with surrounding landowners (including the U.S. Military) may help curb some of the effects from adjacent land use.

Landfills

Human activities have been changing the landscape of Guam since the first inhabitants settled on the island more than 3,000 years ago. Development leading up to, during, and after World War II has dramatically altered the island. Artificial fill (geologic map unit Qaf) created new land areas, often using material dredged from adjacent harbors. Sinkholes formed in the island's limestone have been filled or used as dumps. At least 45 waste disposal sites exist at Andersen Air Force Base and the Guam Naval Complex, some of which are natural sinkholes (Finley 1987, Boudreau et al. 2002). One such sinkhole site is the 3.8-ha (9.4-ac) Orote Landfill in the Apra Harbor Naval Complex on Guam. This landfill, used from 1944 to 1969, filled a sinkhole with residential, commercial, and industrial waste including construction debris, asbestos, paints, and other municipal wastes (Boudreau et al. 2002). The seaward edge of this landfill has been eroding since 1990, and landfill waste is washing up on adjacent beaches (Boudreau et al. 2002). These issues prompted a U.S. Navy project to assess the magnitude of the contamination and to construct a seawall of large concrete cubes over an impermeable lining to prevent future erosion of landfill materials into the beach and marine environment (Boudreau et al. 2002).

Soil Degradation

The geologic framework is intimately tied to soil formation and overall ecosystem health. Different bedrock lithologies weather to different soil compositions; bedrock features such as permeability and porosity contribute to soil drainage. Anthropogenic activities may also impact soils. Forest clearing in southern Guam caused significant increases in soil temperature (more than 0.7°C) (Neubauer 1981). A 1998 soil study (Motavalli and McConnell 1998) targeting the effects of land use in Guam indicated that continued soil disturbance increases soil bulk density and soil pH while lowering water-holding capacity, organic carbon, total nitrogen, and nitrogen mineralization in comparison with forest soils. These data trigger concern about the potential for groundwater pollution.

The NPS Geologic Resources Division completed a soil resources inventory for War in the Pacific National Historical Park and may be consulted for further recommendations to help stop soil degradation (National Park Service 2007).

Sewer Outfalls

Several abandoned post-war (ca. 1945) sewer outfall pipes exist within the park and are visible at low tide. They extend across shallow fringing reefs at Asan Beach, Agat Beach (near Ga'an Point), on the west side of Adelup Peninsula, and at the Japanese pier at Adelup Point (used during the Japanese occupation and shortly thereafter) (figs. 11 and 12) (M. Gawel, email communication, April 11, 2011). The outfall pipe at Agat Beach, used by the Guam Government during the 1970s and 1980s, is now broken and falling into the water. The 65-m-long (215-ft-long) Asan Beach outfall—unused since the mid-1970s—is intact and supported by approximately 27 concrete block pylons.

Figure 11. Exposed sewage outfall at Asan Beach Unit. National Park Service photograph by Deanna Greco (Grand Canyon NP), 2003.

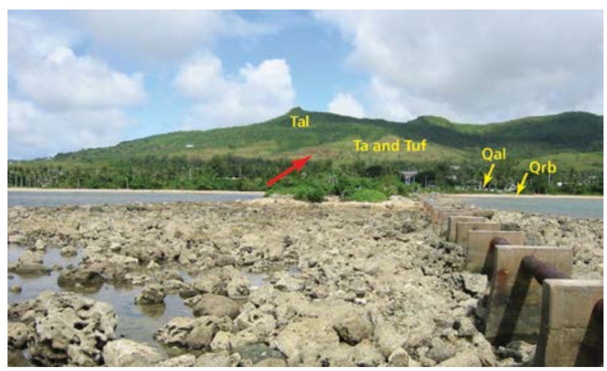

Figure 12. Sewage outfall at Ga'an Point, looking landward (east) at low tide toward the Mt. Alifan Unit. Disturbed orange areas on the cliffs are noted by the red arrow. Approximate locations of geologic units are noted in yellow text. Beach deposits (Qrb) are located at the beach, alluvium (Qal) is located inland of the beach deposits, the Alutom Formation and Facpi Volcanic Member of the Umatac Formation (Ta and Tuf) make up the lower slopes, and the Alifan Limestone (Tal) caps Mt. Alifan. National Park Service photograph by Deanna Greco (Grand Canyon NP), 2003.

War in the Pacific National Historical Park submitted a funding proposal (National Park Service 2003) to remove this outfall or convert it to a boardwalk, but the project was not funded. Although the outfall pipes no longer transport sewage into the reefs, their continued impact on the marine and nearshore environment is unknown. At minimum, they pose a safety threat to visitors, who may attempt to climb on them. Removal of the pipes may be undesirable because it could further impact coral resources. After more than 60 years, they are part of the area's history, and corals and other marine species use them as artificial reefs (M. Gawel and B. Alberti, conference call, March 2, 2011).

Two active sewage treatment plant outfall pipes on Guam—outside of the park—were more recently constructed to emerge at depth, thereby avoiding the destruction of surface pipes in shallow water by waves. These pipes were drilled through coral reefs. One is maintained by the U.S. Navy in northern Agat Bay, offshore of the Orote Peninsula. The original outfall in this area, a surface pipe like those in the park, was destroyed by a typhoon more than 30 years ago and was reconstructed in the 1980s to discharge at a depth of about 37 m (120 ft). The Hagatna Sewage Treatment Plant, located in Agana Bay, completed a new discharge pipe in 2009 at a depth of 85 m (280 ft). Though not within the park, these outfalls may affect park reefs (M. Gawel, email communication, April 11, 2011). Cooperation and communication with local and military entities is important to mitigate impacts of old or new outfalls.

Off-Road Vehicle Use

As mentioned in other "Geologic Issues" sections, ORV and mountain bicycle use exacerbates upland erosion that, among other issues, contributes increased sediment to the park's coastal waters. Erosion leads to the formation of "badlands" as soil is scoured from the surface, leaving broad, undulating, unvegetated areas (M. Gawel and B. Alberti, conference call, March 2, 2011). ORVs have disturbed much of the remote Mt. Tenjo Unit between Mt. Chaochao and Mt. Tenjo (Hess and Pratt 2006). Although this unit is located within the legislated boundary of War in the Pacific National Historical Park, the NPS does not own the land. Therefore, it is neither developed nor managed for visitor use. However, park managers are aware of the erosion issue and periodically assess the extent of erosion. Public outreach and education programs may help to stem this recreational vehicle use.

Ouren et al. (2007) prepared a report detailing the environmental impacts of ORV use on Bureau of Land Management lands within the continental U.S., including effects on soils and watersheds, vegetation, wildlife and habitats, water quality, and air quality. They also discussed the socioeconomic implications of ORV use. Their report describes potential indicators for evaluating and monitoring ORV effects, as well as mitigation and site-restoration techniques. This document could serve as a resource in developing ORV management strategies.

Unexploded Ordnance

Following the World War II battles, much unexploded ammunition remained on the island and is associated with various geologic resources in War in the Pacific National Historical Park. Caves in the uplands may still house stockpiled Japanese ordnance. An ammunition dump site was located at the culturally significant Camel Rock. These sites pose a serious safety threat to park visitors, staff, and infrastructure. Unexploded ordnance still washes up on park beaches, usually after a large wave event such as a typhoon (M. Gawel and B. Alberti, conference call, March 2, 2011). A contractor completed a study and report for the U.S. Navy regarding unexploded ordnance that washes up on the shallow reef flat at Asan (Naval Facilities Engineering Command, Pacific 2011). As of 2012, after attempts with partners such as the Environmental Protection Agency to obtain Department of Defense support of the removal of submerged unexploded ordnance, the military claims no responsibility for removing material originating in a war area not owned by the Department (M. Gawel and J. Oelke, email communication, July 2, 2012). The park is anticipating the results of a study of toxic chemicals from submerged unexploded ordnance in 2013. This study will detail the risk to environmental and human health from unexploded ordnance in the shallow reefs of Guam (M. Gawel and J. Oelke, email communication, July 2, 2012).

Groundwater Withdrawal and Contamination

Due to its isolated location and small size, Guam has limited groundwater resources. Historically, these resources have been the subject of much study. Groundwater resource management requires an understanding of hydrogeologic system characteristics, including the freshwater aquifer, types of discharge, recharge issues associated with the limestone karst landscape, and contamination potential in areas of development.

In 1937, U.S. Geological Survey geologist Harold T. Stearns conducted a two-month study of Guam's water resources (Tracey et al. 1959). In 1945, shortly after the island was liberated, a U.S. Naval Reserve officer studied the potential for extensive groundwater development on the island (Abplanalp 1945). In 1964, the Government of Guam established a policy of sourcing drinking water from the limestone aquifers of northern Guam. Studies such as those by Mink (1976), Goodrich and Mink (1983), and Contractor and Jenson (2000) employed techniques such as drilling, seismic surveys, and computer modeling to understand the hydrogeologic framework of Guam and predict sustainable water production (yield). The U.S. military commissioned groundwater studies to understand the potential contamination hazards from various trenches, borrow pits, quarries, and sinkholes that have been used for waste disposal (Barner 1995, Boudreau et al. 2002). To date, models cannot fully account for the differences between simulated and observed groundwater phenomena (Contractor and Jenson 2000). Mink and Vacher (1997) summarized the results of previous studies of the northern aquifer, and a short description is presented below.

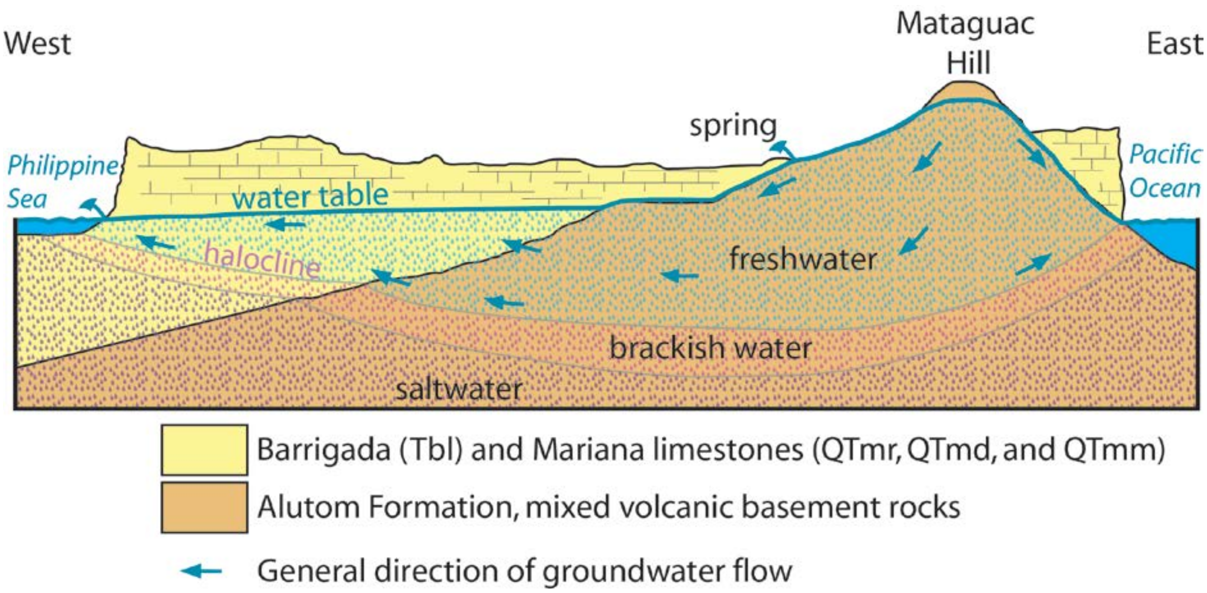

Figure 13. Cross-sectional view through the freshwater lens within limestone and volcanic bedrock of northern and central Guam. Figure shows the example of Mataguac Hill, located northeast of War in the Pacific National Historical Park, but similar settings exist within the park. Vertical scale is exaggerated. Graphic adapted from Gingerich (2003) by Trista L. Thornberry-Ehrlich (Colorado State University).

Guam's increasing population requires clean, reliable groundwater resources. Historically, obtaining sufficient water supplies has been problematic around the Agana area (Smalley and Zolan 1981). In southern Guam, the main public source of freshwater is stored in reservoirs. Surface water flows over the relatively impermeable volcanic rocks and locally provides some freshwater to residents (Gingerich 2003). Freshwater springs such as Agana and Asan springs are also used as water sources, the latter being part of the watershed that exists within the Asan Inland and Beach units (Smalley and Zolan 1981; Daniel 2006; M. Gawel and B. Alberti, conference call, March 2, 2011). The Northern Guam Lens Aquifer (NGLA) supplies nearly 80% of the island's water and is supported by carbonate rocks of the Barrigada and Mariana limestone formations (geologic map units Tbl and QTmr, QTmd, QTmm, QTmf, and QTma). Identifying, mapping, and interpreting the geologic framework of this aquifer facilitate its protection. Understanding the aquifer's recharge threshold—the amount of rainfall required to recharge it—is also important in determining water supplies (Taborosi 1999, Gingerich 2003, Jones and Banner 2003). Conditions impacting the dynamics and extent of the NGLA are the result of the transient relationship between freshwater and saltwater, with contributing factors such as tidal fluctuations, storm surges, stratigraphic settings, and the development of karst features within the limestones (Barner 1995). Karst is described in detail in the "Geologic Features and Processes" section. Within the aquifer, freshwater floats as a "lens" on denser saline water, separated by a transition zone (halocline) of brackish water that is several meters thick (fig. 13) (Gingerich 2003). The elevation of the halocline varies constantly with recharge, tidal, and pumping fluctuations, but is commonly below sea level. The saturated thickness of the freshwater lens can exceed 60 m (200 ft) (Barner 1995, Gingerich 2003).

Groundwater is pumped out of Guam's aquifers to supply the island's water needs; however, it also discharges naturally from the aquifers. The size and distribution of porespace (porosity) in a rock determine how groundwater will discharge. In northern Guam, groundwater seeps and springs are associated with more diffuse porosity, whereas concentrated discharges on the rocky coasts emerge from widened fractures and conduits (Taborosi et al. 2009). Like surface water, groundwater flows downhill toward a base level, which is sea level on Guam. Where groundwater meets the sea, it discharges through springs, seeps, fractures, caves, and submarine vents (Barner 1995; Taborosi et al. 2009).

As mentioned previously, the Asan Spring was historically used as a freshwater source. It is currently being revived and remodeled for further use. The Asan Inland Unit contains the source area for that spring, which may be connected to a historic pond within park boundaries (M. Gawel and B. Alberti, conference call, March 2, 2011).

Groundwater flow conduits are a common feature of karst-dominated aquifers and typically facilitate rapid infiltration and flow following recharging precipitation events. However, groundwater movement is relatively slow through the NGLA in northern Guam, probably resulting from the varied types of porosity in the aquifer and low hydraulic gradient. Predicting groundwater flow directions and response times is thus very difficult (Barner 1995, 1998), which could be problematic in areas where groundwater contamination and ecosystem degradation are concerns for park resource managers. Further complicating the issue is the lack of accurate maps, easements, or drawings detailing the locations of sewer and water lines and other infrastructure in place prior to the park's establishment (M. Gawel and B. Alberti, conference call, March 2, 2011). In the past, chemical compounds and microbiologic agents from numerous wastewater spills, leaks, and overflows have threatened to taint the island's groundwater, but careful management has avoided serious water quality issues (Matson 1987, Denton and Sian-Denton 2010). Recent vegetation surveys within War in the Pacific National Historical Park revealed a raw sewage pipe leak in the rainforest that drains into the Matgue River Watershed (Asan Inland Unit), which empties into Piti Bay at the base of Asan Ridge (M. Gawel, email communication, April 11, 2011; M. Gawel and B. Alberti, conference call, March 2, 2011). The NPS Water Resources Division (http://www.nature.nps.gov/water/) is the primary contact for water quality issues.

Seismicity and Tsunamis

Earthquakes are very common on Guam and are often felt at War in the Pacific National Historical Park. Seismic events of magnitude 5–6 occur frequently (M. Gawel and B. Alberti, conference call, March 2, 2011). Such activity is expected along the tectonically active margin between the Pacific, Mariana, and Philippine plates that is part of the larger "Ring of Fire"— the boundary of the Pacific tectonic plate. Historically, buildings, bridges, and roadways have been damaged by earthquakes on Guam, and landslides are commonly triggered by seismic shaking (von Hake 1978). Some of the larger recorded earthquakes on Guam are listed in figure 14.

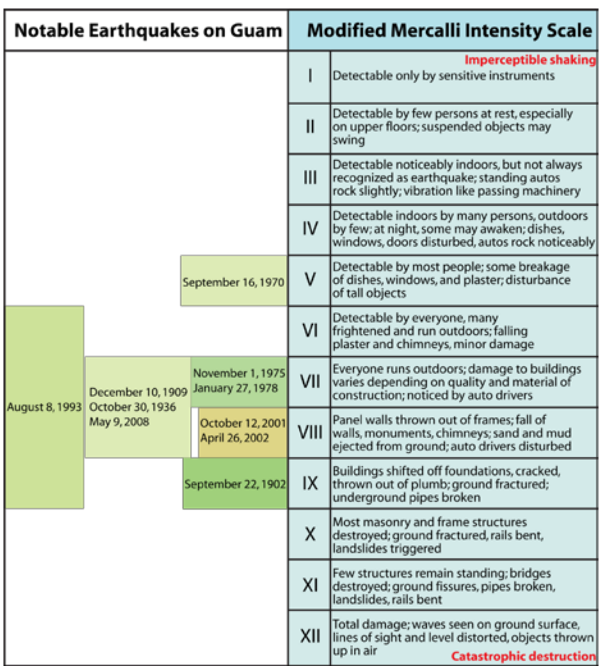

Figure 14. List of notable earthquakes that affected the island of Guam. The Modified Mercalli scale is based on perceived intensity of seismic shaking based on human response and damage. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) using information from von Hake (1978), Comartin (1995), Santi (1998), Harada and Ishibashi (2008), and U.S. Geological Survey (2007).

A 1993 earthquake, centered 76 km (46 mi) southeast of Guam, was the largest to occur in the world over the previous four years. It caused major damage to commercial and naval port facilities on the island of Guam due to liquefaction and lateral spreading; limestone bluffs experienced local slumps and rockfalls, water storage reservoirs were significantly damaged, and lagoonal deposits underlying Agana subsided 8–10 cm (3–4 in.) (Comartin 1995). At the Piti Power Plant, the ground subsided more than 1 m (3 ft) and coral sand spewed from ground fissures and sand boils (Comartin 1995). According to the Earthquake Engineering Research Institute, several faults on Guam are capable of generating large earthquakes that could cause serious threats to the island's population; these faults include the Pago-Adelup Fault, which runs through the center of the island near Asan Beach, Asan Inland, and Fonte Plateau units of the park (Comartin 1995).

Geologic hazards associated with moderate to large earthquake events are a serious concern for park resource managers because artificial fill (geologic map unit Qaf) underlies some park coastal lands, in particular the Asan Beach Unit. Filled areas are especially vulnerable to liquefaction and lateral spreading. Guam building codes require a high degree of structural integrity to withstand earthquakes, but a strong earthquake could compromise park infrastructure, particularly along coastal areas underlain by unconsolidated beach, alluvium, or fill deposits (geologic map units Qrb, Qaf, Qal). Studies of the 1993 earthquake noted that liquefaction and lateral spreading (seen as sand boils, ground subsidence, and differential settlement) occurred in naturally deposited, loose, silty sand of lagoon deposits and in the sandy fill of reclaimed areas (Vahdani et al. 1994).

Tsunamis, or massive waves, occur when the water column is displaced by submarine earthquakes or landslides. Tsunami waves may be generated locally or virtually anywhere within the Pacific Ocean Basin, travelling the entire distance of the basin within hours. Because of its reef formations and rapid dropoff of the surrounding seafloor, Guam has less runup area for tsunami waves to attain large heights than many other coastlines (M. Gawel and B. Alberti, conference call, March 2, 2011). Locally generated tsunamis occurred in 1849, 1892, 1990, and 1993, whereas tsunamis in 1952 and 1960 were caused by earthquakes in Kamchatka and Chile, respectively; historically, few tsunamis have caused significant damage to Guam (Daniel 2006). Tsunamis triggered by the 1993 earthquake caused some damage on the eastern side of Guam (Harada and Ishibashi 2008).

Due to the frequent occurrence of earthquakes and tsunamis, seismic monitoring and warning networks have been constructed and implemented throughout the Pacific Basin. Guam experiences extremely high seismicity and is vulnerable to hazards associated with the boundaries between the Pacific and Philippine plates (Mueller et al. 2006, U.S. Geological Survey 2007). Seismic monitoring data can be used for many purposes, such as determining the frequency of earthquake activity, evaluating earthquake risk, interpreting the geologic and tectonic activity of an area, and providing an effective vehicle for public information and education (Braile

2009). In the seismic monitoring chapter of *Geological Monitoring*, Braile (2009) highlighted methods for seismic monitoring such as monitoring earthquake activity, statistical and other analysis of recent, historic, and prehistoric earthquake activity, earthquake risk estimation, and analysis of geomorphic and geologic indications of active tectonics. Braile (2009) also provided a summary of the required personnel and expertise, special equipment, cost, and labor intensity of each method.

The National Earthquake Information Center (NEIC) has operated a seismic station on Guam since 1985 (Rutherford and Kaye 2006). The U.S. Geological Survey has maintained a seismological observatory at Pott's Junction in northern Guam, adjacent to Andersen Air Force Base, with daily monitoring for approximately the last 30 years (M. Gawel, email communication, April 11, 2011). The Pacific Tsunami Warning Center (PTWC) in Ewa Beach, Hawaii, provides warnings for tsunamis throughout the Pacific. Websites for the Global Seismic Hazard Assessment Program (which has produced global seismic hazard maps and reports) and the U.S. Geological Survey earthquake monitoring and earthquake hazard programs are listed in the "Additional References" section.

Mass Wasting

Guam's steep topography, geologic framework, active tectonic environment, tropical climate, and human activities create a setting that is prone to mass-wasting events such as landslides, blockfalls, debris flows, and slumps. Guam is only 6–12 km (4–8 mi) wide, but elevations range from sea level to nearly 425 m (1,400 ft) above sea level. Steep slopes are present in the upland units of War in the Pacific National Historical Park.

Two very different types of bedrock exist on Guam—limestone and volcanic rocks. Both are mapped within War in the Pacific National Historical Park (see "Map Unit Properties Table"). These two types of bedrock, and the overlying, unconsolidated, weathered material derived from them (called "regolith" or "residuum" if still in place), behave very differently in terms of structural integrity and mass wasting (Santi 1998). The low-permeability volcanic rocks (basalts and andesites) predominant on southern Guam allow less rainfall infiltration. During heavy precipitation events, high runoff causes intense flooding in the stream drainage basins (Gingerich 2003). Volcanic tuff, a vesicular, relatively weak rock, forms much of the bedrock near the Asan Inland Unit (part of geologic map unit Ta). These and other volcanic-rich bedrocks are deeply weathered to clayey regolith, with many joints and fractures creating zones of weakness throughout the rock. Seepage is frequently noted at the interface between weathered, unconsolidated regolith and more competent bedrock, forming a regional slip surface where mass wasting may initiate (Callender 1975); this setting exists within the Mt. Alifan unit.

The limestones underlying most of the park units are soluble and often contain small pockets, cavities, and widened fractures typical of karst landscapes. They weather to produce thin, clayey to gravelly residuum soils (Santi 1998). Limestone knobs and cliffs are prone to rockfall in the upland units, whereas dissolved cavities may be locations of localized collapse or sinkhole subsidence. Examples of limestone knobs and cliffs include Asan Ridge, Apaca (in Agat unit), cliffs in the upper reaches of the Asan and Mt. Alifan units, and cliffs surrounding the former rock quarry in the Fonte Plateau unit (M. Gawel and J. Oelke, email communication, July 2, 2012).

Typhoons and other seasonal storms bring extreme precipitation that can quickly saturate unconsolidated regolith atop bedrock on Guam's slopes and facilitate landslides and slumps. Earthquakes can fracture and weaken rocks, and trigger landslides on slopes. Small landslides occurred within the park during the 1993 earthquake on the western (Piti) side of Asan Ridge near several pillboxes (Rutherford and Kaye 2006). Since 1993, sparse vegetation has covered the slide areas. The sparcity is likely due to the lack of soils upon the now-

Figure 15. Local resident excavating into the toe of a hillslope failure near the boundary of the Asan Inland Unit (located at the top of the hill). Leaning trees on the hillside suggest long-term, ongoing slump issues at this location. Construction of a retaining wall at the back of the residence did not abate the problem. National Park Service photograph by Deanna Greco (Grand Canyon NP), 2003.

Figure 16. Erosion and mass wasting along a slope above private residences near War in the Pacific National Historical Park boundary. Pipes in the bank show the extent of erosion and the scarp is evidence of active mass wasting. National Park Service photograph by Deanna Greco (Grand Canyon NP), 2003.

exposed limestone base of the slopes (M. Gawel and J. Oelke, email communication, July 2, 2012).

As development continues on Guam, human-induced landscape changes may exacerbate mass-wasting potential (figs. 15 and 16). Cutting into the toe or loading the top of a slope destabilizes the slope material and may trigger a slide or slump. Clearing areas of stabilizing vegetation may increase erosion and trigger adjacent hillslope failures (Greco 2003).

Developers address potential mass-wasting issues by using artificial fill in areas underlain by porous limestone, and engineering structures such as drains, ditches, and retaining walls in an attempt to minimize land movement (Callender 1975). Development adjacent to War in the Pacific National Historical Park has the potential to impact park resources. The hillslopes underlying the inland boundaries of the Asan Unit are prone to sliding and have been the subject of several geo-engineering reports (Greco 2003). In 2003, a geologist from the NPS Geologic Resources Division responded to a technical assistance request from the park to evaluate a large landslide behind a residence adjacent to park property (Greco 2003). That study recommended monitoring lands adjacent to the landslide for signs of instability and continued involvement in discussions about stabilization efforts in lands adjacent to the park. Some local concern has been voiced that park management practices have affected slope stability near the Piti Guns Unit. However, that issue concerns power line rights of way and access roads that are not under the jurisdiction of the park (M. Gawel and B. Alberti, conference call, March 2, 2011).

Mass wasting at War in the Pacific National Historical Park is most common in the southern upland areas. Land-use practices such as clearing, burning, and ORV use reduce the vegetation cover and create "badlands." Soils are eroded to the underlying saprolite (deeply weathered bedrock), where very little vegetation, except perhaps scattered grass, can grow (Rutherford and Kaye 2006). The park is currently monitoring burned versus unburned tropical savanna grassland areas for erosion (Daniel 2006).

In the mass-wasting monitoring chapter of *Geological Monitoring*, Wieczorek and Snyder (2009) described the various types of slope movement and mass-wasting trigger, and suggested five methods and "vital signs" for monitoring slope movements: types of landslide, landslide triggers and causes, geologic materials in landslides, measurement of landslide movement, and assessing landslide hazards and risks. Their publication provides guidance for using the vital signs and monitoring methodology. The Department of Agriculture (Natural Resources Conservation Service) based in Guam (http://www.agriculture.guam.gov) is a technical contact for mass-wasting issues associated with development (M. Gawel and B. Alberti, conference call, March 2, 2011).

Storm Damage

Guam's tropical climate is prone to typhoons during the rainy season, from July to December. Winds of these storms can exceed 240 km/h (150 mi/h) (Comartin 1995). Listed in Boudreau et al. (2002), some of the larger typhoons to hit the island include:

- Typhoon Karen, November 1962 (winds 232 km/h [144 mi/h]),
- Typhoon Pamela, May 1976 (winds 204 km/h [127 mi/h]), and
- Typhoon Omar, August 1992 (winds 175 km/h [109 mi/h]).

Supertyphoon Pongsona, considered the worst to hit Guam in living memory, devastated the island on December 8, 2002, with sustained wind speeds estimated at 240 km/h (150 mi/h) and gusts exceeding 290 km/h (180 mi/h). Wind and waves associated with this event extensively damaged park infrastructure and natural features along the shoreline, including the Haloda Building (park headquarters), parking lots, concrete pathways, the World War II museum and Visitor Center, the shoreline embankment of the Asan Beach Unit, the maintenance facility, Piti Guns, Asan Overlook, Ga'an Point, Apaca Point, and Fonte Plateau (Greco 2003, Winzler and Kelly Consulting Engineers 2003). Cultural features, such as the inner-reef flat-rock revetment barrier constructed by the U.S. Navy as part of the 1944 invasion, were damaged by wave action (Winzler and Kelly Consulting Engineers 2003). Heavy rainfall from such typhoons triggers landslides on hillslopes within and adjacent to the park (Greco 2003). In 2004, Supertyphoon Chaba caused extensive overwash and erosion along the park's shoreline areas (Pendleton et al. 2005). Riprap and breakwaters (figs. 17 and 18) have been constructed along the park's shoreline in an attempt to buffer it from wave energy, but the energy associated with major storms overruns these structures. The park prefers to avoid shoreline structures; local permits for such shoreline modifications would be difficult to obtain (M. Gawel and J. Oelke, email communication, July 2, 2012).

Figure 17. Large waves along a rocky section of the Asan Beach Unit's shoreline. National Park Service photograph.

Visitor Center Stability

Subsurface stability is a concern at the Visitor Center of War in the Pacific National Historical Park. The building was constructed in the mid-1970s on artificial fill (geologic map unit Qaf) comprised of dredge spoil and, possibly, rubble from a limestone quarry (M. Gawel, email communication, April 11, 2011). The building continues to subside as the artificial fill material settles beneath it, with several centimeters of subsidence noticeable between its two halves. This settling impacts drainage around the building, causing hazardous mold accumulations in the interior. Park staff are currently conducting environmental assessments to determine the nature of this drainage problem and the best way to remediate the situation in cooperation with the U.S. Military that owns the building (M. Gawel and B. Alberti, conference call, March 2, 2011).

Figure 18. Breakwater feature (rubble in foreground) at Asan Beach Unit constructed by the U.S. Military in an attempt to buffer the sandy shoreline from high wave energy. National Park Service photograph by Deanna Greco (Grand Canyon NP), 2003.

Radon Potential

According to the U.S. Environmental Protection Agency's (EPA's) radon website (http://www.epa.gov/radon/), exposure to radon in buildings and drinking water is responsible for an estimated 20,000 deaths from lung cancer each year. Radon is a radioactive, toxic, colorless, gaseous product of the decay of radium, itself a radioactive decay product of uranium. Uranium naturally occurs in many minerals and can be found in low levels within essentially all rock, soil, and water. When uranium decays in the regolith surrounding a building's basement or foundation, radon typically moves up through the ground to the air above, often becoming trapped inside the structure. Radon can also enter a building through well water.

The EPA has an action guideline of 4 picocuries radon per liter air (pCi/L), above which the EPA recommends steps to reduce radon levels. Ideally, levels should be lower than 2 pCi/L. The U.S. Geological Survey produced a generalized map of radon potential for Guam (Otton 1993). Utilizing radon measurements in combination with geologic and geophysical factors, the map can guide focused monitoring. Factors included in the mapping were the geologic radon potential of rocks, soils, and surficial deposits. Limestones (geologic map units Tal, QTmr, and QTma) in War in the Pacific National Historical Park, in the southern part of northern Guam and the area fringing the volcanic terrane in southern Guam, are clayey and contain abundant fragments weathered from the volcanic rocks (geologic map units Ta and Tuf). Soils developed on these rocks may contain high concentrations of radium, some of which is from weathered bedrock or imported from windborne particles (Otton 1993). Unconsolidated beach deposits and alluvium (geologic map units Qrb and Qal) do not seem to retain much radon (Otton 1993).

The geologic radon potential map indicates that park units occur within areas of low (Mt. Alifan, Mt. Chachao/Mt. Tenjo, and Piti Guns units) and moderate/variable (Agat, Asan Beach, and Asan Inland units) potential. Ground-disturbing construction can contribute to increased radon potential by exposing highly permeable weathered bedrock. Similarly, earthquakes can open entry pathways for radon (Otton 1993). Although radon testing in 1991 found relatively low levels in buildings in the park area (schools, private homes, and military buildings), radon values can vary widely, even in small areas, and every building should be tested individually. Otton (1993) suggests contacting the Guam EPA for radon evaluation, testing, and mitigation services, if necessary. In 2011, the U.S. Department of the Interior (DOI) partnered with the EPA to increase radon awareness and testing throughout the country. As part of this effort, the DOI will test approximately 5,000 residential units on Guam for radon (Rhea Suh, Assistant Secretary for Policy, Management and Budget, U.S. Department of the Interior, e-mail communication, June 19, 2011).

Geologic Features and Processes

Geologic resources underlie park ecosystems and geologic processes shape the landscape of every park. This section describes the most prominent and distinctive geologic features and processes in War in the Pacific National Historical Park.

Karst Features

The term "karst" comes from a Slavic word that means "barren, stony ground." A karst landscape is a terrain produced by the dominant geomorphic processes of chemical erosion and weathering of carbonate rocks such as limestone (Palmer 1984). The extensive limestones of Guam exhibit a variety of typical karst features that have been formed by the dissolution of carbonate rocks, including surficial features (karren, runnels, and closed-contour depressions), subsurface features such as caves, and coastal discharge features (Taborosi 1999, Taborosi et al. 2004). Striking karst features, described as "macabre", occur within the northern third of the Asan Inland unit, covered by a thick carpet of *lumot* (moss) (M. Gawel and J. Oelke, War in the Pacific NHP staff, email communication, July 2, 2012).

Guam also exhibits world-class island karst features that have formed in response to the interaction of marine and fresh groundwater, such as flank margin caves. Karst carbonate islands have several unique conditions that yield distinctive features. Such features form via enhanced solution at the surface, base, and margins of the freshwater lens floating atop denser saline water, recording its spatial migration through time (Mylroie et al. 2001). The development of island karst is strongly influenced by freshwater-saltwater mixing, sea-level change, recharge inputs, and limestone characteristics including burial depth (Mylroie et al. 2001, Taborosi et al. 2004). Biokarst features are also present on the island. Broadly, the karst features on the northern plateau are characteristic of those found on small carbonate islands, whereas those in the southern highlands are more closely related to the karst of continental settings at similar latitudes (Mylroie et al. 2001, Taborosi et al. 2004). Many karst features visible in War in the Pacific National Historical Park or elsewhere on Guam are described in subsections below. Karst features are described in detail in publications such as Taborosi (2000), Taborosi et al. (2004), and Mylroie et al. (2001), and discussed per geologic map unit in the Map Unit Properties Table (see "Geologic Map Data" section). Some karst features—particularly caves—figured prominently in the Japanese occupation and Allied liberation of Guam during World War II.

Limestones and Dissolution

Dissolution occurs when acidic water reacts with carbonate rock surfaces. Most rainfall is of relatively low pH ("acidic") due to the reaction between atmospheric carbon dioxide (CO_2) and water (H_2O). The product of this reaction is carbonic acid (H_2CO_3), which reacts with calcium carbonate ($CaCO_3$) in rocks to produce soluble calcium (Ca_2^+) and bicarbonate (HCO_3^-) ions; that is, "rocks in solution" or "dissolved rocks." Dissolution tends to be enhanced in pore space between limestone grains and along fractures within limestone, creating voids that become progressively larger.

Most of Guam's limestone is porous and heterogeneous in composition. It retains many of the original textures and features formed during its original deposition in environments including coral reefs, lagoons, beaches, and forereefs. Indeed, vast areas of Guam's limestones were never buried, compacted, and significantly altered into dense, recrystallized, relatively nonporous limestone beds that are commonly associated with terrestrial karst landscapes (Reale et al. 2002, Taborosi and Jenson 2002, Taborosi et al. 2004). Exceptions are the older Maemong Limestone Member of the Umatac Formation (geologic map unit Tum), which has an average porosity of about 3%, and the Bonya Limestone (geologic map unit Tb), the porosity of which was almost completely eliminated by calcite precipitated from solution into former pores (Schlanger 1964, Tracey et al. 1964a). By contrast, the porosity of the younger Mariana Limestone (geologic map units QTmr, QTmd, QTmm, QTmf, and QTma) may be as high as 30% (Schlanger 1964, Taborosi et al. 2004). In an investigation of the Barrigada Limestone (geologic map unit Tbl), Reale et al. (2002) determined that the degree of intraformational diagenetic alteration may be unpredictable in Guam's limestones.

The porous nature of most of Guam's limestone facilitates dissolution by transmitting groundwater through the many pores and providing increased surface area available for chemical reaction. Some karst conduits discharge water at the coast; however, Guam's small size facilitates diffuse discharge through porous limestones and limits the development of large conduit networks (prevalent in continental karst systems such as that at Mammoth Cave National Park, Kentucky; Thornberry-Ehrlich 2011) that promote more efficient discharge (Barner 1995, Mylroie et al. 2001).

Surface Features: Karren, Runnels, Epikarst, and Closed-Contour Depressions

The term "karren" refers to small-scale (millimeters to meters) features that form by dissolutional sculpting of limestone, primarily through direct contact with rainwater. Karren features on Guam are quite diverse and unique (Taborosi 1999). This diversity is due to the depositional nature and burial depth of the limestones, combined with the effects of tropical climate, recharge, and proximity to the ocean environment. The dominant karren features on Guam, present on the surfaces of all young reef limestones, are highly irregular, composite forms, including assemblages of densely packed solution pits separated by jagged ridges and sharp tips (Taborosi et al. 2004). This composite form of karren can cover large areas of jagged pit and pinnacle topography on surfaces of the Alifan and Mariana limestones underlying most units of the park (geologic map units Tal and QTmr, QTmd, QTmm, QTmf, and QTma, respectively). Taborosi et al. (2004) proposed the term "eogenetic karren" to emphasize the eogenetic nature of the host limestone as the dominant controlling factor of its development.

The limited areas of older, denser limestones (geologic map units Tum and Tb) on Guam lack sculptured, irregular, karren-dominated karst. Instead, features more typical of continental settings, such as solution runnels, are present (Taborosi et al. 2004). Solution runnels resemble small channels with smooth walls, approximately 20 cm (8 in.) deep and wide, running down steep slopes. Runnel formation requires low overall porosity to allow surface flow and to focus water into discrete pathways (Taborosi et al. 2004). These features are characteristic of telogenetic limestone terrains.

Epikarst generically refers to the uppermost zone of karst dissolution extending down from the bedrock surface to an indefinite, but usually relatively shallow, depth. Epikarst on Guam appears identical to that found on many other carbonate islands (Taborosi 1999). Epikarst features include pit-and-tunnels, localized cavernous weathering, shafts, and soil pipes (Taborosi et al. 2004), which are narrow (<2 cm [0.79 in] in diameter) tubular cavities that conduct water from the surface to the bedrock below. Near the coastline, epikarst surfaces tend to be more jagged and irregular than inland surfaces due to enhanced solution caused by salt spray mixing with meteoric water. Below the upward projections of the karren, soil and weathered bedrock debris overlie the solution fissures, holes, and other shallow, small cavities in the bedrock that make up the epikarst on Guam (Mylroie et al. 2001).

Closed depressions (karstic or otherwise) form by the removal of underlying material (rock and/or soil), which undermines the foundation for surficial rock or soil. Such features are sometimes called closed-contour depressions because they have closed topographic contours on topographic maps. Closed depressions on Guam may be dissolutional, constructional, and/or anthropogenically modified. Dissolutional closed depressions include blind valleys, point recharge sinkholes, collapse sinkholes, and large cockpit karst sinkholes (deep closed depressions separated by narrow limestone ridges). Dissolution depressions (fig. 19) are generally of small to moderate size (meters to tens of meters in diameter) and shallow (Mylroie et al. 2001). An exception to this on Guam's northern plateau is Harmon Sink, a deep elongate depression near Tumon Bay that is fed by an ephemeral sinking stream northeast of the Asan Inland Unit. Collapse sinkholes exist on Guam, but are not common (Mylroie et al. 2001). Constructional closed depressions are the largest of this category; they are the result of focused dissolution along topographic features in weathered bedrock that form 1) along natural features such as bedding planes that formed during original deposition, or 2) during subsequent tectonic deformation (Mylroie et al. 2001). Large, closely spaced closed depressions form in local exposures of Bonya and Alifan limestones (geologic map units Tb and Tal, respectively) (Mylroie et al. 2001). Humans have modified many depressions on Guam to act as stormwater ponding basins, or filled them to support construction or function as dumps such as the Orote Landfill (Taborosi 1999; Boudreau et al. 2002; Taborosi et al. 2004).

Figure 19. Sinkhole at Asan Inland Unit. The fence was installed for visitor safety. National Park Service photograph by Deanna Greco (Grand Canyon NP), 2003.

Caves

Cave features on Guam, although integral to the park's history, have remained relatively undocumented until recently. Rogers and Legge (1992) listed 74 caves on the island, but many more are thought to exist. Cave development occurs in both inland and coastal areas (Reece et al. 2000). Cave types include flank margin caves, stream caves, and pit caves (Taborosi 1999). There is a considerable number of caves (both natural and manmade cavities) within the park. (M. Gawel and J. Oelke, email communication, July 2, 2012).

Flank margin caves, the most abundant type on Guam, form along coastal margins of the freshwater lens where it intersects marine water at sea level via dissolution or percolation (Mylroie et al. 2001; M. Gawel and J. Oelke, email communication, July 2, 2012). Their exposures on the cliffs of northern Guam indicate previous sea-level stillstands, and these caves are generally oriented parallel to past shorelines (Mylroie et al. 2001, Stafford et al. 2009). Other related types of cave are fracture caves and voids that form on the top, bottom, and within the freshwater lens (Mylroie et al. 2001, Taborosi et al. 2004). Cliff-structure fracturing forms rooms under large sections of karst that have fallen at odd angles (M. Gawel and J. Oelke, email communication, July 2, 2012). In southern Guam, where limestones are perched above the influence of the freshwater lens/saline water contact, caves are well-developed and may resemble continental karst caves (Mylroie et al. 2001).

Traversable (accessible to human passage) stream caves form where underlying volcanic basement rocks funnel water into a directed flow that dissolves overlying carbonate rocks on contact, creating vertical walls along a channel-like cave (Taborosi 1999, Taborosi et al. 2004). Such caves are forming on Guam today, and some may mark relative sea-level stillstands. During such stillstands, flowing vadose streamwater mixes underground with the top of the freshwater lens, creating a broad lateral region of accelerated dissolution (Mylroie et al. 2001). Other traversable stream caves with broad chambers may have formed via cavern collapse when vadose streamways undercut the contact between volcanic rocks and limestones (Mylroie et al. 2001). Traversable caves include Awesome Cave and Piggy Cave on the slopes of Mt. Santa Rosa, north of War in the Pacific National Historical Park (Mylroie et al. 2001). In southern Guam, traversable stream caves occur in the Bonya and Alifan limestones (geologic map units Tb and Tal, respectively) in areas such as Mt. Almagosa. Some springs are fed from traversable spring cave discharge (Mylroie et al. 2001).

Pit caves are vertical shafts that may or may not open to the surface. They are of variable depth, but on Guam can approach 50 m (165 ft) deep. They form where abundant water flowed along a primarily direct route into the subsurface, dissolving a vertical pit in the bedrock. Once formed, they carry vadose water to the subsurface. Pit caves are relatively rare on Guam, but do occur in the Mariana and Alifan Limestone units(geologic map units QTmr, QTmd, QTmm, QTmf, QTma, Tal, and Tt) in locations such as Amantes Point (Mylroie et al. 2001) north of Tumon Bay, northeast of the Asan Inland Unit (fig. 20).

Figure 20. Cave dissolved in Mariana Limestone (geologic map unit QTma) or Alifan Limestone (geologic map unit Tal) near Asan Point. National Park Service photograph by Deanna Greco (Grand Canyon NP), 2003.

Discharge Features

Many types of freshwater discharge feature, such as beach seeps and springs, reef springs and seeps, fracture springs, and cave springs (Taborosi et al. 2004, 2009), occur along Guam's coastline. Springs emerge from distinct points, whereas seeps display only diffuse outflow over a larger area. Beach springs and seeps occur in the intertidal zone of sandy beaches and may be found at the Asan Beach and Agat units. Beach discharge features are best observed at low tide, when they form meandering channels through the sand, parallel rills, and mini-deltas of beach sand. At high tide, although most such features are submerged, large springs appear as shallow-water boils (Taborosi et al. 2009). Reef springs and seeps occur in the subtidal zone of some of Guam's fringing reefs, appearing as plumes of blurry water due to the refraction of light by density differences. A large reef spring emerges from the reef flat below the low tide mark in Agana Bay (Taborosi et al. 2009). Fracture springs form where cracks in the rock carrying freshwater intersect the coast. On Guam, these fractures are typically vertical and perpendicular to the coast, and vary in scale from several millimeters to several meters in diameter. The largest fracture springs can be followed for some distance inland, and mixing of freshwater atop saline water is evident. In effect, seawater provides the "impermeable" base for freshwater flow instead of rock (Taborosi et al. 2009). Cave springs also occur at various scales and exhibit diverse morphologies. Most are located at or near sea level and discharge freshwater from conduit flows. Some cave springs are wholly submerged and are thus submarine vents (Taborosi et al. 2009). Asan Spring is utilized by the Guam Waterworks Authority only several meters from the park boundary; it is not a beach or shoreline seep (M. Gawel and J. Oelke, email communication, July 2, 2012).

On the limestone-dominated northern plateau, discharge features vary by coastline type: 1) deeply scalloped embayments with broad beaches, 2) linear beaches fronted by fringing reefs, and 3) sheer cliffs with narrow or no benches and local small reefs. In embayments such as Agana and Tumon bays, groundwater discharges both as diffuse flow from seeps and concentrated flow from springs along the broad beaches. Linear beaches also have seeps, but these coasts lack obvious springs or coastal caves. Examples of such stretches include the coast from Uruno Point around Ritidan Point to Tagua Point in northwestern Guam (Mylroie et al. 2001, Taborosi et al. 2009). Cliff-dominated coasts boast spectacular flows from coastal caves, dissolution-widened fractures, and submarine vents (Mylroie et al. 2001). The largest cliff-related discharge feature is Coconut Crab Cave. Because they are fed by subterranean freshwater, submarine vents locally create areas of cooler water (~26°C [79°F]) that contrast with the solar-heated, shallow lagoon temperature (>30°C [86°F]) (Mylroie et al. 2001).

In southern Guam, discharge features resemble those of classic tropical continental karst, including contact springs flowing from well-developed caves and sinking streams with resurgences (Mylroie et al. 2001). Several springs emerge from the limestone plateaus at Mt. Alifan and Asan units (M. Gawel and J. Oelke, email communication, July 2, 2012). Karst features associated

Table 1. Biologic and inorganic influences on karst features.

Karst Feature	Biologic Influences	Inorganic Influences
Coral reefs	Constructed by living coral and coralline algae; bioerosion	Wave action; freshwater discharge; underlying topography
Intertidal benches and terraces	Constructed by coralline algae and vermetid mollusks; bioerosion	Dissolution by wave-agitated seawater; abrasion by wave-borne stones
Marine notches	Bioerosion, including bioabrasion by grazing organisms and biocorrosion by burrowers	
Beach rock	Intertidal microflora and heterotrophs influence local pH and carbon dioxide levels that control cementation	Dissolution by meteoric water
Epikarst: karren, solution pans, and solution pits	Organically acidified water accelerates dissolution; lichen mechanically erode; root action creates openings	
Root grooves, root holes, and root tubules (rhizoliths)	Dissolution by organic acids derived from plants; mechanical action by roots	None
Caves and cave deposits	Organically produced acids enhance dissolution; microbial precipitation and corrosion	Chemical precipitation; dissolution by flowing water; collapse due to gravity

Data are from Taborosi (2002).

with stream-like flows (fluviokarst) on Guam include sinking streams, blind valleys, ponors, swallets, dry valleys, valley dolines, losing streams, through valleys, gorges, stream caves, natural bridges, exsurgences, and resurgences (see "Glossary"). Their presence on Guam is uncommon for an oceanic carbonate island (Taborosi and Jenson 2002).

Biokarst

In addition to abiotic processes, karst landscapes can also be influenced by biotic processes. The term "biokarst" describes karst features influenced by biologic action (living organisms; table 1) (Viles 1984). Living organisms have profound ecosystem-scale on the karst geomorphology of Guam. Nearly all small-and medium-scale karst features on the island have been affected by biologic action and exhibit biokarst characteristics (Taborosi 2002).

Biokarst occurs in a variety of environments on Guam, including coastal reefs, intertidal benches and terraces, marine notches, and beachrock; caves and cave deposits; and epikarst features such as karren, solution pans, and pits (Taborosi 2002). Much of the limestone on the island is the result of biogenic action, and limestone continues to form today in reefs. Coral and algal reefs are bioconstructed deposits, and are thus considered depositional biokarst (Viles 1984, 1988, Taborosi 2002). As described below in the "Coastal Features" section, modern fringing reefs almost entirely surround the island and large reef flats developed in Agana, Tumon, Pago, and Tarague bays (Taborosi 2002).

Bioerosion, facilitated by creatures such as limpets, chitons, and boring barnacles, is partly responsible for the formation of marine notches. As described in the "Surface Features" section, exposures of Mariana Limestone (geologic map units QTmr, QTmd, QTmm, QTmf, and QTma) along the coast are dominated by chaotic and rough karren. These features form in part due to the erosive actions of marine-organism grazing and boring (Taborosi 2002). Decaying plant debris releases CO_2, making stagnant water in solution pans more corrosive and thus facilitating additional dissolution. Similarly, organic processes in soils within limestone depressions deepen solution pits. Plant roots likely contribute to the formation of karst features such as root grooves, root holes, and root tubules (rhizoliths). Black films of cyanobacteria have been noted in several coastal caves on Guam and may contribute to the development of small-scale pits on cave walls (Taborosi 2002). Certain cave formations, including calcified algal filaments, moonmilk, and biomats, are also influenced by the biologic activity of precipitation (Taborosi 2002).

Monitoring Caves and Karst Landscapes

Signs are posted warning visitors of the dangers of caves (i.e. low ceilings, crumbling walls, particularly in the manmade cavities that were blown up during the war, and the potential for unexploded ordnance). No known natural resource studies have been completed within the park's caves (M. Gawel and J. Oelke, email communication, July 2, 2012). Toomey (2009) described caves and karst landscapes, as well as methods to inventory and monitor cave-related vital signs: 1) cave meteorology (microclimate and air composition of the cave), 2) airborne sedimentation (dust and lint), 3) direct visitor impacts (e.g., breakage of cave formations, trail use in caves, graffiti, cave lighting), 4) permanent or seasonal ice, 5) cave drip and pool water (drip locations, rate, volume, and water chemistry; microbiology, temperature), 6) microbiology, 7) stability (breakdown, rockfall, and partings), 8) mineral growth (speleothems such as stalagmites and stalactites), 9) surface expressions and processes (karst processes link the surface to caves through features such as springs, sinkholes, cracks), 10) regional groundwater levels and quantity, and 11) fluvial processes (underground streams and rivers) (Toomey 2009).

Coastal Features

The coastal features of War in the Pacific National Historical Park are within the Asan Beach and Agat Beach units. Coralline, sandy beaches (geologic map unit Qrb) flank most of the park's coastline (fig. 21), whereas other areas are rocky or deltaic (near river outlets; figs. 17 and 22). Most of the park's reefs are fringing and extend an average of about 100 m (330 ft) offshore before dropping sharply to depths of 25–30 m (82–98 ft). Along Guam's coast, Emery (1964) noted the presence of four submarine terraces at average depths of 17, 32, 59, and 96 m (55, 105, 195, and 315 ft).

Figure 21. Broad sandy beach at Asan Beach Unit, one of two landing sites for American forces invading in 1944. The high vantage point from which this image was taken was utilized by the Japanese in their defense of the island. National Park Service photograph by Deanna Greco (Grand Canyon NP), 2003.

The reefs provide habitat for many species of coral, fish, algae, and other marine invertebrates, some of which occur nowhere else on Earth. Reef slopes are covered with coral, and extensive lagoonal flats occur landward of the reef. Ephemeral and perennial streams (fig. 22) and other discharge features such as springs incise the reef flats, providing microhabitats (Emery 1964, Daniel 2006). The health and condition of the coral reefs act as indicators of local and global climate change (Daniel 2006).

Bush and Young (2009) delineated the following "vital signs" for monitoring coastal features and processes: 1) shoreline change, 2) coastal dune geomorphology, 3) coastal vegetation cover, 4) topography/elevation, 5) composition of beach material, 6) wetland position/acreage, and 7) coastal wetland accretion. This study includes detailed recommendations for resource managers, including descriptions of the expertise, personnel, and equipment needed, approximate cost, and labor intensity.

Figure 22. Moderately sized stream discharging to the ocean near Asan Point. Note the presence of limestone boulders on the beach. National Park Service photograph by Deanna Greco (Grand Canyon NP), 2003.

Limestone Forests

Limestone forests are old and stable climax forests or plant communities found in areas with abundant limestone. Tropical limestone forests are the most diverse natural plant communities on Guam, and are adapted to extreme disturbance conditions such as frequent tropical storms (Hess and Pratt 2006). These forests harbor flora and fauna unique to Guam and the Mariana Islands in a mosaic of different community subtypes (Daniel 2006, Hess and Pratt 2006). Examples of flora that thrive within the limestone forests of Guam include fadang trees (*Cycas micronesica*; a cycad that grows only about 2.5 cm [1 in] per year), the endemic *Guamia mariannae*, screw pine (*Pandanus*), fago (*Neisosperma*), and banyan trees (Loban 2000).

Guam's limestone forests are restricted to ancient, uplifted coral reef systems (now limestone) surrounded by a mosaic of volcanic substrates (Ainsworth 2010). War in the Pacific National Historical Park contains the only remnants of limestone forest in the National Park System (Ainsworth 2010) and limestone forests are mentioned as a significant resource in the park's enabling legislation. Limestone forests are found in many units of War in the Pacific National Historical Park, but are particularly well developed in the Asan Beach and Fonte Plateau units (geologic map units QTma, Ta, and Tal). Native strand and limestone vegetation exist in the Agat Beach Unit at Ga'an Point (geologic map unit QTma).The Asan Inland Unit hosts native limestone forest on a ridge at its southern boundary and on a rocky slope at its northern boundary (geologic map units QTma, Ta, and Tal) (Hess and Pratt 2006). The Mt. Alifan Unit contains limestone forests on exposures of Alifan Limestone (geologic map unit Tal) (Tracey et al. 1964a, Yoshioka 2005, Hess and Pratt 2006). On the limestone ledge of the Fonte Plateau Unit is a limestone forested area with native vegetation growing down the north-facing slope (Daniel 2006). Recent surveys have revealed new limestone outcrops that have the potential to host more limestone forests on Guam. Detailed mapping is necessary to manage this resource (M. Gawel and B. Alberti, conference call, March 2, 2011).

The extent, biodiversity, and overall health of the limestone forests of Guam are in decline due to anthropogenic influences. Such influences include large-scale clearing and conversion, the introduction of exotic species (flora and fauna), the reduction or disappearance of native pollinators and seed dispersers, and predatory regulation of herbivorous insects (Hess and Pratt 2006). Recovery of limestone forests on Guam may require intensive management in small, isolatable patches of land (Hess and Pratt 2006).

Wetlands

A wetland is an area of land whose substrate is permanently or seasonally saturated with water. Such areas may be partially or completely covered by shallow pools of still water. Wetlands may be freshwater, brackish, or saline and include swamps, marshes, and bogs. Wetlands are often influenced by the underlying geology, forming in areas of poor drainage. On Guam, the underlying geology and geologic history of the area controlled the formation of Agana Swamp, which is among the largest coastal wetlands in the Mariana Islands. It likely originated as marine embayments or lagoons that were isolated from the open ocean when relative sea level dropped and began to fill with carbonate and organic sediments (Hill 1996). This process reflects the active uplift currently associated with Guam's tectonic setting near the collision zone between the Pacific and Mariana plates. The Agana River flows through Agana Swamp. Rainfall and surface water runoff maintain water level in the swamp, and it is hydraulically connected to the basal freshwater lens. The swamp functions as a groundwater recharge zone during wet periods and a discharge zone during dry spells (Ayers and Clayshulte 1983, Hill 1996). Agana Swamp is adjacent to the Agana community, and its integrity has suffered as a result. Developers cut a channel through the swamp and dredged it in 1933–1934. This disturbance resulted in drying of the swamp surface, decreased groundwater levels in the vicinity, and increased flow in the Agana River (Ayers and Clayshulte 1983, Hill 1996). The town of Agana is partly developed over the thick, soft, marsh soils of Agana Swamp. Soft soils may be up to 30 m (100 ft) thick in places (Comartin 1995). Soft, water-saturated deposits are particularly susceptible to liquefaction and subsidence during earthquakes, making them a relatively undesirable foundation for development.

The U.S. Fish and Wildlife Service has grouped wetlands into five ecological systems: palustrine (small, pond-like), lacustrine (larger, flooded, lake-like), riverine (channelized, river-like), estuarine (low-wave-energy, brackish-water tidal areas), and marine (tidal areas exposed to waves, e.g., coral reefs). The Guam Department of Parks and Recreation inventoried wetlands on Guam in 1988 and calculated a total of approximately 5,700 ha (14,000 ac) of wetland, of which 3,600 ha (9,000 ac) are marine coral reefs and 1,400 ha (3,500 ac) are palustrine wetlands (most forested with mangroves). Wetlands exist around Apra Harbor (managed by the U.S. Navy), and coastal and inland wetlands are present within the Asan Inland, Mt. Alifan, Mt. Tenjo, and Fonte Plateau units (Hill 1996, Daniel 2006). The Guam Coastal Management Program designated an area in the Apaca Point region of the Agat Unit as part of the Namo River floodplain wetland (recognized as significant by the United Nations Protected Area Program) (Daniel 2006).

Paleontological Resources

No formal, field-based paleontological survey has been conducted at War in the Pacific National Historical Park. Hunt et al. (2007) completed a literature-based summary of known and potential fossil resources within the park. Fossils are present in the various limestones that crop out in the park and may exist in lava tubes and caves within the park. Limestones host dozens of marine invertebrate species and are the primary source of paleontological resources on the island and in the park. Caves might host fossils of animals, particularly vertebrates that utilized or were transported into the caves. However, such occurrences have not yet been documented. Foraminifera, a large group of tiny, single-celled organisms that produce "shells" of calcium carbonate, are likely the most common fossils on Guam. Fossil foraminifera are very important for age determination and the correlation of rock units across time and space. In addition to foraminifera, Johnson (1964) described 82 species of fossil calcareous algae from Guam.

The Alutom Formation (geologic map units Ta and Tam) crops out in the Asan Inland, Fonte Plateau, Mt. Chachao, Mt. Tenjo, and Piti Guns units of the park and contains at least 14 species of planktonic foraminifera. The Mariana and/or Alifan limestone formations (geologic map units QTmr, QTmd, QTmm, QTmf, and QTma and Tal, respectively) occur within the Asan Inland, Mt. Alifan, Asan Beach, and Agat units. The Mariana Limestone is very fossiliferous, containing remains of creatures from reefs and lagoons including sea urchins, mollusks, foraminifera, and corals. The Alifan Limestone contains foraminifera. Fossil crabs, shrimp, barnacles, mollusks, corals, and ray teeth may wash up on park beaches (Hunt et al. 2007).

Fossils may also appear in cultural contexts within War in the Pacific National Historical Park (Kenworthy and Santucci 2006). Many fortifications were constructed using “coral limestone” or “crushed coral” sourced from local formations, which may include identifiable Pleistocene or older fossil remains (Hunt et al. 2007).

Santucci et al. (2009) outlined potential threats to *in situ* paleontological resources and suggested monitoring “vital signs” to qualitatively and quantitatively assess the potential impacts of these threats. Paleontological vital signs include: 1) erosion (geologic factors), 2) erosion (climatic factors), 3) catastrophic geohazards, 4) hydrology/bathymetry, and 5) human access/public use. The authors also suggested methodologies for monitoring each vital sign.

Plate Tectonic Processes

Guam’s location and features result from the plate tectonic process of subduction, which occurs when two tectonic plates collide and the denser plate plunges (subducts) beneath the less dense plate. The temperature of the subducting plate increases as it descends, causing it to “sweat” molten fluids. This facilitates the melting of surrounding rock material. Molten material then rises toward the surface and can erupt as volcanoes. Because plates subduct at an angle, volcanoes are located inland from the actual plate boundary rather than immediately above the trench (fig. 4). Earthquakes occur when the plates shift suddenly or large bodies of molten material move toward the surface.

Along the Pacific “Ring of Fire,” the Pacific Plate subducts beneath various continental and other oceanic plates and drives the volcanoes and earthquakes associated with the region. The Mariana Trench—east of Guam—is the deepest point of Earth’s crust, extending more than 11 km (7 mi) below the ocean’s surface. Here, the Pacific Plate subducts northwestward beneath the Mariana and Philippine plates at a rate of about 7.6 cm (3.0 in) per year (figs. 4, 5) (Comartin 1995, Harada and Ishibashi 2008). Guam and the other Mariana Islands are a classic example of an island arc, or a curved line of volcanoes that rise up from the ocean floor—fueled by molten material created during subduction. The oldest volcanic rocks on Guam, the Facpi volcanics (originally mapped as part of the Umatac Formation, geologic map unit Tuf), erupted approximately 44 million years ago and record some of the early phases of island-building volcanism. The Facpi volcanics (pillow basalts, columnar joints) are mapped in the Mt. Alifan unit. Guam has the most complete subaerially exposed section of the early phase of volcanism associated with the subducting Pacific Plate (Reagan and Meijer 1984), although this section is not exposed within War in the Pacific National Historical Park. Volcanic breccias formed during explosive pyroclastic eruptions are within the Alutom Formation (Ta) exposed in the Mt. Chachao/Mt. Tenjo, Agat, Piti Guns, and Asan Inland units. Volcanism continues in the Mariana Island arc north and west of Guam, where volcanism largely ceased approximately 5 million years ago (Reagan and Meijer 1984).

Because of its location along an active convergent margin, Guam frequently experiences earthquakes, which are a major geologic resource management issue (see “Geologic Issues” section). Earthquakes facilitate ongoing uplift of the island; limestones that formed in marine environments are currently exposed hundreds of feet above sea level. The earthquake of August 8, 1993 provided a wealth of information about subduction zone dynamics and seismic phenomena with implications for similar areas elsewhere, including the Pacific Northwest (Comartin 1995, Chen 1998). The epicenter was about 60 km (37 mi) south of Agana at an intermediate depth of approximately 40–50 km (25–30 mi). At first, geologists were not sure if this earthquake event occurred along a plane between the Pacific and Mariana plates (interplate) or within the subducting slab of the Pacific Plate (intraplate) (Comartin 1995). Interplate earthquakes seldom occur within the Mariana subduction zone. Interpretation of the background seismicity (very frequent small tremors that geologists use to delineate the shape of the Pacific slab) in concert with the locations of major earthquakes and aftershocks occurring in 1993, 2001, and 2002 revealed they were most likely intraplate events within the subducted Pacific Plate (Harada and Ishibashi 2008). Thus, earthquakes on Guam have contributed to the greater knowledge of seismicity, and techniques developed with the seismology field continue to evolve, enabling a more in-depth understanding of the active plate boundary just east of Guam.

Connections Between Geology and Park Stories

Geologic features—particularly caves and topographic highs—played a major role in the history of Guam and the events commemorated at War in the Pacific National Historical Park. The first human inhabitants of Guam, the ancient Chamorro, used sea-level caves containing freshwater as water sources. Agana and Asan springs were long-used local drinking water sources until well pumping in upland areas diminished the flows from the springs and provided a more consistent supply (Mylroie et al. 2001). Visible remains of Guam’s early inhabitants include the latte stone remnants of ancient houses (primarily constructed around 1100 CE). These two-piece structures consist of 1) a supporting column or pillar (halagi), usually composed of quarried coralline limestone; and 2) a capstone (tasa) made from natural, hemispherical coral heads collected from the fringing reefs. In coastal settings of Guam, the long axes of latte structures (stone arrangements) were parallel to the coastline. These coastal sites customarily contain ancient human remains and possessions buried below the parallel arrangements of stones (Villaverde 2011). There are ancient Chamorro latte structures within park-owned land that is currently beyond the legislative boundary. An archeological survey would help catalog Chamorro artifacts (including possibly latte structures) within legislative boundaries (M. Gawel and J. Oelke, email communication, July 2, 2012).

Many sites within the park have cultural importance for the Chamorro resident population. Local legends are associated with Camel Rock in the Asan Beach Unit and islets in the Agat Unit; Camel Rock is a large block of coralline limestone that may have been dislodged during a prehistoric typhoon (M. Gawel and B. Alberti, conference call, March 2, 2011). Per legend, Camel Rock was intended to be placed across Agana Bay to block ancient invaders by a super-strong, pure Chamorro race; however, it was dropped en route and the ancient races intermixed (Villaverde 2011). Many cultural sites have marine-related importance, such as a food-gathering site on the reef flat at Asan Beach and a fishing area within the Agat Beach Unit (Daniel 2006). Prehistoric pottery found in the Mt. Alifan Unit was likely sourced from clay deposits weathered from the volcanic and limestone rocks (Daniel 2006). At Fonte Plateau, a historic limestone quarry (geologic map unit Tal) predates World War II. It was used by the Japanese during the war and by the U.S. Department of Defense after the war (M. Gawel, email communication, April 11, 2011; M. Gawel and B. Alberti, conference call, March 2, 2011).

Prior to World War II, geologic interest in Guam was largely academic. Stroup (1940) described the "satin-stones" of Guam, formed when secondary minerals filled voids in the rock (zeolites) and then weathered out as pebbles. These polishable rocks wash up in Guam's beach and alluvium deposits (geologic map units Qrb and Qal). In 1940, Stearns published a brief geologic history of Guam that has since been revised in light of plate tectonic theory of the 1960s (see "Geologic History" section). His history involved nine important events: 1) building of a submarine volcano, 2) cessation of volcanism, 3) intense folding and faulting, 4) shallow-water limestone deposition, 5) faulting, 6) emergence and erosion, 7) resubmergence and coral reef development, 8) series of marine transgressions and regressions and terrace development, and 9) late-stage emergence (Stearns 1940). Once the strategic importance of the island was noted by the military, interest in Guam's geology intensified, particularly with respect to groundwater resources and infrastructure support.

The strategic location of Guam is the result of island-forming geologic processes around the Pacific Rim. The subduction of the Pacific Plate beneath the Philippine Plate created multiple island arcs throughout the region. Many of these islands are too small to harbor the military infrastructure necessary to establish major bases and airfields. Guam's early volcanic history was relatively long lived, limestone accumulation was significant, and active tectonics uplifted the island even further, making it the largest of the Mariana Islands. It was a natural target for the Japanese military, which sought to establish supply depots and expand territory throughout the range of their aircraft and naval vessels.

Geology was a major factor in the 1944 battle for Guam, setting the stage for the Japanese defense of the island and its liberation by the Americans. Agat and Asan invasion beaches, Asan Ridge Battle Park, Hill 40, Matgue River Valley Battlefield, Memorial Beach Park, and Piti Coastal Defense Guns appear on the National Register of Historic Places (Daniel 2006). The Japanese used high-elevation areas, such as Asan Ridge, Fonte Plateau, and the Piti Guns Unit, to shell American troops, who were forced to land at sea level on a broad open beach. The airfield and Apra Harbor were major operational goals. Much of Guam's northern coastline is fronted by nearly insurmountable limestone cliffs; Asan and Agat beaches, where the American forces chose to land, are at the base of hillslope and cliff areas fortified by the Japanese. From their vantage point, Japanese troops had a broad, unobstructed view of the landing beaches and could fire on the landing troops below (fig. 21).

Karst features and processes greatly influenced the nature and progress of World War II conflict on Guam. The karst terrain provided very little surface water; although streams flow out of some caves on the steep coasts, upland caves did not provide perennial, consistent water sources (D. Weary, Geologist, U.S. Geological Survey, writtten communication, March 1, 2012). Groundwater wells in southern Guam provided almost no water (Ward et al. 1964). Thus, water supplies became a significant tactical barrier. The Japanese forces utilized containers of various forms to store the limited water available, and caves may still house such containers.

While the karst terrain created many challenges for water supply, it also provided many tactical advantages. Japanese garrisons modified natural limestone caves and forced local Chamorro people to excavate new cavities for fortification during the occupation of Guam. Local limestones and concrete were used as building materials (Taborosi et al. 2009; M. Gawel and B. Alberti, conference call, March 2, 2011).

The flank margin caves (see "Caves" section) formed at various ancient water-table positions provided natural defensive bastions that were extensively exploited by Japanese forces. Other cave types, such as stream caves and fissure caves, were also used. Caves were integrated with tunnels and concrete into extensive defense networks with interlocking fields of fire that proved deadly to invading American forces. The Japanese also employed cave expansion and exploitation skills learned on Guam in their defense of Iwo Jima (Mylroie et al. 2004). The Micronesian Area Research Center of the University of Guam is assessing the cave-related history of War in the Pacific National Historical Park as part of a larger coastal vulnerability study (see "Coastal Vulnerability and Relative Sea-level Rise" sections; contact Dr. John Peterson and Dr. Steve Acabado) (M. Gawel, email communication, April 11, 2011).

Near the end of the battle for Guam, resisting stragglers sought refuge in the island's limestone caves. The Northern Caves (in northern Guam, outside park boundaries) contain many World War II artifacts left behind by Japanese hiding there after the island was liberated (Taborosi et al. 2009). The caves may still contain unexploded ordnance. The park is aware of large amounts of unexploded ordnance in areas of extensive karst formation. This concentration is because the extensive karst precludes thorough travel and survey. In 2012 alone, the park uncovered six grenades, three mortars, and several dozen bullets within a survey grid of less than 200 m^2 (2000 ft^2) (M. Gawel and J. Oelke, email communication, July 2, 2012).

Following the battles on Guam, the American military rapidly began development of several bases and other installations on the island. The geology of the island was the focus of a military study (see Tracey et al. 1959) and a multifaceted U.S. Geological Survey study (Professional Paper 403) in the 1960s (see Carroll and Hathaway 1964, Emery 1964, Johnson 1964, Schlanger 1964, Stark 1964, Tracey et al. 1964a–c, Ward et al. 1964).

Because geology forms the framework for the ecosystems of Guam and so strongly influenced history at War in the Pacific National Historical Park, knowledge of the island's geology contributes to understanding the past, present, and future narrative of the park. This narrative continues to evolve as the military presence on the island increases and geologic processes continue to shape the land.

Geologic History

This section describes the rocks and unconsolidated deposits that appear on the digital geologic map of War in the Pacific National Historical Park, the environment in which those units were deposited, and the timing of geologic events that formed the present landscape.

The geologic history of War in the Pacific National Historical Park and the island of Guam 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 Mariana Plate along the Mariana Trench. Rocks in the park area record only a brief portion of Earth's 4.5-billion-year history; Guam's history began just 44 million years ago, during the Eocene Epoch (fig. 8). The geologic history of the island greatly influenced its cultural history and the history commemorated by War in the Pacific National Historical Park. Ongoing, dynamic coastal and weathering processes continue to shape the landscape.

Pre-Cenozoic History of the Pacific Basin

In the late Paleozoic, all continental landmasses joined to form one large supercontinent called "Pangaea." During this time, mountain ranges such as the Appalachians, formed by continental collision. A huge water body, the Panthallassic Ocean, surrounded Pangaea. The supercontinent Pangaea began to break apart early in the Triassic Period. Pangaea split into a northern continent called Laurasia and a southern continent called Gondwana. Further rifting divided Laurasia into the North American and Eurasian continents, whereas Gondwana eventually separated into the continents of South America, Africa, Australia, and Antarctica (Condie and Sloan 1998). Continental rifting (extension) opened new oceans, such as the Atlantic Basin, between the Americas, and between Europe and Africa. The Indian Ocean Basin formed between Africa, Antarctica, and Australia. Rifting continued throughout the Mesozoic. The oceanic crust of the Panthallassic Ocean Basin was also changing and splitting during this time.

Approximately 125 million years ago (early to middle Cretaceous), evidence suggests that a massive increase in volcanic activity in the western Pacific Ocean Basin produced large volcanic plateaus above several large mantle plumes. This activity was concurrent with a rapid increase in sea-floor spreading rates (speed at which oceanic crust on one side of the rift moved with respect to the other side). Rates increased by 50% to 100%, and remained high until the late Cretaceous (Condie and Sloan 1998). This activity correlates with rising sea level, global climate change (warming), and several extinction events in the middle Cretaceous.

The present Pacific plate fills most of the North Pacific Ocean Basin, but this situation was not always so. The Pacific plate, on which the Hawaiian-Emperor volcanic chain is located, is relatively young in geologic terms. In the Cretaceous, several plates existed within the basin, likely derived from the partitioning of the Panthalassic Ocean upon the breakup of Pangaea.

The Pacific plate started as a small central plate, surrounded by the Aluk plate to the south, the Farallon plate to the east, and the Kula plate to the north (fig. 23) (Condie and Sloan 1998; University of California Santa Barbara 2006). Separated by mid-ocean ridges, the plates surrounding the Pacific plate began moving away from it. During the middle Tertiary, the surrounding plates had mostly assimilated into the earth's crust by subduction. Oceanic crust is denser than continental crust; thus, in a collision between the two, the oceanic crust tends to sink (subduct) beneath the continental crust. This subduction generates heat, as the plate sinks into the upper mantle. The oceanic crust melts and rises to the surface, often forming a volcanic arc above the melting plate, in effect recycling the oceanic crust material.

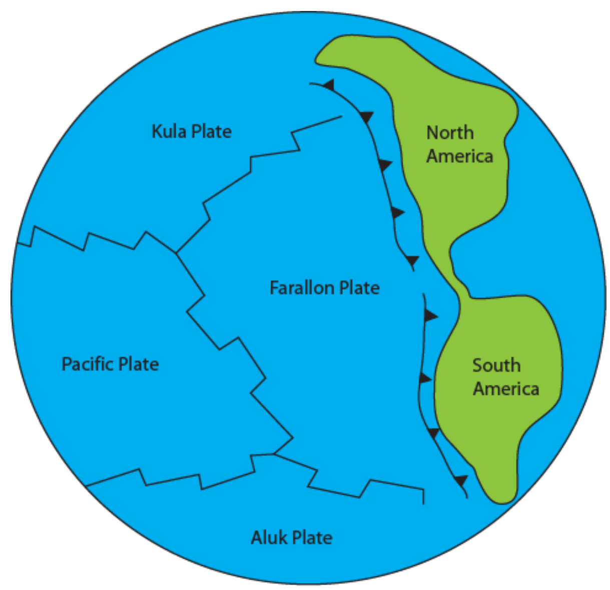

Figure 23. Generalized arrangement of plates in the Pacific Ocean Basin during the middle Cretaceous. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University).

The Kula plate plunged into the mantle at the northeast Asian subduction zone, possibly coinciding with the opening of the Sea of Japan. The Farallon plate subducted beneath North and South America resulting in the Sevier-Laramide orogenic event. Remnants of this plate include the Juan de Fuca plate off the coast of

Oregon and Washington, the Cocos plate off the coast of Central America, and the Nazca plate subducting beneath South America (Condie and Sloan 1998). During this time, the Pacific plate had been enlarged by seafloor spreading, nearly filling the north Pacific Basin. It now is moving slowly northward and westward—toward the subduction zones bordering the Australian-Indian plate, the Philippine plate (where Guam is located), the Eurasian plate and the Aleutian Islands of the North American plate (figs. 4 and 5) (University of California Santa Barbara 2006). The Pacific plate now covers about 20% of the Earth's crust, and is the largest tectonic plate on the planet (fig. 5). There are linear chains of volcanic islands and seamounts (submerged volcanoes) throughout the Pacific basin.

Eocene through Oligocene Epochs (55.8–23.0 million years ago): Island Arc Volcanism Created a Framework for the Mariana Islands

Guam began to form around the time when the direction of Pacific Plate movement changed over a period of 8 million years, from 50 to 42 million years ago (Sharp and Clague 2006). This change in direction is visible at the "kink" in the line of Emperor Seamounts and Hawaiian Island volcanoes that formed above a stationary mantle plume (hotspot) (figs. 4 and 5). The Pacific Plate traveled a more westerly course and subducted beneath the Mariana and Philippine plates along the Mariana Trench. Between about 43 and 32 million years ago, island arc–forming volcanism, which occurs above subduction zones, laid the foundation for Guam (Randall 1979, Reagan et al. 1981, Reagan and Meijer 1984). Approximately 32 million years ago, the ridge of volcanoes split and Guam was located on the southwestern side of the newly formed West Mariana Ridge. This ridge experienced volcanism between 32 and 20 million years ago and volcanism ceased between 9 and 5 million years ago.

The oldest dated rocks (44 million years old) on Guam are the pillow basalts, linear basalt dikes, and chaotic and angular volcanic breccia of the Facpi Formation [originally mapped as part of the Umatac Formation (geologic map unit Tuf). These rocks represent the first stage of island-arc volcanism, when the ancient volcano was still submerged (Tracey et al. 1964b, Reagan and Meijer 1984, Mohler 2003, Siegrist et al. 2007, Wortel 2007). Pillow basalts form underwater, where the water rapidly cools erupting lava to form "pillows." Continued volcanism and island-building processes caused the future island of Guam to approach the ocean's surface, and deposited the mixed volcanic ash, lava flows, shales, sandstones, and coarse-grained conglomerates and breccias of the Alutom Formation (geologic map unit Ta) and its fine-grained, shale-rich subunit, the Mahlac Member (geologic map unit Tam) (Tracey et al. 1964b). These units accumulated during the Middle Eocene and Oligocene epochs (approximately 45–23 million years ago) (Tracey et al. 1964b, Reagan and Meijer 1984).

Mixed volcanic and sedimentary deposits continued to accumulate in the Oligocene and early Miocene (approximately 28–14 million years ago). These deposits became the Talisay Member (geologic map unit Tt, assigned to the Oligocene by Siegrist et al. 2007) and Geus River Member (new geologic map unit defined by Siegrist et al. 2007) of the Umatac Formation (Tracey et al. 1964b, Siegrist et al. 2007). Geologists have surmised that two volcanic centers contributed to Guam's formation. One volcano was active in the Eocene to Oligocene and may have collapsed as a caldera. The other volcanic center was active during the Miocene and was located southwest of the present island.

Miocene through Pliocene Epochs (23.0–2.6 million years ago): Volcanism Slowly Ceased and Carbonates Accumulated

Following a period of erosion or non-deposition (an "unconformity" in the rock record), the mixed volcanic and sedimentary deposits of the Umatac Formation accumulated throughout the Miocene (approximately 23 through 5 million years ago) (geologic map units Tud, Tub, Tum, and Tus) (Tracey et al. 1964a, 1964b; Siegrist et al. 2007). Contemporaneous with the accumulation of the Umatac Formation, a carbonate reef formed off the coast of the volcanic island of Guam and calcareous coral, algae, and foraminifera collected; these would later become the Maemong Limestone Formation (geologic map unit Tum) that crops out in central Guam (Tracey et al. 1964b, Mylroie et al. 2001, Siegrist et al. 2007). Movement of the Mariana Microplate slowly pushed Guam away from a lava source. Volcanism ceased about 5 million years ago when the arc rifted apart to form the Mariana Trough. The trough now separates the Mariana Microplate from the rest of the Philippine Plate. Spreading of this rift moved Guam and the rest of the Mariana forearc to their present locations (Reagan and Meijer 1984). Paleomagnetic data suggest that the volcanic rocks of Guam have shifted laterally and rotated clockwise, but have not experienced significant latitudinal movement since their emplacement (Larson et al. 1975). During the Miocene, volcanism was located southwest of the present island (Randall 1979). The cessation of volcanism on Guam is reflected by the lack of volcanic deposits after the deposition of the Umatac Formation.

During the Late Miocene (between approximately 10 and 5 million years ago), carbonate accumulation began to dominate the rock-forming processes on Guam. In an off-reef environment of moderately deep water, fine-grained limestones of the Bonya Limestone (geologic map unit Tb) were deposited atop the Miocene volcanics (Tracey et al. 1964a; Mylroie et al. 2001; Siegrist et al. 2007). The Janum Formation and Barrigada Limestone (geologic map units Tj and Tbl, respectively) comprise mixed carbonate deposits, and the coral-rich Alifan Limestone (geologic map unit Tal) accumulated in nearshore, shallow coral-reef and lagoon environments (Tracey et al. 1964b; Siegrist et al. 2007). The Alifan Formation—originally deposited along the coast—now caps the highest peaks of Guam, recording a history of substantial tectonic uplift.

An unconformity separates the Miocene–Pliocene limestone units from the overlying Mariana Limestone, whose subunits (facies or members: geologic map units QTmr, QTmd, QTmm, QTmf, and QTma) accumulated during the transition from the Pliocene to the Pleistocene , 2.6 million years ago (Tracey et al. 1964b; Siegrist et al. 2007). Depositional environments recorded in the rocks of the Mariana Limestone resemble a modern fringing reef system including a coral reef, forereef, lagoon, and deeper-water areas (Tracey et al. 1964b; Siegrist et al. 2007). The Mariana Limestone occupies the largest surface area of any carbonate unit on Guam (Mylroie et al. 2001).

Pleistocene Epoch through Today (the past 2.6 million years): Sea-Level Changes, Differential Uplift, and Intense Weathering

The Mariana Limestone continued to accumulate in shoreline areas during the Pleistocene Epoch, which is defined by major climatic shifts, including global ice ages. During ice ages, global sea level dropped 120 m (400 ft) as marine water was locked into continent-sized sheets of ice on both poles. In Guam, sea-level changes during the Pleistocene and Holocene were in addition to uplift and subsidence associated with its tectonic setting above the Mariana Trench. Geologists have identified at least four terrace levels recording prolonged relative sea-level stillstands on Guam (Emery 1964, Mylroie et al. 2001). Fossil ghost shrimp and crabs (collected from Dadi Beach, near Agat Bay) indicate that extensive mangrove habitats or sublittoral mudflats were common on the island's western flanks during the Late Pleistocene, possibly during periods of lower sea level associated with glaciations (the most recent glacial maximum occurred approximately 20,000 years ago) (Pochedly et al. 2004).

Geochemical analyses of a stalagmite from Guam have revealed evidence of changing hydrology and climate in the equatorial Pacific over the last 22,000 years, following the last major glacial advance (Sinclair et al. 2008). Cave formations such as stalagmites grow slowly, and each successive growth ring can record contemporary cave environment conditions, much like tree rings can reflect forest conditions throughout the growth of a tree. Concentrations of certain elements, such as magnesium and strontium, indicate dry periods in the western Pacific during the mid-Holocene, approximately 5,000–6,000 years before present (Sinclair et al. 2008).

Although volcanism ended on Guam during the Miocene, volcanoes have been active in the Mariana arc north of Guam for about 1.3 million years and remain active today (Reagan and Meijer 1984). Compositions of modern lavas are chemically similar to those of the Miocene Umatac Formation, suggesting a similar source and melting process (Mohler 2003). Volcanism is not considered likely on Guam today, although health warnings have been issued recently due to ash emission from Anatahan Island, north of Saipan (M. Gawel, email communication, April 11, 2011)

The geomorphic features of Guam suggest that uplift and tilting have occurred throughout the late Quaternary. Marine terraces occur at higher elevations on the eastern side of the island than on the western side, indicating that Guam is being gradually uplifted and tilted westward as deformation continues along the convergent boundaries between the Pacific and Mariana plates, and between the Mariana and Philippine plates (Comartin 1995). Deformation on the island is accommodated by gentle folding of the rock strata and by fracturing and faulting within the rocks. Normal faults (fig. 24) appear in the digital geologic map data produced by the GRI (see "Geologic Map Data" section).

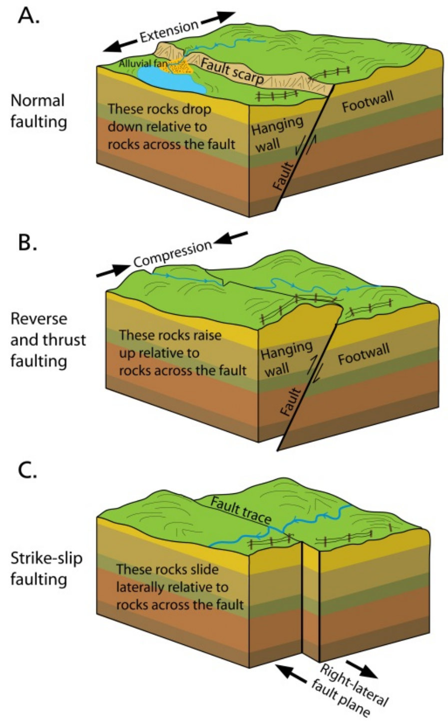

Figure 24. Fault types. In a normal fault (A), the hanging wall moves down relative to the footwall in response to extension (pulling apart) of the crust. In a reverse fault (B), the hanging wall moves up relative to the foot wall in response to compression of the crust. A thrust fault is similar to a reverse fault, but the dip angle is less than 45°. A strike-slip fault (C) results in relative horizontal movement. If the relative direction of movement has been to the right (as in this example), the fault is a right-lateral (dextral) strike-slip fault. If movement is to the left, the fault is a left-lateral (sinistral) strike-slip fault. A strike-slip fault between two plate boundaries is called a transform fault. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

The predominant structural feature, the Pago-Adelup Fault, trends northwest–southeast across central Guam, with the southern block uplifted relative to the northern block (fig. 25). This major feature separates the limestone plateau in the north from the primarily volcanic terrane in the south (Mylroie et al. 2001). Other named faults trend roughly parallel to the Pago-Adelup Fault, including, from south to north, the Cocos, Talofofo, and Tamuning-Yigo fault zones (Tracey et al. 1964b, Comartin 1995). Faults throughout the island have displaced very young rocks, including Quaternary-aged marine limestone terraces, a late-Holocene raised carbonate platform, and modern reefs (Comartin 1995), indicating tectonic activity into the modern era.

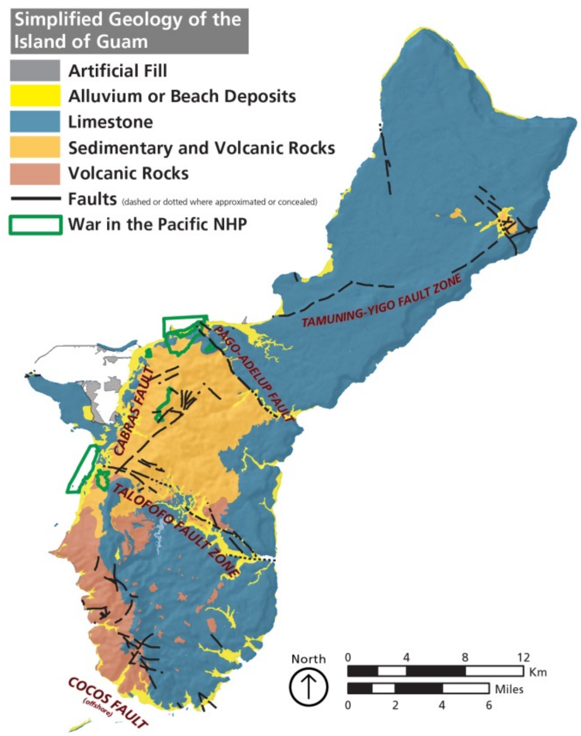

Figure 25. Simplified geology of Guam. Major rock types of Guam, showing major faults and fault zones, from south to north, Cocos Fault (offshore), Talofofo Fault Zone, Cabras Fault, Pago-Adelup Fault, and Tamuning-Yigo Fault Zone. Adapted from Tracy (1964b) using GRI digital geologic data, by Jason Kenworthy and Philip Reiker (NPS Geologic Resources Division).

The Holocene Merizo Limestone (geologic map unit Qrm) and local Tarague Limestone (geologic map unit defined by Siegrist et al. 2007), which appears only in the Tarague Embayment, are the youngest units of the limestone succession on Guam. Raised terraces of Merizo Limestone along the coast attest to recent uplift; elsewhere, the unit caps modern reefs and platforms eroded into basalt flows at sea level (Tracey et al. 1964b, Mylroie et al. 2001). The coral-rich Merizo Limestone occurs in exposures up to 1.8 m (5.9 ft) above sea level around most of Guam's shoreline, including areas near Facpi Point, just south of the Agat Unit. Radiocarbon dating has yielded an average age of about 3,600 years for the Merizo Limestone. The subaerial exposure of corals within this limestone indicate a net sea-level reduction of 2 m (6 ft) due to tectonic uplift, global sea-level change, or a complex combination of both since the coral reef was active (Easton et al. 1978).

The most recent geologic units on Guam include foraminiferal beach sands (geologic map unit Qrb) and reefs of coralline algae and corals (Stark and Schlanger 1956). Corals contain important paleoclimatic and paleo-oceanographic records because they occur in shallow tropical to subtropical environments and preserve geochemical tracers in their skeletons. The corals at Guam contain modern records (present as carbon and oxygen isotope compositions) of shifting climate and oceanic conditions, including El Niño/Southern Oscillation warm phases and cool phases (Asami et al. 2004). Between the years 1787 and 2000, Guam corals record 46 El Niño (warm) and 53 El Niña (cool) phases, in addition to increasing average sea surface temperature and decreasing sea surface salinity (Asami et al. 2005).

Beach sands and alluvial deposits (geologic map units Qrb and Qal, respectively) are associated with dynamic environments of shorelines and stream systems in the present day (Tracey et al. 1964a). They are subject to rapid change; a single storm or heavy surface-water runoff event can dramatically alter their geomorphology and spatial distribution. The alluvial unit also includes muck and clay deposited in relatively still waters of estuarine marshes and wetlands. These types of deposit accumulate slowly over time and contain important paleoclimatic records as fossil remains, spores, and pollen.

Ongoing geologic processes of deposition and erosion continue to shape the landscape of Guam. Alluvium is accumulating in sinks, depressions, coastal lowlands, and valley floors. Carbonate sediments and reef-building (future limestones) continues in submerged areas, whereas subaerially exposed carbonates are dissolving. Erosion and weathering of the upland areas scours valleys and slopes while supplying sediment to the lowland areas (Randall 1979). Volcanic initiation and cessation, subsequent reef construction and uplift, and more recent Earth surface processes form the foundation of War in the Pacific National Historical Park.

Geologic Map Data

This section summarizes the geologic map data available for War in the Pacific National Historical Park. The Geologic Map Overview Graphics display the geologic map data draped over a shaded relief image of Guam. The foldout Map Unit Properties Table summarizes this report's content for each geologic map unit. Complete GIS data are included on the accompanying CD and are also available at the GRI publications website (http://www.nature.nps.gov/geology/inventory/gre_publications.cfm).

Geologic Maps

Geologic maps facilitate an understanding of an area's geologic framework and the evolution of its present landscape. Using designated colors and symbols, geologic maps portray the spatial distribution and relationships of rocks and unconsolidated deposits. There are two primary types of geologic maps: surficial and bedrock. Surficial geologic maps encompass deposits that are frequently unconsolidated and formed during the past 2.6 million years (the Quaternary Period). Surficial map units are differentiated by geologic process or depositional environment. Bedrock geologic maps encompass older, generally more consolidated sedimentary, metamorphic, and/or igneous rocks. Bedrock map units are differentiated based on age and/or rock type. For reference, a geologic time scale is included as figure 8. Bedrock and surficial geologic map units are included in the map data for the park.

Source Maps

The Geologic Resources Inventory (GRI) team converts digital and/or paper source maps into GIS formats that conform to the GRI GIS data model. The GRI digital geologic map product also includes essential elements of the source maps, including unit descriptions, map legend, map notes, references, and figures. The GRI team used the following source maps to produce the digital geologic data for the park. These source maps provided information for the "Geologic Issues," "Geologic Features and Processes," and "Geologic History" sections of this report. Siegrist et al. (2007) provides updated nomenclature and ages for some of the map units in the GRI data.

Tracey, J. I., S. O. Schlanger, J. T. Stark, D. B. Doan, and H. G. May. 1964b. Geologic map and sections of Guam, Mariana Islands (scale 1:50,000). Plate 1/3 *in* General geology of Guam. Professional Paper 403-A. U.S. Geological Survey, Reston, Virginia, USA.

Tracey, J. I., S. O. Schlanger, J. T. Stark, D. B. Doan, and H. G. May. 1964c. Sample locality map of Guam, Mariana Islands (scale 1:50,000). Plate 2/3 *in* General geology of Guam. Professional Paper 403-A. U.S. Geological Survey, Reston, Virginia, USA.

Geologic GIS Data

The GRI team implements a GIS data model that standardizes map deliverables. The data model is included on the enclosed CD and is also available online (http://science.nature.nps.gov/im/inventory/geology/GeologyGISDataModel.cfm). This data model dictates GIS data structure including layer architecture, feature attribution, and relationships within ESRI ArcGIS software. The GRI team digitized the data for War in the Pacific National Historical Park using data model version 2.1.

GRI digital geologic data are included on the attached CD and are available through the NPS Integrated Resource Management Applications (IRMA) portal (https://irma.nps.gov/App/Reference/Search?SearchType=Q). Enter "GRI" as the search text and select the park from the unit list.

The following components and geology data layers are part of the data set:

- Selected data layers in Google Earth (.kmz) format
- Data in ESRI geodatabase and shapefile GIS formats
- Layer files with feature symbology
- Federal Geographic Data Committee (FGDC)-compliant metadata
- A help file (.pdf) document that contains all of the ancillary map information and graphics, including geologic unit correlation tables and map unit descriptions, legends, and other information captured from source maps.
- An ESRI map document file (.mxd) that displays the digital geologic data.

Table 2. Geology data layers in the War in the Pacific National Historical Park GIS data.

Data Layer	Code	On Geologic Map Overview?	On Google Earth Layers?
Geologic Cross-Section Lines	SEC	No	No
Geologic Attitude Observation Localities	ATD	No	No
Geologic Sample Localities	GSL	No	No
Mine Point Features	MIN	No	No
Brecciated Zone	GLF	No	Yes
Linear Joints	JLN	No	Yes
Fault and Fold Map Symbology	SYM	Yes	No
Folds	FLD	Yes	Yes
Faults	FLT	Yes	Yes
Linear Dikes	DKE	No	Yes
Geologic Contacts	GLGA	Yes	Yes
Geologic Units	GLG	Yes	Yes

Geologic Map Overview Graphics

The Geologic Map Overview Graphics (in pocket) display the GRI digital geologic data draped over a shaded relief image of Guam and includes basic geographic information. For graphic clarity and legibility, not all GIS feature classes are visible on the overview. Cartographic elements and basic geographic information have been added to overviews. Digital elevation data and geographic information, which are part of the overview graphics, are not included with the GRI digital geologic GIS data for the park, but are available online from a variety of sources.

Map Unit Properties Table

The geologic units listed in the Map Unit Properties Table (in pocket) correspond to the accompanying digital geologic data. Following the structure of the report, the table summarizes the geologic issues, features, and processes, and geologic history associated with each map unit. The table also lists the geologic time period, map unit symbol, and a simplified geologic description of the unit. Please refer to the geologic timescale (fig. 8) for the geologic period and age associated with each unit.

Use Constraints

Graphic and written information provided in this section is not a substitute for site-specific investigations, and ground-disturbing activities should neither be permitted nor denied based upon the information provided here. Minor inaccuracies may exist regarding the location of geologic features relative to other geologic or geographic features on the overview graphic. Based on the source map scale (1:50,000) and U.S. National Map Accuracy Standards, geologic features represented here are horizontally within 25 m (83 ft) of their true location.

Please contact GRI with any questions.

Glossary

This glossary contains brief definitions of geologic terms used in this report. Not all geologic terms used are listed. Definitions are based on those in the American Geological Institute Glossary of Geology *(fifth edition; 2005). Additional definitions and terms are available at: http://geomaps.wr.usgs.gov/parks/misc/glossarya.html.*

absolute age. The geologic age of a fossil, rock, feature, or event in years; commonly refers to radiometrically determined ages.

accretionary prism. A wedge-shaped body of deformed rock consisting of material scraped off of subducting oceanic crust at a subduction zone. Accretionary prisms form in the same manner as a pile of snow in front of a snowplow.

active margin. A tectonically active margin where lithospheric plates come together (convergent boundary), pull apart (divergent boundary) or slide past one another (transform boundary). Typically associated with earthquakes and, in the case of convergent and divergent boundaries, volcanism. Compare to "passive margin."

alkalic. Describes rocks that are enriched in sodium and potassium.

allogenic. Pertaining to a stream that derives much of its water from a distant terrain to from beyond its surface drainage area.

alluvial fan. A fan-shaped deposit of sediment that accumulates where a hydraulically confined stream flows to a hydraulically unconfined area. Commonly out of a mountainous area into an area such as a valley or plain.

alluvium. Stream-deposited sediment.

amygdule. A gas cavity or vesicle in an igneous rock, which is filled with secondary minerals.

angular unconformity. An unconformity where the rock layers above and below are oriented differently. Also see "unconformity."

anticline. A convex-upward ("A" shaped) fold. Older rocks are found in the center.

aphanitic. Describes the texture of fine-grained igneous rocks where the different components are not distinguishable with the unaided eye.

aphyric. Describes the texture of fine-grained or aphanitic igneous rocks that lack coarse (large) crystals.

aquifer. A rock or sedimentary unit that is sufficiently porous that it has a capacity to hold water, sufficiently permeable to allow water to move through it, and currently saturated to some level.

arc. See "volcanic arc" and "magmatic arc."

argillaceous. Describes a sedimentary rock composed of a substantial amount of clay.

argillite. A compact rock, derived from mudstone or shale, more highly cemented than either of those rocks. It does not easily split like of shale or have the cleavage of slate. It is regarded as a product of low-temperature metamorphism.

ash (volcanic). Fine material ejected from a volcano (also see "tuff").

asthenosphere. Earth's relatively weak layer or shell below the rigid lithosphere.

autogenic. Said of a type of drainage that is determined entirely by the conditions of the land surface over which the streams flow.

axis (fold). A straight line approximation of the trend of a fold which divides the two limbs of the fold. "Hinge line" is a preferred term.

badlands. Eroded topography characterized by steep slopes and surfaces with little or no vegetative cover, composed of unconsolidated or poorly cemented clays or silts.

basalt. A dark-colored, often low-viscosity, extrusive igneous rock.

base flow. Stream flow supported by groundwater; flow not attributed to direct runoff from precipitation or snow melt.

base level. The lowest level to which a stream can erode its channel. The ultimate base level for the land surface is sea level, but temporary base levels may exist locally.

basement. The undifferentiated rocks, commonly igneous and metamorphic, that underlie rocks exposed at the surface.

basin (structural). A doubly plunging syncline in which rocks dip inward from all sides.

basin (sedimentary). Any depression, from continental to local scales, into which sediments are deposited.

beach. A gently sloping shoreline covered with sediment, commonly formed by the action of waves and tides.

beach face. The section of the beach exposed to direct wave and/or tidal action.

beachrock. A friable to well-cemented sedimentary rock formed in the intertidal zone.

bed. The smallest sedimentary strata unit, commonly ranging in thickness from one centimeter to a meter or two and distinguishable from beds above and below.

bedding. Depositional layering or stratification of sediments.

bedrock. A general term for the rock that underlies soil or other unconsolidated, surficial material.

bentonite. A soft clay or greasy claystone composed largely of smectite. Formed by the chemical alteration of glassy volcanic ash in contact with water.

block (fault). A crustal unit bounded by faults, either completely or in part.

bioturbation. The reworking of sediment by organisms.

blind valley. A valley in karst that ends abruptly downstream at the point at which its stream disappears underground as a sinking stream.

breccia. A coarse-grained, generally unsorted sedimentary rock consisting of cemented angular clasts greater than 2 mm (0.08 in).

breccia (volcanic). A coarse-grained, generally unsorted volcanic rock consisting of partially welded angular fragments of ejected material such as tuff or ash.

brittle. Describes a rock that fractures (breaks) before sustaining deformation.

calcareous. Describes rock or sediment that contains the mineral calcium carbonate ($CaCO_3$).

calc-silicate rock. A metamorphic rock consisting mainly of calcium-bearing silicates and formed by metamorphism of impure limestone or dolomite.

calcic. Describes minerals and igneous rocks containing a relatively high proportion of calcium.

calcite. A common rock-forming mineral: $CaCO_3$ (calcium carbonate).

caldera. A large bowl- or cone-shaped depression at the summit of a volcano. Formed by explosion or collapse.

carbonate. A mineral that has CO_3^{-2} as its essential component (e.g., calcite and aragonite).

carbonate rock. A rock consisting chiefly of carbonate minerals (e.g., limestone, dolomite, or carbonatite).

cataclastic. Describes structures in a rock such as bending, breaking, or crushing of minerals that result from extreme stresses during metamorphism.

cementation. Chemical precipitation of material into pores between grains that bind the grains into rock.

chemical sediment. A sediment precipitated directly from solution (also called nonclastic).

chemical weathering. Chemical breakdown of minerals at Earth's surface via reaction with water, air, or dissolved substances; commonly results in a change in chemical composition more stable in the current environment.

clast. An individual grain or rock fragment in a sedimentary rock, produced by the physical disintegration of a larger rock mass.

clastic. Describes rock or sediment made of fragments of pre-existing rocks (clasts).

clastic dike. A tabular mass of sedimentary material that cuts across the structure or bedding of pre-existing rock in a manner of an igneous dike; formed by filling cracks or fissures from below, above, or laterally.

clay. Can be used to refer to clay minerals or as a sedimentary fragment size classification (less than 1/256 mm [0.00015 in]).

claystone. Lithified clay having the texture and composition of shale but lacking shale's fine layering and fissility (characteristic splitting into thin layers).

cleavage. The tendency of a rock to split along parallel, closely spaced planar surfaces. It is independent of bedding.

colluvium. A general term applied to any loose, heterogeneous, and incoherent mass of rock fragments deposited by unconcentrated surface runoff or slow continuous downslope creep, usually collecting at the base of gentle slopes or hillsides.

concordant. Strata with contacts parallel to the orientation of adjacent strata.

confining bed. A body of relatively impermeable or distinctly less permeable material stratigraphically adjacent to one or more aquifers. Replaced the term "aquiclude."

conglomerate. A coarse-grained, generally unsorted, sedimentary rock consisting of cemented, rounded clasts larger than 2 mm (0.08 in).

convergent boundary. A plate boundary where two tectonic plates are colliding.

cordillera. A Spanish term for an extensive mountain range; used in North America to refer to all of the western mountain ranges of the continent.

core. The central part of Earth, beginning at a depth of about 2,900 km (1,800 mi), probably consisting of iron-nickel alloy.

cornice. An overhang of rock on the edge of a steep slope or cliff face.

country rock. The rock surrounding an igneous intrusion or pluton. Also, the rock enclosing or traversed by a mineral deposit.

creep. The slow, imperceptible downslope movement of mineral, rock, and soil particles under gravity.

cross-bedding. Uniform to highly varied sets of inclined sedimentary beds deposited by wind or water that indicate flow conditions such as water flow direction and depth.

cross section. A graphical interpretation of geology, structure, and/or stratigraphy in the third (vertical) dimension based on mapped and measured geological extents and attitudes depicted in a vertically oriented plane.

crust. Earth's outermost compositional shell, 10 to 40 km (6 to 25 mi) thick, consisting predominantly of relatively low-density silicate minerals (also see "oceanic crust" and "continental crust").

cryptocrystalline. Describes a rock texture where individual crystals are too small to be recognized and separately distinguished with an ordinary microscope.

crystalline. Describes a regular, orderly, repeating geometric structural arrangement of atoms.

crystal structure. The orderly and repeated arrangement of atoms in a crystal.

debris flow. A moving mass of rock fragments, soil, and mud, in which more than half the particles of which are larger than sand size.

deformation. A general term for the process of faulting, folding, and shearing of rocks as a result of various Earth forces such as compression (pushing together) and extension (pulling apart).

delta. A sediment wedge deposited where a stream flows into a lake or sea.

detritus. A collective term for lose rock and mineral material that is worn off or removed by mechanical means.

diagenesis. The sum of all chemical and physical changes in minerals during and after their initial accumulation.

dike. A narrow igneous intrusion that cuts across bedding planes or other geologic structures.

dip. The angle between a bed or other geologic surface and horizontal.

dip-slip fault. A fault with measurable offset where the relative movement is parallel to the dip of the fault.

disconformity. An unconformity where the bedding of the strata above and below are parallel.

discordant. Describes contacts between strata that cut across or are set at an angle to the orientation of adjacent rocks.

dissected. Describes a landscape that has been deeply cut into by streams, forming a closely-spaced network of gullies, ravines, canyons or other kinds of valleys.

divergent boundary. An active boundary where tectonic plates are moving apart (e.g., a spreading ridge or continental rift zone).

doline. A basin- or funnel-shaped hollow in limestone.

dolomite. A carbonate sedimentary rock of which more than 50% by weight or by areal percentages under the microscope consists of the mineral dolomite (calcium-magnesium carbonate).

dolomitic. Describes a dolomite-bearing rock, or a rock containing dolomite.

downcutting. Stream erosion process in which the cutting is directed in primarily downward, as opposed to lateral erosion.

drainage basin. The total area from which a stream system receives or drains precipitation runoff.

dripstone. A general term for a mineral deposit formed in caves by dripping water.

ductile. Describes a rock that is able to sustain deformation (folding, bending, or shearing) before fracturing.

eogenetic. Pertaining to the period of time between final deposition of a sediment and burial of that sediment below the depth to which surface or near-surface processes are effective.

ephemeral stream. A stream that flows briefly only in direct response to precipitation in the immediate locality and whose channel is at all times above the water table.

epicenter. The point on Earth's surface that is directly above the focus (location) of an earthquake.

epikarst. The uppermost zone of karst dissolution.

escarpment. A steep cliff or topographic step resulting from vertical displacement on a fault or by mass movement. Also called a "scarp."

estuary. The seaward end or tidal mouth of a river where freshwater and seawater mix; many estuaries are drowned river valleys caused by sea-level rise (transgression) or coastal subsidence.

eustatic. Relates to simultaneous worldwide rise or fall of sea level.

extension. A type of strain resulting from forces "pulling apart." Opposite of compression.

extrusive. Describes molten (igneous) material that has erupted onto Earth's surface.

exurgence. The exit point of a subterranean river.

facies (sedimentary). The depositional or environmental conditions reflected in the sedimentary structures, textures, mineralogy, fossils, etc. of a sedimentary rock.

fan delta. An alluvial fan that builds into a standing body of water. This landform differs from a delta in that a fan delta is next to a highland and typically forms at an active margin.

fault. A break in rock along which relative movement has occurred between the two sides.

feldspar. A group of abundant (more than 60% of Earth's crust), light-colored to translucent silicate minerals found in all types of rocks. Usually white and gray to pink. May contain potassium, sodium, calcium, barium, rubidium, and strontium along with aluminum, silica, and oxygen.

felsic. Describes an igneous rock having abundant light-colored minerals such as quartz, feldspars, or muscovite. Compare to "mafic".

flat slab subduction. Refers to a tectonic plate being subducted beneath another tectonic plate at a relatively shallow angle.

floodplain. The surface or strip of relatively smooth land adjacent to a river channel and formed by the river. Covered with water when the river overflows its banks.

fold. A curve or bend of an originally flat or planar structure such as rock strata, bedding planes, or foliation that is usually a product of deformation.

foliation. A preferred arrangement of crystal planes in minerals. In metamorphic rocks, the term commonly refers to a parallel orientation of planar minerals such as micas.

footwall. The mass of rock beneath a fault surface (also see "hanging wall").

formation. Fundamental rock-stratigraphic unit that is mappable, lithologically distinct from adjoining strata, and has definable upper and lower contacts.

fracture. Irregular breakage of a mineral; also any break in a rock (e.g., crack, joint, or fault).

fracture. Irregular breakage of a mineral. Any break in a rock (e.g., crack, joint, fault).

geology. The study of Earth including its origin, history, physical processes, components, and morphology.

groundmass. The material between the large crystals in a porphyritic igneous rock. Can also refer to the matrix of a sedimentary rock.

gully. A small channel produced by running water in earth or unconsolidated material (e.g., soil or a bare slope).

halocline. A layer over which the rate of salinity variation with depth is much larger than layers immediately above or below it. .

hanging wall. The mass of rock above a fault surface (also see "footwall").

hot spot. A volcanic center that is thought to be the surface expression of a rising plume of hot mantle material.

hydraulic conductivity. Measure of permeability coefficient.

hydrogeologic. Refers to the geologic influences on groundwater and surface water composition, movement and distribution.

hydrolysis. A decomposition reaction involving water, frequently involving silicate minerals.

igneous. Refers to a rock or mineral that originated from molten material; one of the three main classes of rocks—igneous, metamorphic, and sedimentary.

incision. The process whereby a downward-eroding stream deepens its channel or produces a narrow, steep-walled valley.

intrusion. A body of igneous rock that invades (pushes into) older rock. The invading rock may be a plastic solid or magma.

island arc. A line or arc of volcanic islands formed over and parallel to a subduction zone.

isostacy. The condition of equilibrium, comparable to floating, of the units of the lithosphere above the asthenosphere. Crustal loading (commonly by large ice sheets) leads to isostatic depression or downwarping; removal of the load leads to isostatic uplift or upwarping.

isotopic age. An age expressed in years and calculated from the quantitative determination of radioactive elements and their decay products; "absolute age" and "radiometric age" are often used in place of isotopic age but are less precise terms.

joint. A break in rock without relative movement of rocks on either side of the fracture surface.

karren. Channels or furrows cause by solution on massive, bare limestone surfaces.

karst topography. Topography characterized by abundant sinkholes and caverns formed by the dissolution of calcareous rocks.

lacustrine. Pertaining to, produced by, or inhabiting a lake or lakes.

landslide. Any process or landform resulting from rapid, gravity-driven mass movement.

lapilli. Pyroclastics in the general size range of 2 to 64 mm (0.08 to 2.5 in.).

lava. Still-molten or solidified magma that has been extruded onto Earth's surface though a volcano or fissure.

left lateral fault. A strike slip fault on which the side opposite the observer has been displaced to the left Synonymous with "sinistral fault."

lens. A sedimentary deposit characterized by converging surfaces, thick in the middle and thinning out toward the edges, resembling a convex lens.

limestone. A sedimentary rock consisting chiefly of calcium carbonate, primarily in the form of the mineral calcite.

lineament. Any relatively straight surface feature that can be identified via observation, mapping, or remote sensing, often reflects crustal structure.

lithic. A sedimentary rock or pyroclastic deposit that contains abundant fragments of previously formed rocks.

lithification. The conversion of sediment into solid rock.

lithify. To change to stone or to petrify; especially to consolidate from a loose sediment to a solid rock through compaction and cementation.

lithofacies. A lateral, mappable subdivision of a designated stratigraphic unit, distinguished from adjacent subdivisions on the basis of rock characteristics (lithology).

lithology. The physical description or classification of a rock or rock unit based on characters such as its color, mineral composition, and grain size.

lithosphere. The relatively rigid outmost shell of Earth's structure, 50 to 100 km (31 to 62 miles) thick, that encompasses the crust and uppermost mantle.

lithostratigraphy. The element of stratigraphy that deals with the lithology of strata, their organization into units based on lithologic characteristics, and their correlation.

littoral. Pertaining to the benthic ocean environment or depth zone between high water and low water.

littoral zone. The benthic ocean environment or depth zone between high water and low water.

longshore current. A current parallel to a coastline caused by waves approaching the shore at an oblique angle.

losing stream. A stream or reach of stream that contributes water to the zone of saturation and develops bank storage; its channel lies above the water table.

mafic. Describes dark-colored rock, magma, or minerals rich in magnesium and iron. Compare to "felsic."

magma. Molten rock beneath Earth's surface capable of intrusion and extrusion.

magma reservoir. A chamber in the shallow part of the lithosphere from which volcanic materials are derived; the magma has ascended from a deeper source.

magmatic arc. Zone of plutons or volcanic rocks formed at a convergent boundary.

mantle. The zone of Earth's interior between the crust and core.

marine notch. A deep, narrow cut or hollow along the base of a sea cliff near the high-water mark formed by undercutting by waves and/or chemical solution.

marine terrace. A narrow coastal strip of deposited material, sloping gently seaward.

marl. An unconsolidated deposit commonly with shell fragments and sometimes glauconite consisting chiefly of clay and calcium carbonate that formed under marine or freshwater conditions.

marlstone. An indurated rock of about the same composition as marl, called an earthy or impure argillaceous limestone.

mass wasting. A general term for the downslope movement of soil and rock material under the direct influence of gravity.

matrix. The fine grained material between coarse (larger) grains in igneous rocks or poorly sorted clastic sediments or rocks. Also refers to rock or sediment in which a fossil is embedded.

maximum credible earthquake. The largest hypothetical earthquake that may be reasonably expected to occur along a given fault.

mechanical weathering. The physical breakup of rocks without change in composition. Synonymous with "physical weathering."

megabreccia. A term for a coarse breccia containing individual blocks as much as 400 m (1,300 ft) long.

member. A lithostratigraphic unit with definable contacts; a member subdivides a formation.

microcrystalline. A rock with a texture consisting of crystals only visible with a microscope.

mid-ocean ridge. The continuous, generally submarine and volcanically active mountain range that marks the divergent tectonic margin(s) in Earth's oceans.

mineral. A naturally occurring, inorganic crystalline solid with a definite chemical composition or compositional range.

monocline. A one-limbed fold in strata that is otherwise flat-lying.

moonmilk. A white, creamy substance found inside caves comprising aggregates of fine crystals of varying composition usually made of carbonate materials. Development of moonmilk probably involves bacterial action.

neck (volcanic). An eroded, vertical, pipe-like intrusion that represents the vent of a volcano.

nonconformity. An erosional surface preserved in strata in which crystalline igneous or metamorphic rocks underlie sedimentary rocks.

normal fault. A dip-slip fault in which the hanging wall moves down relative to the footwall.

obduction. The process by which the crust is thickened by thrust faulting at a convergent margin.

oblique fault. A fault in which motion includes both dip-slip and strike-slip components (also see "dip-slip fault" and "strike-slip fault").

obsidian. A black or dark-colored volcanic glass, usually of rhyolite composition with conchoidal fracture. Can be used as a raw material for arrowheads, jewelry, and art objects.

oceanic crust. Earth's crust formed at spreading ridges that underlies the ocean basins. Oceanic crust is 6 to 7 km (3 to 4 miles) thick and generally of basaltic composition.

olivine. An olive-green mineral rich in iron, magnesium, and manganese that is commonly found in low-silica (basaltic) igneous rocks.

outcrop. Any part of a rock mass or formation that is exposed or "crops out" at Earth's surface.

paleofill. Ancient sediment that filled caves and sinkholes existing before the present cave passages formed.

paleogeography. The study, description, and reconstruction of the physical landscape from past geologic periods.

paleontology. The study of the life and chronology of Earth's geologic past based on the fossil record.

parent material. Geologic material from which soils form.

partings. A plane or surface along which a rock readily separates.

passive margin. A margin where no plate-scale tectonism is taking place; plates are not converging, diverging, or sliding past one another. An example is the east coast of North America. (also see "active margin").

pebble. Generally, small rounded rock particles from 4 to 64 mm (0.16 to 2.52 in) in diameter.

pendant. A solutional remnant hanging from the ceiling or wall of a cave.

perched aquifer. An aquifer containing unconfined groundwater separated from an underlying main body of groundwater by an unsaturated zone.

permeability. A measure of the relative ease with which fluids move through the pore spaces of rocks or sediments.

phenocryst. A coarse (large) crystal in a porphyritic igneous rock.

phosphatic. Pertaining to or containing phosphates; commonly refers to a sedimentary rock containing phosphate minerals.

phreatic explosion. A volcanic eruption or explosion of steam, mud, or other material that is not hot enough to glow; it is caused by the heating and consequent expansion of groundwater due to an underlying igneous heat source.

phreatic zone. The zone of saturation. Phreatic water is groundwater below the water table.

pinnacle. A small, isolated spire or column of rock.

plate tectonics. The concept that the lithosphere is broken up into a series of rigid plates that move over Earth's surface above a more fluid asthenosphere.

plateau. A broad, flat-topped topographic high (terrestrial or marine) of great extent and elevation above the surrounding plains, canyons, or valleys.

platform. Any level or nearly-level surface, ranging in size from a terrace or bench to a plateau or peneplain.

plume. A persistent, pipe-like body of hot material moving upward from Earth's mantle into the crust.

pluton (plutonic). A body of intrusive igneous rock that crystallized at some depth beneath Earth's surface.

pluvial. Describes geologic processes or features resulting from rain.

ponor. Hole in the bottom of side of a closed depression through which water disappears into a cave.

porosity. The proportion of void space (e.g., pores or voids) in a volume of rock or sediment deposit.

porphyry. An igneous rock consisting of abundant coarse crystals in a fine-grained matrix.

porphyritic. Describes an igneous rock wherein the rock contains conspicuously large crystals in a fine-grained groundmass.

porphyroclast. A partly-crushed, non-metamorphosed rock fragment within a finer-grained matrix in a metamorphic rock.

prodelta. The part of a delta below the level of wave erosion.

progradation. The seaward building of land area due to sedimentary deposition.

protolith. The parent or unweathered and/or unmetamorphosed rock from which regolith or metamorphosed rock is formed.

provenance. A place of origin. The area from which the constituent materials of a sedimentary rock were derived.

pyroclast. An individual particle ejected during a volcanic eruption.

pyroclastic. Describes clastic rock material formed by volcanic explosion or aerial expulsion from a volcanic vent; also pertaining to rock texture of explosive origin. In the plural, the term is used as a noun.

radioactivity. The spontaneous decay or breakdown of unstable atomic nuclei.

radiometric age. An age expressed in years and calculated from the quantitative determination of radioactive elements and their decay products.

recharge. Infiltration processes that replenish groundwater.

recrystallization. The formation, essentially in the solid state, of new crystalline mineral grains in a rock.

reflection survey. Record of the time it takes for seismic waves generated from a controlled source to return to the surface. Used to interpret the depth to the subsurface feature that generated the reflections.

regolith. General term for the layer of rock debris, organic matter, and soil that commonly forms the land surface and overlies most bedrock.

regression. A long-term seaward retreat of the shoreline or relative fall of sea level.

relative dating. Determining the chronological placement of rocks, events, or fossils with respect to the geologic time scale and without reference to their numerical age.

resurgence. The point at which a subterranean river, having exurged above ground, reenters the subterranean channel.

reverse fault. A contractional high-angle (greater than 45°) dip-slip fault in which the hanging wall moves up relative to the footwall (also see "thrust fault").

rift. A region of crust where extension results in formation of many related normal faults, often associated with volcanic activity.

rift valley. A depression formed by grabens along the crest of an oceanic spreading ridge or in a continental rift zone.

rill. A very small channel incised by a small stream.

ripple marks. The undulating, approximately parallel and usually small-scale ridge pattern formed on sediment by the flow of wind or water.

riprap. A layer of large, durable, broken rock fragments irregularly thrown together in an attempt to prevent erosion by waves or currents and thereby preserve the shape of a surface, slope, or underlying structure.

roundstone. Any naturally-rounded rock fragment larger than a sand grain.

rock. A solid, cohesive aggregate of one or more minerals.

rock fall. Mass wasting process where rocks are dislodged and move downslope rapidly; it is the fastest mass wasting process.

roundness. The relative amount of curvature of the "corners" of a sediment grain.

runnel. A channel eroded by a small stream.

sand. A clastic particle smaller than a granule and larger than a silt grain, having a diameter in the range of 1/16 mm (0.0025 in) to 2 mm (0.08 in).

saprolite. Soft, often clay-rich, decomposed rock formed in place by chemical weathering.

scarp. A steep cliff or topographic step resulting from displacement on a fault, or by mass movement, or erosion. Also called an "escarpment."

scoria. A bomb-size pyroclast that is irregular in form and generally very vesicular.

scoriaceous. Volcanic igneous vesicular texture involving relatively large gas holes such as in vesicular basalt. Coarser than pumiceous.

seafloor spreading. The process by which tectonic plates pull apart and new lithosphere is created at oceanic ridges.

seamount. An elevated portion of the sea floor, 1,000 m (3,300 ft)or higher, either flat-topped or peaked.

sediment. An eroded and deposited, unconsolidated accumulation of rock and mineral fragments.

sedimentary rock. A consolidated and lithified rock consisting of clastic and/or chemical sediment(s). One of the three main classes of rocks—igneous, metamorphic, and sedimentary.

sequence. A major informal rock-stratigraphic unit that is traceable over large areas and defined by a sediments associated with a major sea level transgression-regression.

sheet flow. An overland flow or downslope movement of water taking the form of a thin, continuous film over relatively smooth soil or rock surfaces and not concentrated into channels larger than rills.

sheetwash (sheet erosion). The removal of thin layers of surface material more or less evenly from an extensive area of gently sloping land by broad continuous sheets of running water rather than by streams flowing in well-defined channels.

shield volcano. A volcano in the shape of a flattened dome, broad and low, built by flows of very fluid basaltic lava. The Hawaiian Mauna Loa volcano is one example.

shoreface. The zone between the seaward limit of the shore and the more nearly horizontal surface of the offshore zone; typically extends seaward to storm wave depth or about 10 m (32 ft).

sill. An igneous intrusion that is of the same orientation as the surrounding rock.

silt. Clastic sedimentary material intermediate in size between fine-grained sand and coarse clay (1/256 to 1/16 mm [0.00015 to 0.002 in]).

siltstone. A variably lithified sedimentary rock composed of silt-sized grains.

sink. A depression formed on karst landscapes by dissolution of limestone, then collapse or subsidence of overlying material.

slope. The inclined surface of any geomorphic feature or measurement thereof. Synonymous with "gradient."

slump. A generally large, coherent mass movement with a concave-up failure surface and subsequent backward rotation relative to the slope.

soil. Surface accumulation of weathered rock and organic matter capable of supporting plant growth and often overlying the parent material from which it formed.

solution pan. A shallow solution basin formed on bare limestone characterized by a flat bottom and overhanging sides.

solution pit. An indentation up to about 1 mm in diameter formed on a rock surface by solution.

specific conductance. The measure of discharge of a water well per unit of drawdown.

speleothem. Any secondary mineral deposit that forms in a cave.

spreading center. A divergent boundary where two lithospheric plates are spreading apart. It is a source of new crustal material.

spring. A site where water issues from the surface due to the intersection of the water table with the ground surface.

stillstand. A period of time during which there is relatively little change to mean sea level.

strata. Tabular or sheet-like masses or distinct layers of rock.

stratification. The accumulation, or layering of sedimentary rocks in strata. Tabular, or planar, stratification refers to essentially parallel surfaces.

Cross-stratification refers to strata inclined at an angle to the main stratification.

stratigraphy. The geologic study of the origin, occurrence, distribution, classification, correlation, and age of rock layers, especially sedimentary rocks.

stratovolcano. A volcano that is constructed of alternating layers of lava and pyroclastic deposits, along with abundant dikes and sills.

stream. Any body of water moving under gravity flow in a clearly confined channel.

stream channel. A long, narrow depression shaped by the concentrated flow of a stream and covered continuously or periodically by water.

stream terrace. Step-like benches surrounding the present floodplain of a stream due to dissection of previous flood plain(s), stream bed(s), and/or valley floor(s).

strike. The compass direction of the line of intersection of an inclined surface with a horizontal plane.

strike-slip fault. A fault with measurable offset where the relative movement is parallel to the strike of the fault. Said to be "sinistral" (left-lateral) if relative motion of the block opposite the observer appears to be to the left. "Dextral" (right-lateral) describes relative motion to the right.

structural geology. The branch of geology that deals with the description, representation, and analysis of structures, chiefly on a moderate to small scale. The subject is similar to tectonics, but the latter is generally used for the broader regional or historical phases.

structure. The attitude and relative positions of the rock masses of an area resulting from such processes as faulting, folding, and igneous intrusions.

subangular. Somewhat angular, free from sharp angles but not smoothly rounded.

subduction zone. A convergent plate boundary where oceanic lithosphere descends beneath a continental or oceanic plate and is carried down into the mantle.

subrounded. Partially rounded sedimentary particle having many of its edges and corners noticeably rounded off to smooth curves.

subsidence. The gradual sinking or depression of part of Earth's surface.

swallet. The opening through which a sinking stream loses its water to the subsurface.

syncline. A downward curving (concave up) fold with layers that dip inward; the core of the syncline contains the stratigraphically-younger rocks.

system (stratigraphy). The group of rocks formed during a period of geologic time.

talus. Rock fragments, usually coarse and angular, lying at the base of a cliff or steep slope from which they have been derived.

tectonic. Relating to large-scale movement and deformation of Earth's crust.

tectonics. The geologic study of the broad structural architecture and deformational processes of the lithosphere and asthenosphere.

telogenetic. Long-buried sediments that have been significantly affected by burial diagenetic processes

tephra. A collective term used for all pyroclastic material, regardless of size, shape, or origin, ejected during an explosive volcanic eruption.

terrace. A relatively level bench or steplike surface breaking the continuity of a slope (see "marine terrace" and "stream terrace").

terrestrial. Relating to land, Earth, or its inhabitants.

terrigenous. Derived from the land or a continent.

tholeiite. A basalt characterized by the presence of orthopyroxene and/or pigeonite in addition to clinopyroxene and calcic plagioclase.

thrust fault. A contractional dip-slip fault with a shallowly dipping fault surface (less than 45°) where the hanging wall moves up and over relative to the footwall.

topography. The general morphology of Earth's surface, including relief and locations of natural and anthropogenic features.

trace (fault). The exposed intersection of a fault with Earth's surface.

trace fossil. Tracks, trails, burrows, coprolites (dung), etc., that preserve evidence of organisms' life activities, rather than the organisms themselves.

transform fault. A strike-slip fault that links two other faults or two other plate boundaries (e.g. two segments of a mid-ocean ridge). A type of plate boundary at which lithosphere is neither created nor destroyed, and plates slide past each other on a strike-slip fault.

transgression. Landward migration of the sea as a result of a relative rise in sea level.

trend. The direction or azimuth of elongation of a linear geologic feature.

trottoir. A narrow, organic, intertidal reef construction, composed of either a solid mass or a simple crust covering a rocky substratum separating the shoreline from the sea.

tuff. Generally fine-grained, igneous rock formed of consolidated volcanic ash.

tuffaceous. A non-volcanic, clastic sedimentary rock that contains mixtures of ash-size pyroclasts.

turbidite. A sediment or rock deposited from a turbidity current (underwater flow of sediment) and characterized by graded bedding, moderate sorting, and well-developed primary structures in the sequence noted in the Bouma cycle.

type locality. The geographic location where a stratigraphic unit (or fossil) is well displayed, formally defined, and derives its name. The place of original description.

ultramafic. Describes rock composed chiefly of mafic (dark-colored, iron and magnesium rich) minerals.

unconfined groundwater. Groundwater that has a water table; i.e., water not confined under pressure beneath a confining bed.

unconformity. An erosional or non-depositional surface bounded on one or both sides by sedimentary strata. An unconformity marks a period of missing time.

undercutting. The removal of material at the base of a steep slope or cliff or other exposed rock by the erosive action of falling or running water (such as a meandering stream), of sand-laden wind in the desert, or of waves along the coast.

underfit stream. A stream that appears to be too small to have eroded the valley in which it flows; a stream whose whole volume is greatly reduced or whose meanders show a pronounced shrinkage in radius.

uplift. A structurally high area in the crust, produced by movement that raises the rocks.

vadose water. Water of the unsaturated zone or zone of aeration.

vent. An opening at Earth's surface where volcanic materials emerge.

vesicle. A void in an igneous rock formed by a gas bubble trapped when the lava solidified.

vesicular. Describes a volcanic rock with abundant holes that formed from the expansion of gases while the lava was still molten.

vitric. Describes pyroclastic material that is characteristically glassy.

volcanic. Describes anything related to volcanoes. Can refer to igneous rock crystallized at or near Earth's surface (e.g., lava).

volcanic arc. A commonly curved, linear, zone of volcanoes above a subduction zone.

volcaniclastic. Describes clastic volcanic materials formed by any process of fragmentation, dispersed by any kind of transporting agent, deposited in any environment.

volcanogenic. Describes material formed by volcanic processes.

water table. The upper surface of the saturated zone; the zone of rock in an aquifer saturated with water.

weathering. The physical, chemical, and biological processes by which rock is broken down.

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Additional References

This section lists additional references, resources, and web sites that may be of use to resource managers. Web addresses are current as of August 2012.

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University of Guam marine laboratory: http://www.uog.edu/dynamicdata/MarineLab.aspx?siteid=1&p=51

Water and Environmental Research Institute of the Western Pacific (WERI): http://www.weriguam.org/

Geology of National Park Service Areas

National Park Service Geologic Resources Division (Lakewood, Colorado). http://nature.nps.gov/geology/

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NPS Geoscientist-in-the-parks (GIP) internship and guest scientist program. http://www.nature.nps.gov/geology/gip/index.cfm

Resource Management/Legislation Documents

NPS 2006 management policies (Chapter 4; Natural resource management): http://www.nps.gov/policy/mp/policies.html#_Toc157232681

NPS-75: Natural resource inventory and monitoring guideline: http://www.nature.nps.gov/nps75/nps75.pdf

NPS Natural resource management reference manual #77: http://www.nature.nps.gov/Rm77/

Geologic Monitoring Manual
Young, R., and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado, USA. http://nature.nps.gov/geology/monitoring/index.cfm

NPS Technical Information Center (Denver, repository for technical [TIC] documents): http://etic.nps.gov/

Geological Survey Websites

U.S. Geological Survey: http://www.usgs.gov/

U.S. Geological Survey earthquake monitoring program: http://earthquake.usgs.gov/hazards/

Global Seismic Hazard Assessment Program: http://www.seismo.ethz.ch/static/gshap/

Other Geology/Resource Management Tools

U.S. Geological Survey national geologic map database (NGMDB): http://ngmdb.usgs.gov/

U.S. Geological Survey geologic names lexicon (GEOLEX; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/geolex_home.html

U.S. Geological Survey geographic names information system (GNIS; search for place names and geographic features, and plot them on topographic maps or aerial photos): http://gnis.usgs.gov/

U.S. Geological Survey GeoPDFs (download searchable PDFs of any topographic map in the United States): http://store.usgs.gov (click on "Map Locator").

U.S. Geological Survey publications warehouse (many USGS publications are available online): http://pubs.er.usgs.gov

U.S. Geological Survey description of physiographic provinces: http://tapestry.usgs.gov/Default.html

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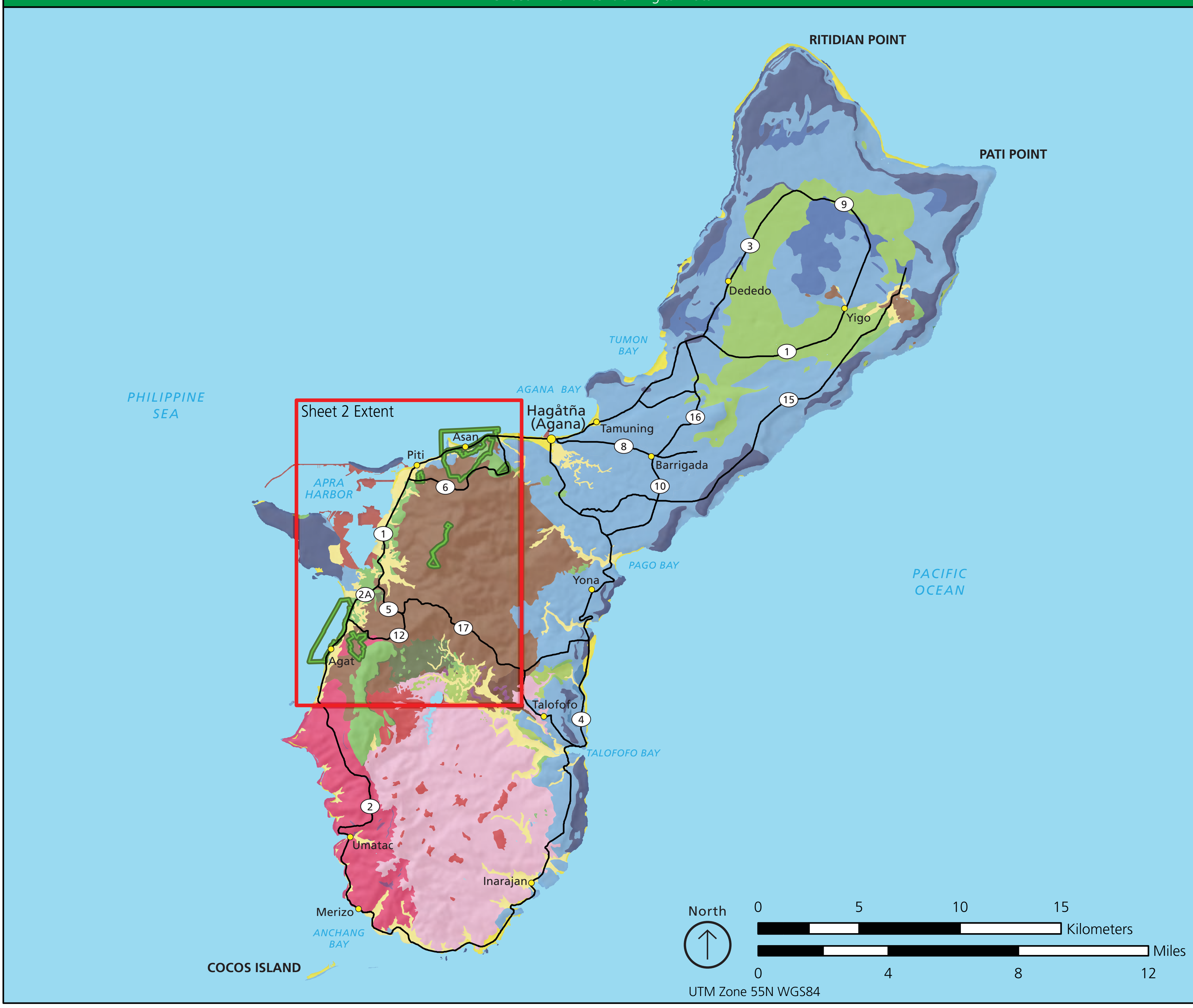
Overview of Digital Geologic Data for War in the Pacific NHP

Sheet 1: Full Extent of Digital Data



NPS Boundary

Folds

- anticline, known or certain, arrow indicates direction of plunge
- syncline, known or certain, arrow indicates direction of plunge

Faults

- unknown offset/displacement, known or certain; D indicates downthrown side
- unknown offset/displacement, approximate
- unknown offset/displacement, concealed
- unknown offset/displacement, queried
- unknown offset/displacement, approximate and queried
- unknown offset/displacement, concealed and queried
- right-lateral fault, vertical displacement/offset unknown, approximate

Geologic Contacts

- known or certain
- approximate
- map boundary
- water or shoreline
- water or shoreline, approximate

Geologic Units

- Qaf - Artificial fill
- Qrb - Beach deposits
- Qrm - Merizo Limestone
- Qal - Alluvium
- QTmr - Mariana Limestone, reef facies
- QTmd - Mariana Limestone, detrital facies
- QTmm - Mariana Limestone, molluscan facies
- QTmf - Mariana Limestone, fore-reef facies
- QTma - Mariana Limestone, Agana Argillaceous Member
- Tal - Alifan Limestone
- Tt - Alifan Limestone, Talisay Member
- Tj - Janum Formation
- Tbl - Barrigada Limestone
- Tb - Bonya Limestone
- Tud - Umatac Formation, Dandan Flow Member
- Tub - Umatac Formation, Bolanos Pyroclastic Member
- Tum - Umatac Formation, Maemong Limestone Member
- Tuf - Umatac Formation, Facpi Volcanic Member
- Tam - Alutom Formation, Mahlac Member
- Ta - Alutom Formation

This figure is an overview of compiled digital geologic data. It is not a substitute for site-specific investigations.

Minor inaccuracies may exist regarding the location of geologic features relative to other geologic or geographic features on the figure. Based on the source map scale (1:50,000) and U.S. National Map Accuracy Standards, geologic features represented here are within 25 meters / 83 feet (horizontally) of their true location.

This figure was prepared as part of the NPS Geologic Resources Division's Geologic Resources Inventory. The source maps used in creation of the digital geologic data product were:

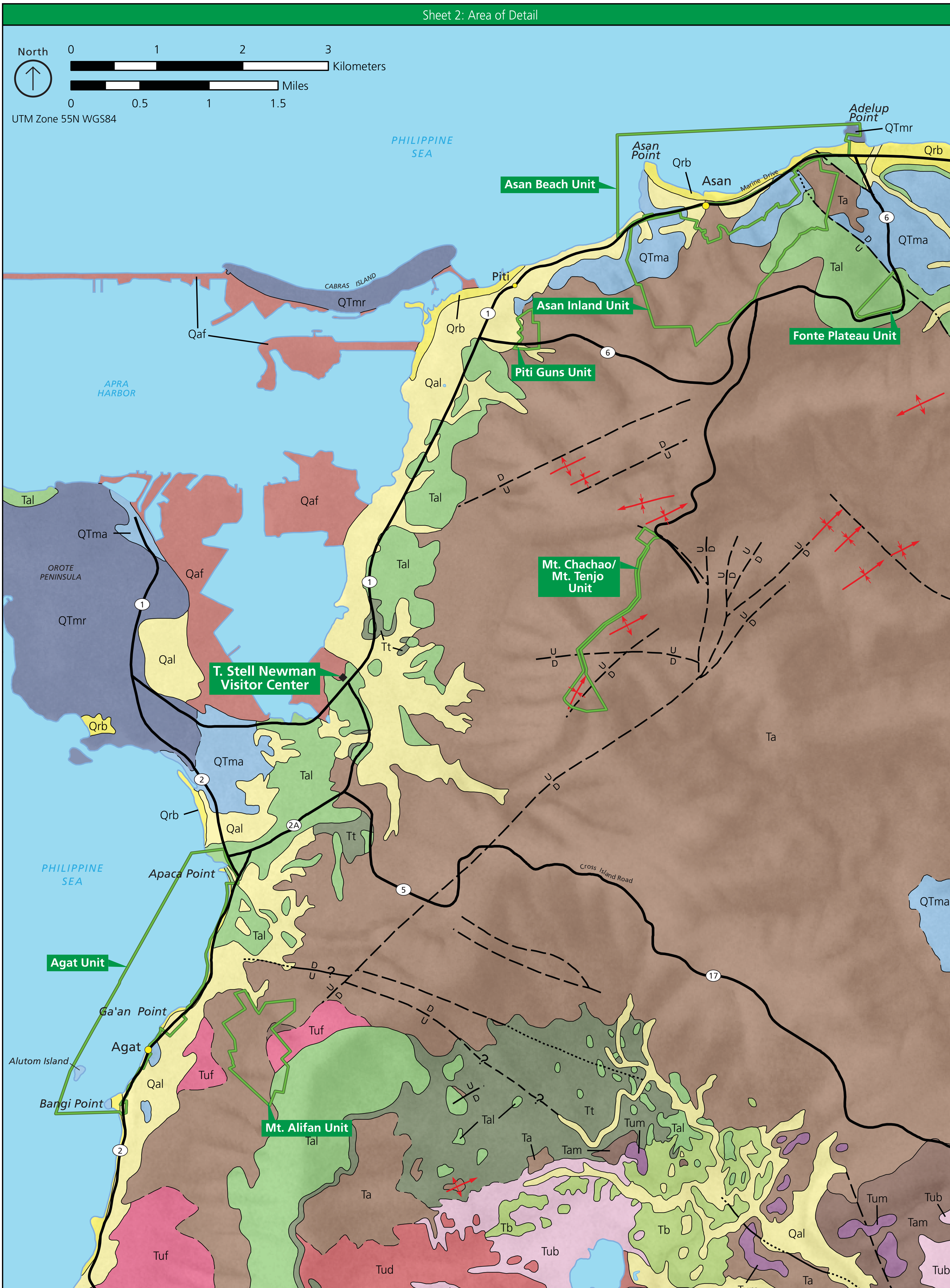
Tracey, J.I., Schlanger, S.O., Stark, J.T., Doan, D.B., and May, H.G. 1964. Geologic Map and Sections of Guam, Mariana Islands (plate 1/3) (scale 1:50,000) In General Geology of Guam, Professional Paper 403-A, plate 1/3, U.S. Geological Survey.

Tracey, J.I., Schlanger, S.O., Stark, J.T., Doan, D.B., and May, H.G., 1964, Sample Locality Map of Guam, Mariana Islands (plate 2/3) (scale 1:50,000) In General Geology of Guam, Professional Paper 403-A, plate 2/3, U.S. Geological Survey.

Digital geologic data and cross sections for War in the Pacific National Historical Park, and all other digital geologic data prepared as part of the Geologic Resources Inventory, are available online at the NPS Natural Resource Information Portal: https://nrinfo.nps.gov/Reference.mvc/Search. (Enter "GRI" as the search text and select War in the Pacific National Historical Park from the unit list.)

Produced by the Geologic Resources Inventory
September 2012

Overview of Digital Geologic Data for War in the Pacific NHP



Map Unit Properties Table: War in the Pacific National Historical Park

Gray-shaded rows indicate units not mapped within War in the Pacific National Historical Park. Italicized text corresponds to sections of the report.

Age	Map Unit (Symbol)	Geologic Description	Geologic Issues	Geologic Features and Processes	Geologic History
QUATERNARY (Recent)	Artificial fill (Qaf)	Unit **Qaf** may include features such as extensive waste dumps, areas of extensive infilling, breakwaters, levees, and dams. Fill material may vary, but is typically unsorted masses of rock, sand, and even recycled road material. Erosion resistance is moderate. **Qaf** underlies the park visitor center near Apra Harbor. *Siegrist et al. (2007) mapping updates: More areas of **Qaf** have been recognized or developed since 1964.	*Adjacent Development and Disturbed Areas*—Landfills may be sources of contaminants. *Relative Sea Level Rise and Coastal Vulnerability*—Subject to inundation and infrastructure impacts as sea level rises. *Visitor Center Stability*—The park's visitor center, built upon artificial fill, has noted settling issues. *Storm Damage*—Subject to inundation and infrastructure damage during storms. *Seismicity and Tsunamis*—Strong earthquake could compromise park infrastructure, particularly along coastal areas underlain by unconsolidated beach, alluvium, or fill deposits. **Qaf** experienced liquefaction during 1993 earthquake. Subject to inundation during tsunamis.	*Connections Between Geology and Park Stories*—Historic military features may have been constructed on **Qaf**.	These features are primarily of World War II or post war vintage. Depending on the era of installation, unit **Qaf** may record historical land-use practices on Guam.
	Beach deposits (Qrb) Merizo Limestone (Qrm) Alluvium (Qal)	Unit **Qrb** contains sand and coarser gravel in beach areas, particularly in the intertidal zone between low and high water levels. Patches of limestone fragments transported from submerged, offshore coral reefs and older limestone deposits are also present in this unit. **Qrb** generally occurs 5–10 m (15–30 ft) above sea level. This dynamic area of the landscape is susceptible to rapid change (particularly erosion and/or deposition) during storms, sea-level rise, and human-induced processes. **Qrm** is reef limestone; it occurs offshore in layers 1–2 m (2–5 ft) thick. This unit caps modern reef flats and platforms eroded into basalt at sea level. Unit **Qal** contains 9–30-m- (30–100-ft-)thick clay deposits associated with streams and rivers, as well as muck and clay deposited in marshy, estuarine areas along Guam's western coast. Very fine-grained clay may also collect in natural depressions or sinks within older limestone units. Erosion resistance is low to moderate for these units. Unconsolidated beach deposits and alluvium have low resistance **Qrb** and **Qal** are mapped within the Asan Beach and Agat units. **Qal** is mapped within the Asan Inland and Piti Guns units. *Siegrist et al. (2007) mapping updates: New unit "Reefs" added to the Recent map units.	*Mass Wasting*—Susceptible to mass wasting, particularly when saturated with water or exposed on slopes. *Relative Sea Level Rise and Coastal Vulnerability*—Subject to inundation and infrastructure impacts as sea level rises. *Storm Damage*—Coastal areas subject to inundation during storms. *Seismicity and Tsunamis*—Strong earthquake could compromise park infrastructure, particularly along coastal areas underlain by unconsolidated beach, alluvium, or fill deposits. Coastal areas subject to inundation during tsunamis.	*Karst Features*—Epikarst and/or karren cover exposed surfaces of **Qrm**. Discharge features (seeps and springs) in beach, reef, and inland limestones. *Coastal Features*—**Qrb**: Coralline, sandy beaches flank much of the park's coastline. **Qrm**: Reef limestones fringe southwest areas of island, outside of the park. *Paleontological Resources*—Modern marine remains and fragments of fossils possible in limestone-clast deposits; modern reef species in **Qrm**. Crustacean fossils (12 species of crabs) may wash up on **Qrb**. Fossil shrimp, barnacles, mollusks, corals, and ray teeth have been collected on Guam's beaches. *Plate Tectonic Processes*—Uplift (as well as sea level change) has left **Qrm** exposed. *Connections Between Geology and Park Stories*—**Qrb** may contain cultural resources associated with the military history of the island that wash up on shore.	Unit **Qrb** is among the most dynamic units at the park. **Qrm** is part of the active reef environment fringing the island, locally capping the Mariana reef rocks at sea level. This unit demonstrates how reef limestone forms, and is only exposed in the intertidal and sea-spray zones. **Qal** forms along streams and rivers, recording the evolution of Guam's fluvial environment. **Qal** is common in the Agat Unit. "Satin-stones" (after Stroup 1940) may wash up in **Qal** and/or **Qrb** and are polishable as semi-precious gemstones.

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Age	Map Unit (Symbol)		Geologic Description	Geologic Issues	Geologic Features and Processes	Geologic History
TERTIARY-QUATERNARY (Pliocene-Pleistocene)	Mariana Limestone	Reef facies (QTmr)	**QTmr**, a subunit of the Mariana Limestone, consists of porous, cavernous, white limestone that formed in a coral reef environment. Few bedding structures or depositional surfaces are visible in exposures. Corals preserved in this unit remain oriented in the direction of growth, indicating that this unit has not been disturbed much since its formation. Surrounding the fossil corals of **QTmr** is a matrix of encrusting calcareous (containing calcium carbonate) fossil algae. Erosion resistance is moderate. **QTmr** is mapped within the Asan Beach unit.	*Relative Sea Level Rise and Coastal Vulnerability*—Subject to inundation and infrastructure impacts as sea level rises. *Adjacent Development and Disturbed Areas*—Groundwater Withdrawal and Contamination: **Tbl** and Mariana Limestone units host Northern Guam Lens Aquifer. *Mass Wasting*—Areas with steep slopes susceptible to mass wasting. *Seismicity and Tsunamis*—Coastal areas mapped as **QTma** or **QTmr** within park are subject to inundation during tsunamis. Pago-Adelup Fault cuts **QTma**. *Storm Damage*—Coastal areas subject to inundation during storms. *Radon Potential*—Soils developed on **QTmr** or **QTma** may contain radium.	*Karst Features*—"Macabre" karst features noted in Asan Inland unit (mapped as **QTma, Ta, Tal**). Epikarst may be present. Karren covers many exposed surfaces and form in part from grazing and boring by marine organisms. Caves are particularly well developed in southern Guam. Rare pit caves are documented in Mariana Limestone. Discharge features (springs) present in limestone plateaus (**QTma, Ta, Tam**) of Mt. Alifan and Asan units. *Limestone Forests*—Particularly well developed at Asan Beach and Fonte Plateau units. **QTma** is mapped in those units. Limestone forests on **QTma** may also be present at Agat Beach and Asan Inland units. *Paleontological Resources*—Units contain fossilized corals (*Acropora*, *Seriatopora*, *Porites*, and *Favia*) and algae; mollusk (pelecypods *Ostrea* and *Tridacna*, and gastropod *Turritella*) casts and molds; sea urchins; and foraminifera. The Mariana Limestone contains seven known species of foraminifera, including *Operculina*, *Marginopora*, *Amphistegina*, *Gypsina*, and *Cycloclypeus*. *Connections Between Geology and Park Stories*—Cliffs of the Mariana Limestone probably figured prominently in the military history of the island. "Coral limestone" from this unit may have provided building material for island fortifications and other cultural sites, including Japanese Emplacement and 1961 Mabini Memorial. Natural caves and man-made cavities figured prominently in the military history of the park.	The Mariana Limestone formation records the conditions present across a broad, Pleistocene- and Pliocene-aged coral reef/lagoon system. As such, it contains a record of past sea level and paleoclimate. It has an unconformable contact with the underlying rocks, indicating a period of erosion or nondeposition prior to the establishment of the reef adjacent to Guam. The Mariana Limestone is the most fossiliferous and extensive formation on Guam, comprising up to 75% of the exposed limestone on the island. Depositional environments recorded in the various facies of the Mariana Limestone include reefs and lagoons
		Detrital facies (QTmd)	Mariana Limestone subunit **QTmd** ranges in texture from well-cemented to loose and friable, and ranges in grain size from coarse- to fine-grained. Like **QTmr**, **QTmd** is generally porous; however, unlike **QTmr**, **QTmd** formed in a lagoon environment. Erosion resistance is moderate.			
		Molluscan facies (QTmm)	Subunit **QTmm** is a lagoonal limestone occurring in white to tan, fine-grained exposures. **QTmm** contains abundant casts and molds of mollusks. Erosion resistance is moderate.			
		Forereef facies (QTmf)	Subunit **QTmf** consists of friable, white limestone featuring obvious bedding surfaces that formed as carbonate sands were deposited in the forereef area and later were cemented together with carbonates precipitated from solution. Erosion resistance is moderate.			
		Agana Argillaceous Member (QTma)	**QTma** contains tan to brown limestone with textures ranging from coarse, with limestone clasts clearly visible to the naked eye, to finer-grained areas with no discernable grains. **QTma** contains abundant clay, typically settling into pockets and cavities and present as lenses atop the rest of the unit. Some exposures of the Mariana Limestone are cliffs up to 150 m (500 ft) in height. Erosion resistance is moderate. **QTma** is mapped within the Asan Beach, Asan Inland, and Agat units.			

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Age	Map Unit (Symbol)	Geologic Description	Geologic Issues	Geologic Features and Processes	Geologic History
TERTIARY (Miocene-Pliocene)	Alifan Limestone (Tal) Talisay Member (Tt)	Unit **Tal** consists of pale pink, buff, or white limestone with localized exposures that are red, yellow, or brown. Some portions near the base of the unit are argillaceous, meaning they contain significant amounts of clay. The unit appears massive, meaning that bedding features are not obvious, and limestone textures range from coarse (individual grains are obvious to the naked eye) to fine-grained. A subunit of **Tal**, **Tt** is yellow, green, and red clay with lenses of 1) coarse conglomerate (large clasts in a clay matrix), 2) gray to green marl, and 3) limestone. These lenses range in thickness from 1 to 9 m (2 to 30 ft). Erosion resistance is moderate for these units. **Tal** is mapped within the Asan Beach, Asan Inland, Fonte Plateau, Agat, and Mt. Alifan units. *Siegrist et al. (2007) mapping updates: **Tt** is now assigned to the Oligocene as a separate unit.	*Terrestrial Erosion and Coastal Sedimentation*—Erosion of upland areas within park (and across the island) may be sources of sediment. *Relative Sea Level Rise and Coastal Vulnerability*—Subject to inundation and infrastructure impacts as sea level rises. *Adjacent Development and Disturbed Areas*—Off-Road Vehicle Use: ORV use in upland areas may lead to erosion and unvegetated areas, particularly in Mt. Chachao/Mt. Tenjo unit. *Storm Damage*—Coastal areas subject to inundation during storms. *Seismicity and Tsunamis*—Coastal areas subject to inundation during tsunamis. Pago-Adelup Fault cuts **Tal**. *Mass Wasting*—Areas with steep slopes susceptible to mass wasting. *Radon Potential*—Soils developed on **Tal** may contain radium.	*Karst Features*—"Macabre" karst features noted in Asan Inland unit (mapped as **QTma**, **Ta**, **Tal**). Large, closed depressions form in **Tal**. Epikarst may be present. Karren covers many exposed surfaces. Caves are particularly well developed in southern Guam. Traversable stream caves noted in **Tal**. *Limestone Forests*—Particularly well developed at Asan Beach and Fonte Plateau units. **Tal** is mapped in those units. Limestone forests on **Tal** are also present at Mt. Alifan unit and potentially at Asan Inland unit. *Paleontological Resources*—**Tal** contains remains of corals (*Porites* and *Acropora*) as well as singular calcite tubes formed by burrowing worms or gastropods. Marl within **Tt** contains stick-like *Porites* and *Acropora*. The Alifan Limestone contains 19 known species of foraminifera (most commonly *Rotalia atjehensis*) and/or calcareous algae. *Connections Between Geology and Park Stories*— "Coral limestone" from this unit may have provided building material for island fortifications and other cultural sites, including Japanese Emplacement and 1961 Mabini Memorial. Limestone quarry within Fonte Plateau unit likely targeted Tal. Natural caves and man-made cavities figured prominently in the military history of the park.	**Tt** unconformably overlies the Umatac (**Tuf**, **Tum**, **Tub**, and **Tud**) and Alutom (**Ta** and **Tam**) formations, indicating a period of nondeposition or erosion. **Tt** locally overlies **Tb**. The Alifan Limestone is exposed in the highest peaks of Guam. The Alifan Limestone is the remnant of a one extensive Miocene reef, recording reef-wall, lagoonal, and off-reef shallow-water depositional environments.
TERTIARY (Miocene-Pliocene)	Janum Formation (Tj) Barrigada Limestone (Tbl)	**Tj** consists of white to tan limestone with obvious bedding structures and abundant fossil remains. In northern Guam, **Tj** directly overlies **Tb** and displays an unconformable (erosional) contact with overlying Mariana Limestone (**QTam**). Lenticular (lens-like) beds of **Tj** interlayer with **Tbl**, which is a coarse-grained, white limestone. **Tbl** contains more abundant and varied fossil remains than **Tj**, including corals and mollusks. **Tbl** exceeds 165 m (540 ft) in thickness and appears massive in exposures (lacking obvious bedding structures). Textures within the unit range from well-cemented to friable. In northern Guam, **Tbl** is unconformable with the overlying Mariana Limestone (**QTam**), but further south, the contact changes to a more continuous, upward-grading relationship. Erosion resistance is moderate for these units.	*Mass Wasting*—Areas with steep slopes susceptible to mass wasting. *Adjacent Development and Disturbed Areas*—Groundwater Withdrawal and Contamination: **Tbl** and Tm units host Northern Guam Lens Aquifer. Vegetation quickly colonizes disturbed surfaces of **Tbl**.	*Karst Features*—Epikarst may be present. Caves are particularly well developed in southern Guam. *Paleontological Resources*—**Tj** contains abundant globigerinid foraminifera (a planktonic genus with walls of radial calcite crystals). **Tbl** contains foraminifera (*Operculina*, *Gypsina*, and *Cycloclypeus*), coral, and mollusks. **Tbl** contains nine known species of foraminifera and/or calcareous algae. *Connections Between Geology and Park Stories*— "Coral limestone" from this unit may have provided building material for island fortifications and other cultural sites, including Japanese Emplacement and 1961 Mabini Memorial. Natural caves and man-made cavities figured prominently in the military history of the park.	These units record the Miocene to Pliocene transition in the development of Guam, and the subsequent period of erosion and/or nondeposition is reflected in the unconformable contact with **QTam**. **Tbl** was named after Barrigada Hill in northern Guam. **Tbl** and **Tj** formed in a deep-water environment on the flank of the volcanic highlands.
TERTIARY (Miocene)	Bonya Limestone (Tb)	Unit **Tb** contains nearly pure limestone in exposures up to 21 m (70 ft) thick. Some portions of the unit are argillaceous, meaning they contain significant amounts of clay. In southern Guam, **Tb** displays obvious bedding features and is coarse-grained and sandy, whereas in northern Guam, closer to the park area, bedding features are less obvious and the limestone is much finer-grained (described as massive and compact). Exposures of **Tb** can be up to 37 m (120 ft) thick. Erosion resistance is moderate.	*Mass Wasting*—Areas with steep slopes susceptible to mass wasting.	*Karst Features*—Low porosity compared to younger limestones. Large, closed depressions form in **Tb**. Epikarst and runnels may be present on exposed surfaces. Caves are particularly well developed in southern Guam. Traversable stream caves are noted in **Tb**. *Paleontological Resources*—Contains 13 known species of foraminifera and/or calcareous algae. *Connections Between Geology and Park Stories*—Natural caves and man-made cavities figured prominently in the military history of the park.	**Tb** records a longstanding carbonate platform system that persisted after volcanism on Guam had largely stopped during the Miocene. It was deposited in off-reef environments in moderately deep water and is among the few limestones of Guam to be diagenetically mature, having been covered until recent uplift of Guam exposed it in a meteoric environment.

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Age	Map Unit (Symbol)		Geologic Description	Geologic Issues	Geologic Features and Processes	Geologic History
TERTIARY (Miocene)	Umatac Formation	Dandan Flow Member (Tud)	**Tud** consists of about 15 m (50 ft) of basalt lava flows with large, visible crystals occurring in a finer grained matrix, separated from the underlying Tub subunit by a 3-m-thick (10-ft-thick) flow breccia (described under **Tub**). Erosion resistance is moderately high.	*Mass Wasting*—Areas with steep slopes susceptible to mass wasting. *Terrestrial Erosion and Coastal Sedimentation*—Erosion of upland areas within park (and across the island) may be sources of sediment. *Mass Wasting*—Areas with steep slopes susceptible to mass wasting. *Storm Damage*—Coastal areas subject to inundation during storms. *Seismicity and Tsunamis*—Coastal areas are subject to inundation during tsunamis.	*Karst Features*—Low porosity compared to younger limestones. Epikarst and runnels may be present on exposed surfaces of **Tum**. Caves are particularly well developed in southern Guam. *Paleontological Resources*—Primarily foraminifera and other marine invertebrates in limestones. **Tum** contains coral reef fossils, globigerinid foraminifera (a planktonic genus with walls of radial calcite crystals), and algae. Tum contains 36 known species of foraminifera and/or calcareous algae. Basalt flows may contain tree molds. Lava tubes and caves may preserve fossils such as avian bones and other Neogene and younger remains. *Plate Tectonic Processes*—Volcanoes that formed **Tud**, **Tub**, and **Tuf** were fueled by a subduction zone. **Tuf** represent the early phases of island-building volcanism. *Connections Between Geology and Park Stories*—"Coral limestone" from this unit may have provided building material for island fortifications and other cultural sites, including Japanese Emplacement and 1961 Mabini Memorial. Natural caves and man-made cavities figured prominently in the military history of the park.	Subunits within the Umatac Formation have complex relationships. **Tum** occurs in part as lenses within **Tuf**. **Tub** rests atop **Tuf** near Umatac and interfingers with **Tud** on the eastern slopes of Mount Almagosa. **Tud** lavas flowed atop **Tub**. These complex interrelationships formed in a longstanding system of intermittent volcanism and coral reef development. Volcanic activity deposited the basalt flows, pyroclastic deposits, and ash deposits. Volcanism must have had longstanding periods of quiescence to allow a carbonate, coral reef complex (**Tum**) to form between flows (**Tuf**).
		Bolanos Pyroclastic Member (Tub)	Subunit **Tub** consists of basal layers of reworked coarse-grained volcanic conglomerate and breccia—differentiated by the roundness of the clasts contained within a finer grained matrix. Breccia has angular clasts, in this case formed during explosive volcanic eruptions whereas in conglomerates, the clasts are more rounded indicating they were weathered and/or transported some distance prior to becoming incorporated into the matrix. **Tub** contains fragments of **Tum**. Upper layers contain mixed sandstone and finer grained shale with some minor layers of conglomerate. The maximum thickness of **Tub** is about230 m (750 ft). Erosion resistance is moderate.			
		Maemong Limestone Member (Tum)	**Tum** is predominantly limestone that formed in a reef environment. The coral remains are still in their growth positions. In south Guam, Tum contains very coarse, conglomeratic lenses that grade into calcareous (contain calcium carbonate) layers of mixed volcanic ash and limestone. The maximum thickness of **Tum** is 80 m (260 ft). Erosion resistance is moderate.			
		Facpi Volcanic Member (Tuf)	Subunit **Tuf** of the Umatac Formation consists of 275 m (900 ft) of pillow basalts formed as lava extruded from the earth underwater at its base. Upon cooling and contraction of the molten rock, columnar joints formed regular patterns within the flows. These flows are in turn cut by linear dikes of basalt that trend at an angle to the flows. The upper 150 m (500 ft) of **Tuf** contains interlayered lava flows, shale, and sandstone with lenses of the limestone of Tum, locally. Erosion resistance is moderately high. **Tuf** is mapped within the Mt. Alifan unit. *Siegrist et al. (2007) mapping updates: Maemong Limestone is a stand-alone unit—Maemong Limestone formation (**Tm**). There is a lumped Umatac Formation undifferentiated unit (**Tu**). Two new units were assigned to the Umatac Formation: Schroeder flow member (**Tus**), and the Geus River Member (**Tug**). **Tug** is now Oligocene in age. **Tuf** is now an Eocene, stand-alone unit—Facpi formation (**Tf**). According to Siegrist et al. (2007), the Facpi formation is now the oldest recognized rock unit on Guam.			

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Age	Map Unit (Symbol)		Geologic Description	Geologic Issues	Geologic Features and Processes	Geologic History
TERTIARY (Eocene-Oligocene)	Alutom Formation	Alutom Formation (Ta)	**Ta** consists of 1) gray, green, and brown shale and sandstone; 2) lenses of limestone; 3) breccia conglomerate formed during explosive volcanism (pyroclastic ejections of lava) that also contains limestone fragments; 4) interbedded lava flows. These units display obvious bedding structures, and textures within the layers range from fine- to coarse-grained (individual clasts easily discernable with the naked eye). Volcanic breccia forms near the center of an explosive eruption, where pre-existing rocks are shattered and mixed with fresh volcanic lava and ash from the eruption. **Ta** contains significant amounts of volcanic ash (tuffaceous) and exceeds 610 m (2000 ft) in thickness. Erosion resistance is moderate to moderately high for lava flows. **Ta** is mapped within the Asan Beach, Asan Inland, Piti Guns, Mt Chachao/Mt. Tenjo, Agat, and Mt. Alifan units.	*Terrestrial Erosion and Coastal Sedimentation*—Erosion of upland areas within park (and across the island) may be sources of sediment. *Adjacent Development and Disturbed Areas*—Off-Road Vehicle Use: ORV use in upland areas may lead to erosion and unvegetated areas, particularly in Mt. Chachao/Mt. Tenjo unit. *Mass Wasting*—Areas with steep slopes susceptible to mass wasting. *Seismicity and Tsunamis*—Pago-Adelup Fault cuts **Tal**. *Radon Potential*—Soils developed on **Ta** may contain radium.	*Karst Features*—"Macabre" karst features noted in Asan Inland unit (mapped as **QTma, Ta, Tal**). Epikarst may be present on exposed limestone. Caves are particularly well developed in southern Guam. Discharge features (springs) present in limestone plateaus (**QTma**, **Ta**, **Tam**) of Mt. Alifan and Asan units. *Limestone Forests*—Particularly well developed at Asan Beach and Fonte Plateau units. **Ta** is mapped in those units. Limestone forests on **Ta** may also be present at Asan Inland unit. *Paleontological Resources*—Primarily forminifera. The Alutom Formation contains 14 known species of foraminifera, the most common species of which are *Bolivinopsis* sp., *Nonion maoricum*, *Bolivina choctawansis*, *Angulogerina vicksburgensis*, and *Angulogerina cooperensis*. Other marine invertebrates may be present. Basalt flows may contain tree molds. Lava tubes and caves may preserve fossils such as avian bones and other Paleogene and younger remains. *Plate Tectonic Processes*—Volcanic breccias of **Ta** resulted from explosive volcanic eruptions. *Connections Between Geology and Park Stories*—Natural caves and man-made cavities figured prominently in the military history of the island.	Units record early volcanism and associated marine conditions present during the Oligocene and Eocene, and are the oldest units that appear in the digital geologic map data for Guam. **Ta** is named for Mt. Alutom in southern Guam
		Mahlac Member (Tam)	Subunit **Tam** is a buff to tan or yellow-tan, calcareous (contains calcium carbonate) shale. The shale occurs in highly laminated layers that are crumbly in texture. **Tam** has a maximum known thickness of 60 m (200 ft). Erosion resistance is moderate. **Tam** is mapped within the Mt. Alifan unit.			