National Park Service
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Natural Resource Stewardship and Science

Palo Alto Battlefield National Historical Park

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2013/710

ON THE COVER
The subdued topography of Palo Alto Battlefield National Historical Park features resacas—abandoned channels of the Rio Grande—that influenced battles during the US-Mexican War in May 1846. National Park Service photograph courtesy Rolando Garza (Palo Alto Battlefield NHP)

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National Park Service
Geologic Resources Division
PO Box 25287
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Executive Summary

The Geologic Resources Inventory (GRI) is one of 12 inventories funded by the National Park Service Inventory and Monitoring Program. The Geologic Resources Division held a Geologic Resources Inventory (GRI) scoping meetings for Palo Alto Battlefield National Historical Park in Texas on 23 April 2008 to discuss geologic resources, the status of geologic mapping, and resource management issues and needs. This report synthesizes those discussions and is a companion document to the previously completed GRI digital geologic map data.

Palo Alto Battlefield National Historical Park preserves the sites of the first major battles of the two-year U.S.-Mexican War on May 8-9, 1846 (Palo Alto and Resaca de la Palma), which contributed greatly to the nascent concept of "manifest destiny", and the vast expansion of the United States. The park uses historical information and perspectives of both nations to tell the story of the battles; the war; the related political, diplomatic, military and social causes; and the lasting consequences.

This Geologic Resources Inventory (GRI) report was written for resource managers at Palo Alto Battlefield National Historical Park to assist in science-based decision making, but it may also be useful for interpretation. The report was prepared using available geologic information. The Geologic Resources Division did not conduct any new fieldwork in association with this report. The report discusses geologic issues facing resource managers at Palo Alto Battlefield National Historical Park, distinctive geologic features and processes within the park, and the geologic history leading to the park's present-day landscape. It also provides information about the GRI geologic map data produced for the park. A geologic map graphic (in pocket) illustrates these geologic data. The Map Unit Properties Table (in pocket) summarizes report content for each map unit. This report also contains a glossary and a geologic time scale.

Brown et al. (1980) and Caran et al. (2005) are the source maps for the digital geologic data for Palo Alto Battlefield National Historical Park. The units mapped by Brown et al. (1980) can be divided into four main types based on the geomorphological system responsible for their formation: 1) very young artificial (manmade) units; 2) bay-estuary-lagoon system; 3) barrier-strandplain and offshore system; and 4) fluvial-deltaic system. The lattermost type is most relevant to the park. However, they are all part of the landward component of a very complex zone of interaction between a major river delta (Rio Grande), a coastal barrier system in the Gulf of Mexico, and a population center.

The Gulf Coast's subtle topography and muted landscape reveal a long history of Earth surface processes acting in concert with changing climate. Long a center of deposition, changing sea levels associated with the Pleistocene ice ages (within the past 2 million years) shifted the shoreline intermittently landward and gulfward for thousands of years. The geologic history of Palo Alto Battlefield National Historical Park is dominated by the relatively recent formation of the Rio Grande deltaic system and the Texas Coastal Zone. When sea level was lower, the river carved a vast valley onto the continental shelf. As the seas rose, this valley became and estuary and later a broad river delta. Now, the barrier islands of the Gulf Coast are moving landward as Laguna Madre (the back barrier water body) slowly fills with sediments. The Rio Grande continues to meander through its valley leaving broad floodplains, abandoned channels (resacas), and levees in its wake as anastomosing traces of its former paths.

Geologic issues of particular significance for resource management at Palo Alto Battlefield National Historical Park were identified during a 2008 GRI scoping meeting. They include the following:

- Fluvial System. The past and present Rio Grande deltaic systems are the single most important factor contributing to the geomorphology of the park's landscape and the influences of the landscape on the 1846 battle fought there. Abandoned river channels called "resacas" across the delta plain provide strategic topography and marshy bottomlands. Some were later manipulated to store water for grazing animals. Irrigation and drainage ditches now traverse the area. The Rio Grande's channel is engineered and flow is reduced via withdrawals, precluding flooding and the high flows necessary to accrete sediment. Sediment accretion (deposition) would offset subsidence and encroachment of salt water as sea level continues to rise. Potential impacts include increased salinization of surface and ground water; reduced water quality; and accelerated coastal erosion.
- Sea Level Rise and Hurricanes. Palo Alto Battlefield National Historical Park is located only 18 km (11 mi) inland from the Gulf of Mexico. It is only 3 m (10 ft) above sea level. Coastal features comprise much of the GRI digital geologic map data. As relative sea level rises, coastal features and processes, including hurricanes, will increasingly impact south Texas.
- Erosion. The processes of erosion and deposition are continuous on the park landscape. Slopes are generally low, but sheet, rill, and gully erosion occur in some areas. Wind erosion is a possibility, particularly where vegetation has been disturbed. Where these processes

fill resacas and mute highlands, the battlefield landscape is altered.

- Disturbed Lands. Disturbances on the landscape result from channel diversion, water storage facility construction, grazing and agricultural practices, and coastal manipulation activities (geomorphic map units Hml, Hsr, Hsae, and Hsaq). All of these have links to geologic features and processes at the national historical park.
- Oil and Gas Exploration and Development. Oil and gas exploration is common in southern Texas. A 1940s-era pipeline crosses the Palo Alto unit of the park. The park grants access to the Texas Gas Service Company to conduct maintenance of the pipeline and adjacent access road provided they avoid the resaca crossing.

Geologic features of particular significance for resource management at Palo Alto Battlefield National Historical Park include the following:

- Rio Grande Resacas. Resacas are abandoned channels of the Rio Grande. They figure prominently on the modern landscape and influenced the 1846 battles.
- Geologic Influences on May 1846 Battles. Landforms including the Palo Alto Resaca (geomorphic map unit PEa), Arista Hill (underlain by Hds), circular marsh (underlain by Hf), and southern high grounds were strategic features during the 1846 battles. American and Mexican soldiers experienced the resaca as a natural barrier and took advantage of ponds and other freshwater sources in the area.
- Geologic Influences on Ecosystems. There are many connections between the ecosystem and geologic resources at Palo Alto Battlefield National Historical Park. In particular, resacas, marshes, and eolian features host distinct habitats. Saline and gypsum-rich soils support particular flora.
- Eolian Features and Processes. Eolian deposits (geomorphic map units Hfi, Hsf, Hf, PEda, PEdi, and PEss) on the map for Palo Alto Battlefield National Historical Park are recent accumulations of windblown clay, silt, and sand, which form sand sheets, dune fields, fore-island dunes, and smaller deposits collecting along the coast and upland areas. Eolian deflation causes local blowout and dune topography.
- Paleontological Resources. Fossils and younger remains of life, primarily pollen and marine organisms, are known from throughout the area. These remains are an important record of recent life. The resacas (PEa) contain an informative pollen record of vegetation changes and the development of the landscape of the park.

Acknowledgements

The GRI is administered by the Geologic Resources Division of the Natural Resource Stewardship and Science Directorate.

The Geologic Resources Division relies on partnerships with institutions such as Colorado State University, the US Geological Survey, state geological surveys, local museums, and universities to develop GRI products.

Special thanks to Rolando Garza (Palo Alto Battlefield National Historical Park) for providing many of the photographs used in this report, as well as detailed descriptions of their locations and visible features.

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Introduction

This section briefly describes the National Park Service Geologic Resources Inventory Program and the regional geologic setting and history of Palo Alto Battlefield 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 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 to 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's geology, including geologic resource management issues, geologic features and process, and the geologic history leading to the park's present-day landscape.

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

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

Park Setting and History

Palo Alto Battlefield National Historical Park commemorates the first major battles of the two-year U.S.-Mexican War on May 8–9, 1846. These battles pitted American forces under General Zachary Taylor against Mexican troops commanded by General Mariano Arista. This struggle contributed greatly to the budding concept of "manifest destiny", ultimately responsible for the vast expansion of the United States. By the end of this conflict the U.S. had added some 2,600,000 km^2 (1,000,000 mi^2) of territory (fig. 1) (Carney 2006). Congress authorized Palo Alto Battlefield National Historical Site on November 10, 1978. The park's boundary changed on June 23, 1992, when it was officially established. The Omnibus Public Land Management Act of 2009 redesignated the site to a national historical park encompassing two units—Palo Alto and Resaca de la Palma. At Palo Alto, the park preserves 1,359 ha (3,357 ac) of broad, flat, coastal prairie 13 km (8 mi) north of Brownsville, Texas at the junction of State highways 511 and 1847 (fig. 2). The Resaca de la Palma unit is approximately 14 ha (34 ac), 4 km (6 mi) south-southwest of Palo Alto. The park interprets not only the battles, but the entire war with its causes and consequences from the perspectives of the United States and Mexico. More than 30,000 people visit the park annually.

In 1844, the short-lived Republic of Texas applied to become an American state—an action that Mexico considered an act of war (fig. 1) (Carney 2006). The 1845 annexation of Texas led President Polk to send forces to protect the new border and force Mexico (which, at the time, controlled more than one-third the North American continent) to negotiate. Weeks prior to the battle, Mexico proclaimed a "defensive war" against the United States after Texas was annexed. The Americans had an artillery advantage using then-new, easily maneuvered guns mounted on light carriages called "flying artillery" (Sanchez 2012). The first battle consisted of a series of brief, intense engagements among infantry, cavalry, and artillery on the "plain of Palo Alto" (Caran et al. 2005). The battle lasted approximately eight hours, ending at nightfall in an indecisive standoff and several hundred casualties (Sanchez 2012). The day after the battle, the Mexican army relocated to Resaca de la Palma to the south to neutralize the American artillery advantage. Before they could regroup, Taylor's forces charged and defeated Arista's army (Sanchez 2012). The Mexican forces fled across the Rio Grande. Days after the Palma de la Resaca battle, the United States declared war on Mexico on May 13, 1846. In 1848, the Treaty of Guadalupe Hidalgo terminated the Mexican War and

Figure 1. Map of the disputed area between the United States and Mexico. National Park Service graphic available online http://www.nps.gov/hfc/cfm/carto-detail.cfm?Alpha=PAAL (accessed 10 September 2013).

established the Rio Grande as the international border between the states of Chihuahua and Texas (Metz 2012).

The park is located within the Coastal Prairies region of the Gulf Coastal Plain physiographic province in Cameron County, south Texas (fig. 3) (Wermund 1996). Former channels of the Rio Grande abandoned during meandering of the river's course, called "resacas," as well as prairies, mesquite forests, and areas of Gulf cordgrass (*Spartina spartinae*) characterize the landscape at the park today. The muted topography and subtle landforms influenced the battles. Natural features that figured prominently in the Palo Alto battle include: Palo Alto pond; Rio Grande resacas; Arista Hill; and a large marsh. Palo Alto pond provided a source of freshwater for American forces and their animals. The army's wagon train stopped there. The shallow ravines of the resacas along the low, coastal plain restricted the movement of troops and artillery during the battle, necessitating troop movements on both sides of the resaca (Caran et al. 2005).

Geologic Setting

A geologic history involving construction of the Rio Grande delta, fluvial meandering, shifting sea levels, and barrier island development, shaped the landscape that influenced the battles at Palo Alto Battlefield National Historical Park. The Gulf Coastal Plain of Texas has been a center of deposition since the Triassic or at least 250 million years (fig. 4). An exceptionally deep pile of sediments (15,000–18,000 m [50,000–60,000 ft, or about 11 *miles*]) overlies a foundation of deformed, crystalline Paleozoic rocks dating back to the Ouachita Orogeny (Baker 1995)—a Late Paleozoic mountain building event.

The Rio Grande embayment is the primary geologic structure influencing sedimentation patterns through the history of deposition in the area (Baker 1995). This synclinal ("U"-shaped) structure is a broad open fold between the San Marcos Arch of central Texas and the Laramide fold systems of Mexico (Ewing 1999). These structures are all oriented roughly northwest-southeast. The modern Rio Grande flows along the southwest side of the Rio Grande embayment (Ewing 1999).

The Coastal Prairies subprovince of the Gulf Coast province begins at the Gulf of Mexico shoreline. The upland prairies of the modern Rio Grande Delta are underlain by unconsolidated sediments that are approximately 100,000 years old. Clays and silts of the Pleistocene Lissie and Beaumont formations and younger alluvium (deltaic sands, silts, and clays) associated with the Rio Grande form the geologic foundation of the park (fig. 5) (Brown et al. 1980; Baker 1995). The sediments erode to nearly flat grasslands and very gently slope to the southeast, toward the gulf (Wermund 1996). These and all the sedimentary units underlying the area are markedly disrupted by fault systems; local faults are "growth faults" in sediments of the coastal plain (Baker 1995). Growth faults form where sedimentation occurs when fault movement and sedimentation are contemporaneous. They are common on the Texas Gulf Coast and other areas where the crust is rapidly subsiding. Some steeper slopes, as much as 3 m (9 ft) high result from subsidence of deltaic sediments along faults (Wermund 1996). However, Palo Alto Battlefield National Historical Park is seismically quiet.

Trees are uncommon except on stream bottoms and in small clusters called "mottes" where coarser sediments from former stream channels transmit groundwater. Resacas at the park are shallow ravines left behind as the Rio Grande shifted course along the low, coastal plain. Today, these ancient river channels have been completely severed from the waterway that once filled them and remain dry for much of the year. Seasonal heavy rains occasionally inundate the ravines with runoff, creating pools of water that may endure for days or months.

Constant winds cause broad sand sheets pocked by low dunes and blowouts to dominate stretches of the landscape between Corpus Christi and Brownsville (Wermund 1996). Blowouts may be scoured deep enough to become ponds (Wermund 1996).

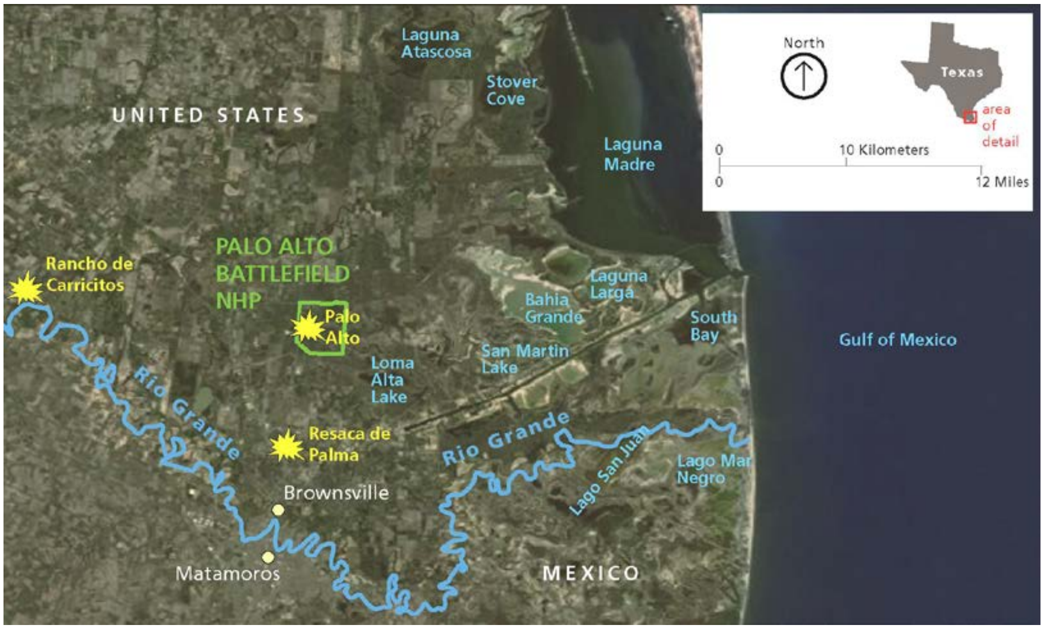


Figure 2. Map of southern Texas. Battle locations are indicated by yellow stars. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) using ESRI ArcMap imagery basemap.

Figure 3. Map of the physiographic provinces of Texas. Physiographic sections and provinces are overlain onto shaded relief. Palo Alto Battlefield National Historical Park is denoted by green star on the southern tip of the Coastal Prairies section of the Gulf Coastal Plains province. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after map by Wermund (1996). Shaded relief map by Tom Patterson (National Park Service), available online: http://www.shadedrelief.com/physical/index.html (accessed 6 September 2013).

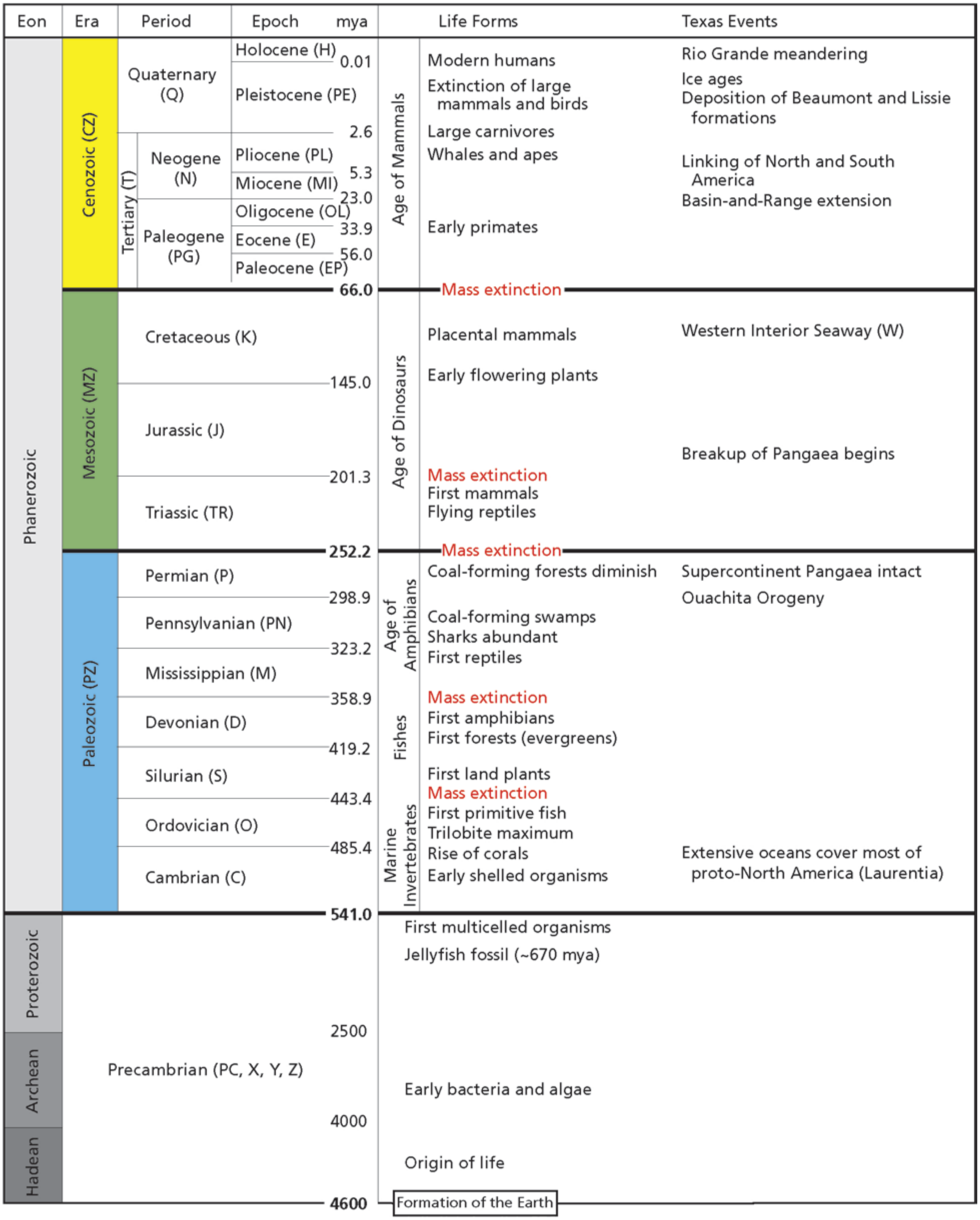
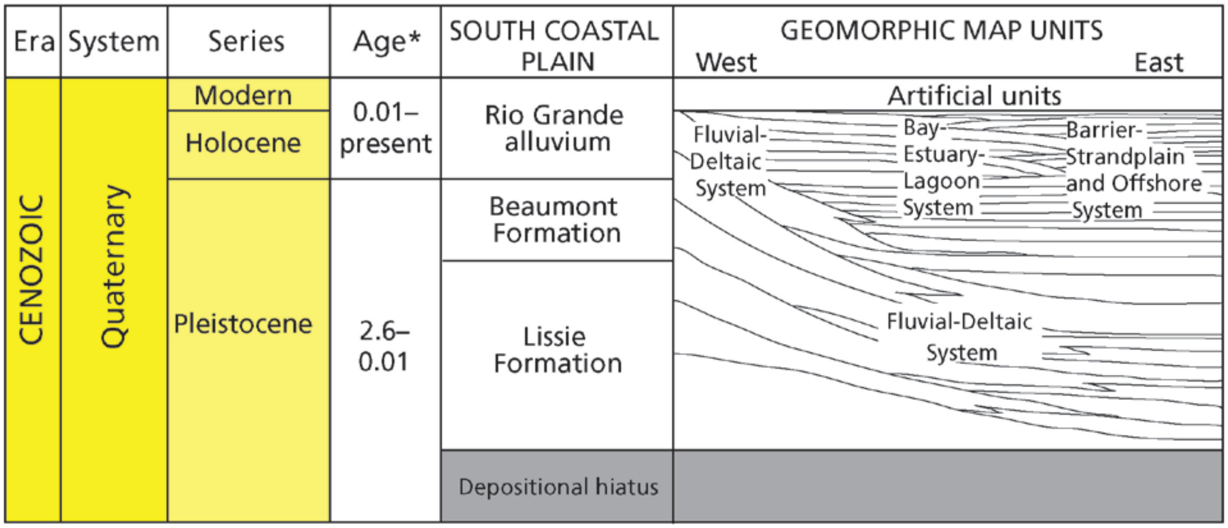


Figure 4. Geologic time scale. The divisions of the geologic time scale are organized stratigraphically, with the oldest at the bottom and youngest at the top. GRI map abbreviations for each geologic time division are in parentheses. Boundary ages are in millions of years ago (mya). Major life history, as well as events affecting south Texas are included. Bold horizontal lines indicate major boundaries between eras. Graphic by Trista Thornberry-Ehrlich (Colorado State University) and Rebecca Port (NPS Geologic Resources Division). Ages are from the International Commission on Stratigraphy (http://www.stratigraphy.org/index.php/ics-chart-timescale; accessed 23 August 2013).



**** Age is in millions of years before present and indicates the time spanned by associated epoch or period. Rock/sediment units associated with those epochs or periods may not encompass the entire age range.***

Figure 5. Generalized stratigraphic column for Palo Alto Battlefield National Historical Park. Major groupings of mapped geomorphic units are included. Beaumont Formation is the bedrock unit underlying the park area. Bedrock units are not part of the park's digital geomorphic map. Colors are standard colors approved by the U.S. Geological Survey to indicate different time periods on geologic maps; they also correspond to the colors on the Map Unit Properties Table. See the Map Unit Properties Table for more detail. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) with information from Baker (1995).

Geologic Issues

Geologic issues described in this section may impact park resources or visitor safety and could require attention from resource managers. Contact the Geologic Resources Division for technical assistance.

During the 2008 scoping meeting, the following geologic resource management issues were identified:

- Fluvial System
- Sea Level Rise and Hurricanes
- Erosion
- Disturbed Lands
- Oil and Gas Exploration and Development

Resource managers may find *Geological Monitoring* (Young and Norby 2009) useful for addressing these geologic resource management issues. The manual provides guidance for monitoring vital signs—measurable parameters of the overall condition of natural resources. Each chapter of *Geological Monitoring* covers a different geologic resource and includes detailed recommendations for resource managers and suggested methods of monitoring.

Fluvial System

Resaca Modifications

Resacas, detailed in "Geologic Features and Processes", cross Palo Alto Battlefield National Historical Park. These historically significant landforms have been muted by anthropogenic activities and natural surface processes. Anthropogenic alterations include flanking ditches, earthen dams, and stock tank excavation (figs. 6 and 7). Since the battles of 1846, approximately 30 cm (12 in.) of sediment has accumulated in the park's resacas (KellerLynn 2008). Resaca de la Palma retains water and associated flood deposits have covered the adjacent 1846-era land surface by at least 30 to 50 cm (12 to 20 in.) (PBS&J 2004). Portions of at least two resacas in the park were engineered or excavated to store water as stock ponds. As described in the "Disturbed Lands" section a ditch constructed in 1916 for flood control drained the lakes (including El Tule Grande) on the northern edge of the Palo Alto unit (Caran et al. 2005; KellerLynn 2008). Prior to 1948, the Rio Grande provided the main source of water in Cameron County. However, after 1948, groundwater sources were developed during drought conditions to keep pace with demand (Baker and Dale 1964). Most local groundwater is slightly saline and may be mineralized; groundwater in eastern Cameron County is generally unsuitable for livestock or human consumption (Baker and Dale 1964). The park is located along the boundary between suitable and unsuitable groundwater reservoirs (Baker and Dale 1964). Many communities in the Rio Grande valley pump river water and/or groundwater into resacas to keep them filled year-round for storage and transport of drinking and irrigation water (Baker and Dale 1964; KellerLynn 2008). The park obtains its water from Brownsville's Public Utility Board (surface water from the Rio Grande). Natural resource staff at the park maintain a GIS layer of excavated tanks and ponds.

Figure 6. Photograph of modified resaca. Resacas throughout the park and surrounding area have been modified for water collection and control. This left bank of this resaca, south of the stock tank and dam, is now a ditch and ridge. These features maximized water collection to increase flow to stock tanks. National Park Service photograph by Rolando Garza (Palo Alto Battlefield NHP).

Sediment Supply, Water Quantity, and Water Quality

Although the Rio Grande no longer flows through the park, the past sweep of the river meandering through the area affected the park's features and history. The river's low channel gradient reduces its sediment-carrying capacity, so that sediment deposition is rapid. The low gradient also diverts the river's flow laterally causing the channel to broaden, shallow, and meander. The modern river flows 15 km (9 mi) to the south of the Palo Alto unit and approximately 5 km (3 mi) south of the Resaca de la Palma unit, but throughout its history has meandered across its broad floodplain in southern Texas. In an arid setting, the deltaic landscape is continually and significantly altered by anthropogenic disruption to the fluvial system. Water control of the Rio Grande began with diversion channels in the late 19th century, and then proceeded with four dam-reservoir systems in the early to mid-20th century. Most of this water is diverted for storage for agricultural and municipal use in over 1,500 km (930 mi) of drainage canals and pond systems in Texas and more in Mexico (Baker and Dale 1964; Stanley 1999; Moring and Setser 2000). As a result of this diversion, the flow actually reaching the Gulf of Mexico is reduced as is the sediment load required to maintain the current delta morphology (Stanley 1999; Stanley and Warne 2001).

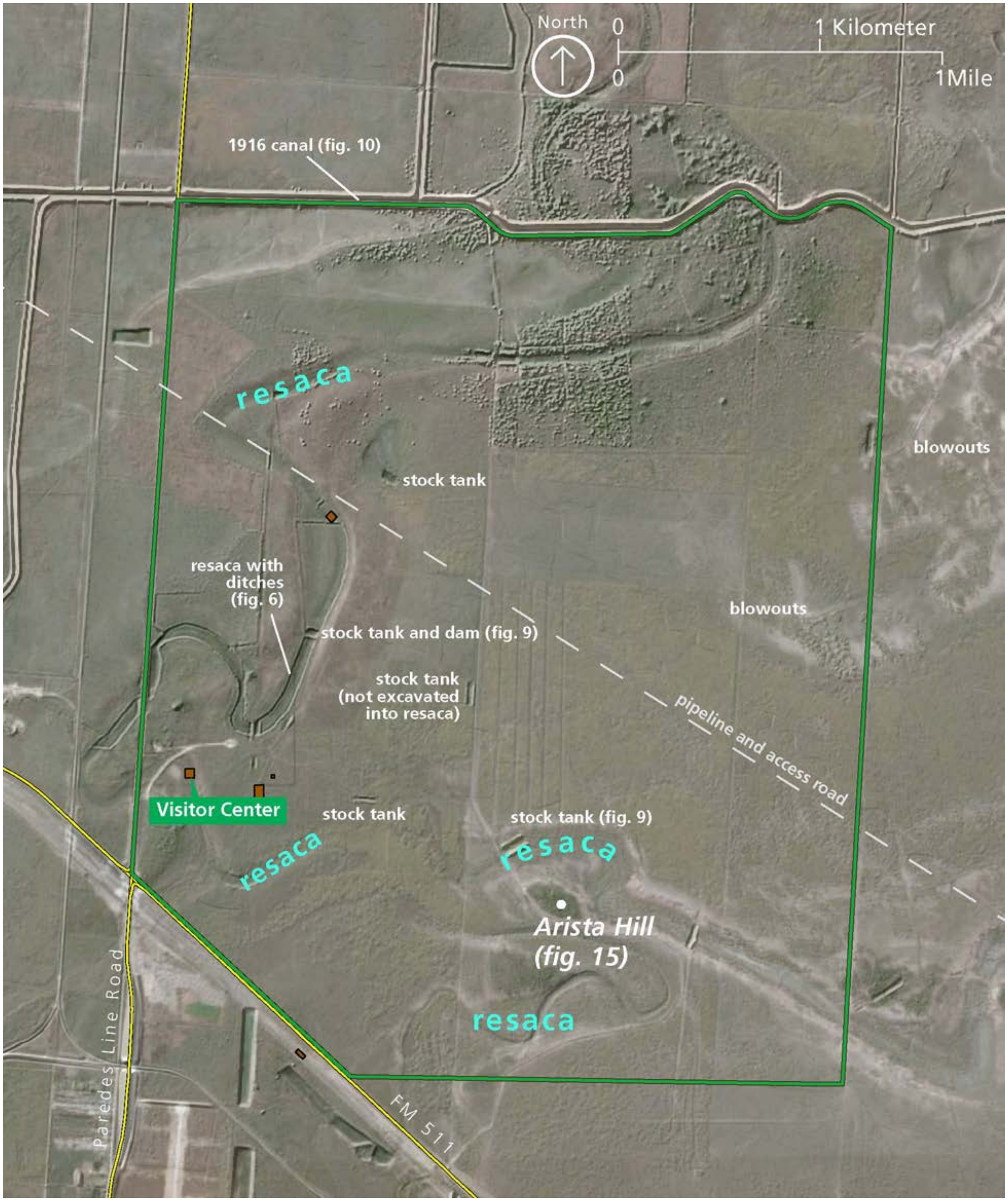


Figure 7. Aerial image of Palo Alto Battlefield National Historical Park. The landscape of the park (green outline) and surrounding area has been extensively modified by anthropogenic activity, primarily related to flood control (e.g., 1916 canal) and agriculture (e.g., stock tanks and ditches along resacas) Compiled by Jason Kenworthy (NPS Geologic Resources Division) with information from Rolando Garza (Palo Alto Battlefield NHP).

Impacts to the deltaic system stretch beyond the river and delta themselves. The surrounding low-lying coastal system is increasingly vulnerable to environmental degradation. Hurricanes and storms periodically modify the coast. The seaward portions of the delta plain continually subside as unconsolidated sediments de-water and compact under their own weight causing relative sea-level rise (see "Sea Level Rise and Hurricanes" section). Climate change models predict a local increase in sea level of up to 0.6 m (2 ft) by 2100 (Karl et al. 2009). As the river's channel is engineered and flow reduced through human modifications, widespread flooding necessary to accrete sediment to the floodplain to keep pace with subsidence and sea level rise is precluded. Major impacts will result, including, 1) increased salinization of surface and ground water; 2) reduced water quality (leads to decreased soil productivity and habitat degradation); and 3) accelerated coastal erosion (Stanley and Warne 2001). Since at least 1950, there has been a marked decrease in higher flow events. Periodic flooding of the floodplain (riparian zone) also affects soil chemistry through the import and removal of organic matter, and flux or replenishment of mineral nutrients and sediments (Moring and Setser 2000).

The semiarid climate of southern Texas is characterized by drought cycles (Baker and Dale 1964). Karl et al. (2009) present climate models that project continued warming and an increase in the rate of warming through the year 2100. Climate models also suggest a decrease in precipitation in winter and spring and thus the frequency, duration, and intensity of droughts are likely to continue to increase (Karl et al. 2009). For more information regarding regional, national, and global climate change impacts, refer to Karl et al. (2009), Loehman and Anderson (2010), and the NPS Climate Change Response Program (http://www.nature.nps.gov/climatechange/index.cfm).

Management and Monitoring of Fluvial System

The Texas Bureau of Economic Geology provides digital data for GIS analyses including shoreline change, coastal hazards, and sand resources available at: (http://www.beg.utexas.edu/info/info_res.php). Wermund and Tremblay (1998) developed a GIS of the surficial depositional systems of the Rio Grande delta. This GIS included political boundaries, transportation, surface hydrology, and geology. The GRI digital geologic map data may provide an important layer toward a similar, park-specific GIS effort.

Caran et al. (2005) present recommendations to restore the resaca at Palo Alto to its battle-era appearance including removing the earthen dams and spreading the backdirt along the edges of the resaca and restoring standing freshwater conditions. The latter suggestion may require a dedicated water source.

In the *Geological Monitoring* chapter about fluvial geomorphology, Lord et al. (2009) described methods for inventorying and monitoring geomorphology-related vital signs, including: 1) watershed landscape (vegetation, land use, surficial geology, slopes, and hydrology), 2) hydrology (frequency, magnitude, and duration of stream flow rates), 3) sediment transport (rates, modes, sources, and types of sediment), 4) channel cross section, 5) channel planform, and 6) channel longitudinal profile.

Sea Level Rise and Hurricanes

Palo Alto Battlefield National Historical Park is located 18 km (11 mi) inland from South Bay, Laguna Madre, and the Gulf of Mexico, but it is only 3 m (10 ft) above sea level. The highest points within the Palo Alto unit are only 6 m (20 ft) above sea level. Coastal grasses and highly saline soils dominate most of the battlefields' landscapes (KellerLynn 2008). Relative sea level is rising globally and can be measured along the Texas Gulf Coast. As sea level continues to rise, coastal shorelines will retreat, coastal ecosystems will be displaced further inland, and wetlands and low-lying areas will be increasingly susceptible to inundation by brackish water (Karl et al. 2009). Coastal features will continue to shift landward, burying deltaic features.

The average frequency of hurricanes along any 80 km (50 mi) stretch of the Texas Gulf Coast is one every six years (Roth 2009). Hurricane-related waters inundated the park's landscape in 1898, 1933, and 1967 (Hurricane Beulah)—all prior to the establishment of Palo Alto Battlefield National Historical Park (KellerLynn 2008). Hurricane Beulah was a category 3 storm with wind speeds of up to 217 km/h (135 mi/h) (Roth 2009). It brought torrential rainfall and more than 115 tornadoes—the most known to be generated by a tropical storm system (Roth 2009). In July 2008, abundant precipitation from Hurricane Dolly caused some short-lived flooding (R. Garza, written communication, 21 February 2013). Sea surface temperatures are also rising and this correlates with an increase in hurricane power (peak wind speeds, rainfall intensity, and storm surge height and strength) (Karl et al. 2009; Loehman and Anderson 2010). Given the low elevation of the park area and the impacts described in the "Fluvial System" section, accelerated climate change could have profound effects on the landscape of the park (geomorphic map units Hds, Hf, and PEa). If a strong hurricane struck southern Texas, the rainfall and a storm surge could affect the park's infrastructure, as well as natural and cultural resources. GRI scoping meeting participants surmised that the visitor center would likely flood during major hurricanes (KellerLynn 2008). Park managers are working on a hurricane response plan but as of summer 2012, they had not completed the plan (R. Garza, written communication, 27 June 2012).

In the *Geological Monitoring* chapter about coastal features and processes, Bush and Young (2009) described the following methods and 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.

Erosion

At Palo Alto Battlefield National Historical Park, slopes are gentle (fig. 8). However sheet, rill, and gully erosion occur across the landscape and particularly on steep resaca banks (Caran et al. 2005). In areas where vegetation is disturbed through grazing, cattle migrating to water sources, other anthropogenic activities, erosion is exacerbated. As climate continues to change, long term changes in precipitation patterns will likely lead to changes in vegetation cover and may increase susceptibility to erosion.

Figure 8. Photograph of low-relief resaca. Resacas, often delineated by distinctive vegetation, in the park now have generally low relief as illustrated here. Nevertheless, erosion can be an issue. National Park Service photograph by Rolando Garza (Palo Alto Battlefield NHP).

Continuous southeast to south-southeast winds from the Gulf of Mexico combined with the relatively dry climate make wind erosion a significant factor in the geomorphic evolution of the park's landscape. Areas where vegetation is missing or has been disturbed are particularly at risk of wind erosion (deflation). Sand sheets (geomorphic map unit PEss) result from mass removal of sand from dunes (Brown et al. 1980). Cultivation and grazing would have increased the potential for wind erosion, but revegetation since the park's establishment has lessened the impact. The vegetation-free floors of ephemeral resacas may experience deflation. Aeolian sediments concentrated on the northwestern side of the Palo Alto unit's resacas may have resulted from such a process (Caran et al. 2005).

Disturbed Lands

Disturbed lands are those park areas where the natural conditions and processes have been directly impacted by anthropogenic activities such as mining, development (e.g., facilities, roads, dams, abandoned campgrounds, and user trails), agricultural practices (e.g., farming, grazing, timber harvest, and abandoned irrigation ditches), overuse, or inappropriate use.

Ultimately the park's management plan is to restore the landscape to 1846-1848 battlefield conditions to best interpret the site's history for visitors (KellerLynn 2008). Since the battles of 1846, alterations to the park's landscape include road construction, pre-park development, intermittent cultivation and ranching, excavation of drainage ditches, and impoundment of resacas for water storage in stock tanks (figs. 6, 7, and 9) (Ramsey III et al. 2004; Caran et al. 2005). Most of the water diversion and storage facilities were constructed between the 1950s and 1970s (Caran et al. 2005). Ditches and trenches on either side of the Palo Alto Resaca were excavated between 1950 and 1962 to divert water to stock ponds and storage tanks also excavated into the resaca (Caran et al. 2005; Seramur and Ficker 2012). Much of the land within the park's legislative boundary is private, and cattle grazing still occurs on some non-federal portions (KellerLynn 2008; R. Garza, written communication, 21 February 2013). Areas of Flood Basin Grading to Interdistributary Mud deposits (geomorphic map unit Hf), exposed within the park, are now cultivated as are some resacas (PEa) and sand sheets (PEss) (Brown et al. 1980).

According to the park's Landscape Classification and Historic Analysis prepared by Ramsey III et al. (2004), the greatest alteration affecting the historic landscape occurred before 1934—excavation of the large drainage canal (figs. 7 and 10) to the north of the Palo Alto unit completed in 1916. Photographs dating back to 1934 revealed the presence of a historic "wet" roadway that was critical to the development and strategies of the 1846 battle of Palo Alto. Although there is no longer a visible trace of the road, it is a critical element to the successful restoration of the battlefield landscape. Another conspicuous change was the disappearance of a lake located in the northwest corner of the Palo Alto unit. This was due to the construction of a cattle tank between 1934 and 1950. Landscape complexity increased between 1924 and 2000. Myriad factors contributed to the landscape evolution, including: mesquite expansion into cordgrass resulting in a bimodal vegetation mix; cordgrass prairie reduction; dead and sparse grasses;

Figure 9. Photographs of stock tanks. Stock tanks and other water control and collection features were excavated into the landscape. The upper picture is of a tank near Arista Hill. The ridges were constructed to hold water in the tank. The lower picture is of the dam and stock tank northeast of the visitor center. These features were excavated into low-lying resacas. See figure 7 for locations. National Park Service photographs by Rolando Garza (Palo Alto Battlefield NHP).

bare soils expansion; and drainage impoundments associated primarily with resaca alterations (cattle tank construction) (Ramsey III et al. 2004). The greatest change in resaca character between 1934 and 2000 was the vegetation of the normally bare ground of the channel, although many resaca areas were undisturbed (Ramsey III et al. 2004).

The Resaca de la Palma unit is within Brownsville city limits and has been privately owned in the past. At the Resaca de la Palma unit significant landscape modifications included: (1) a 1920s-era residential structure moved from Port Isabelle to the site in the 1940s and associated outbuildings, (2) planting of an orange grove, (3) construction of a polo field and

Figure 10. Photograph of canal. The canal along the northern boundary of the park was constructed in 1916 for flood control and drainage. The canal excavation reaches approximately 9 m (30 ft) below grade. National Park Service photograph by Rolando Garza (Palo Alto Battlefield NHP).

associated horse corrals in the 1960s, and (4) dumping of fill materials from nearby highway and commercial construction endeavors (PBS&J 2004). The old pathway that helped U.S. forces across the resaca (see "Geologic Influences on May 1846 Battles") has been replaced by a major urban thoroughfare (National Park Service 2013).

Battlefield restoration would include a woody buffer along the highway and filling livestock water tanks (vintage 1920–1960) at the Palo Alto unit (KellerLynn 2008). At the Resaca de la Palma unit, some artificial fill was added to the southern and eastern portions associated with a polo field. Remains of the residence and outbuildings of former residents including a chimney, garage, patio, septic tank, pump house, and cistern occur in the northern portion of the property (PBS&J 2004). As of summer 2013, the park has nearly completed a draft vegetation management plan, designed in part to aid with the restoration of the historic landscape (KellerLynn 2008). A preferred alternative in the plan would include the use of prescribed fire on the restored gulf cordgrass prairies (R. Garza, written communication, 21 February 2013).

The GRI digital geologic map data includes an entire section devoted to anthropogenic landscape changes: Artificial Units. The geomorphic map units within this section (Hml, Hsr, Hsae, and Hsaq) are all located along the coast, beyond park boundaries. These units are described in detail in the "Map Unit Properties Table". The table also relates how coastal disturbed lands, including jetties, spoil areas, and dredged areas, are 1) reducing fetch and changing the flora and fauna of grass flats (Hg) along the coast; 2) changing the morphology of fore-island dunes (Hfi); 3) prevent the accumulation of inlet-related shoal (Hi) (Brown et al. 1980), which has implications for vegetation communities further inland, including the park area.

Oil and Gas Exploration and Development

A pipeline and associated access road, constructed in 1947, crosses the following geomorphic map units in the Palo Alto unit: Distributary Sands and Silts (Hds), Flood Basin Grading to Interdistributary Mud (Hf), and Abandoned Channel (PEa) (Brown et al. 1980; Caran et al. 2005). Following its establishment in 1992, the park "inherited" the pipeline access road. The Texas Gas Service Company maintains the access road by trimming branches and brush that overhangs the road and impedes access (KellerLynn 2008). Through an agreement between the NPS, the owners of the pipeline are required to maintain the pipeline and regularly inspect it for leaks or other maintenance concerns. Currently, the pipeline owners inspect the pipeline twice per year using the two-track dirt access road (fig. 11). The park permits access along the road, as long as improvements are not made to the road (e.g. bulldozing) or access is otherwise altered. To limit disturbance, access is also limited to periods when the road is not water-saturated. In order to protect vegetation and limit erosion and ground disturbance, the park does not allow access to an area where the pipeline crosses a resaca. At this location, the workers must drive around the outside of the park and return to park lands on the other side of the resaca. The park had initiated an environmental assessment for more comprehensive monitoring of the pipeline, but this remains in progress (R. Garza, written communication, 27 June 2012).

Figure 11. Photograph of pipeline access road. Resource managers at the park limit access to the road to minimize additional disturbance or erosion. National Park Service photograph by Rolando Garza (Palo Alto Battlefield NHP).

Oil and gas exploration and development is common in south Texas. As a result, some seismic investigation for oil and gas has occurred in the vicinity of the park. However, operations within the park's legislative boundary can only be conducted if there is a demonstrated outstanding nonfederal mineral right. Any such operations would also be subject to the NPS regulations at 36 C.F.R. Part 9 Subpart B, which govern nonfederal oil and gas rights (KellerLynn 2008). Impacts from oil and gas extend beyond the actual rigs and exploration efforts. Beyond the boundary of the park, spoil deposits (Hsr, Hsae, and Hsaq) are dredged from shallow water and wind-tidal flats (Hw and Hwa) along the coast for channels providing access to oil and gas well drill sites.

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 Palo Alto Battlefield National Historical Park.

During the 2008 scoping meeting, participants developed a list of geologic features and processes relevant to the park, including:

- Rio Grande Resacas
- Geologic Influences on May 1846 Battles
- Geologic Influences on Ecosystems
- Eolian Features and Processes
- Paleontological Resources

Rio Grande Resacas

Resacas—remains of a 500-year-old abandoned channel incised by the Rio Grande—cut across Palo Alto Battlefield National Historical Park and feature prominently on the park's landscape (figs. 7 and 12) (Hds and PEa) (Brown et al. 1980). Also known as "oxbows," these abandoned bends along the Rio Grande and in other parts of the Southwest are called resacas, derived from the Spanish word "resacar" meaning "to redraw" or "to retake." The evolution of a resaca is recorded in the characteristic sediments deposited within it. Through time, when the Rio Grande overflowed its banks, the unconfined floodwater separated into multiple distributary channels radiating across the delta plain (geomorphic map units Hls, Hms, Hds, Hfe, and Hf) (Brown et al. 1980; Caran et al. 2005). Initially, a river's distributary channel and/or meander bend is lined with coarser, sandy deposits reflecting the continual flow. Once the channel is superceded and abandoned, the bends still function as flood overflow channels, and hold water as ponds and lakes. Over time they fill in with finer-grained sediments and floodplain deposits (fig. 13) (KellerLynn 2008; Seramur and Ficker 2012). Throughout the Rio Grande valley of southern Texas, resacas provide water sources in arid conditions, favorable conditions for woody plants to grow, and hence important natural habitat for birds and other animals (KellerLynn 2008; Seramur and Ficker 2012). Locally, resacas accommodate significant drainage in Cameron County toward the Laguna Madre (Baker and Dale 1964).

Palo Alto Battlefield National Historical Park has several resacas that hold pools of water after heavy rains but are dry at other times of the year. The resacas in the park are on average 50–60 m (160–200 ft) wide and underlain by mud in contrast to sand and silt adjacent to the abandoned channels. Tule Chica, an ephemeral feature, is one of the few remaining "natural" lakes at the Palo Alto unit (KellerLynn 2008). Resaca de la Palma contains water on a regular basis—a local waterway now lined with condominiums (National Park Service 2013).

Figure 12. Photograph of resaca. Resacas are distinctive features on the Palo Alto Battlefield NHP landscape. This photograph was taken in the resaca west of the US Line Trail. National Park Service photograph by Rolando Garza (Palo Alto Battlefield NHP).

In 1846, the climate was cooler and wetter than at present. The battles were fought on a coastal sand flat and the battlefield landscape featured many more marshes and small ponds than no longer exist. The marshes and ponds would have played important roles leading up to and during the battles. Surface water was needed to water horses and cattle, but boggy, wet lands would have impeded troop movements and heavy artillery (Caran et al. 2005).

Fluvial features and processes and surface water includes many components that are located beyond park boundaries. These are along the gulf coast as part of the: 1) Bay-Estuary-Lagoon System; 2) Barrier-Strandplain and Offshore System; and 3) Fluvial-Deltaic System described in detail in the "Map Unit Properties Table" included with this report.

Geologic Influences on May 1846 Battles

A major goal of Palo Alto Battlefield National Historical Park is to restore the condition of the landscape to conform to those conditions existing at the time of the May 1846 battles (fig. 14). Carney (2006) summarizes the events leading up to, during, and after the two battles. Decades of anthropogenic modifications and natural earth surface processes have acted in concert to significantly alter the landscape within the park. This in turn affects the park's ability to interpret the history of the battles and the natural factors and military tactics impacting the outcome. Past changes in climate (due to natural causes) are significant for interpreting the history associated with the Palo Alto landscape (KellerLynn 2008).

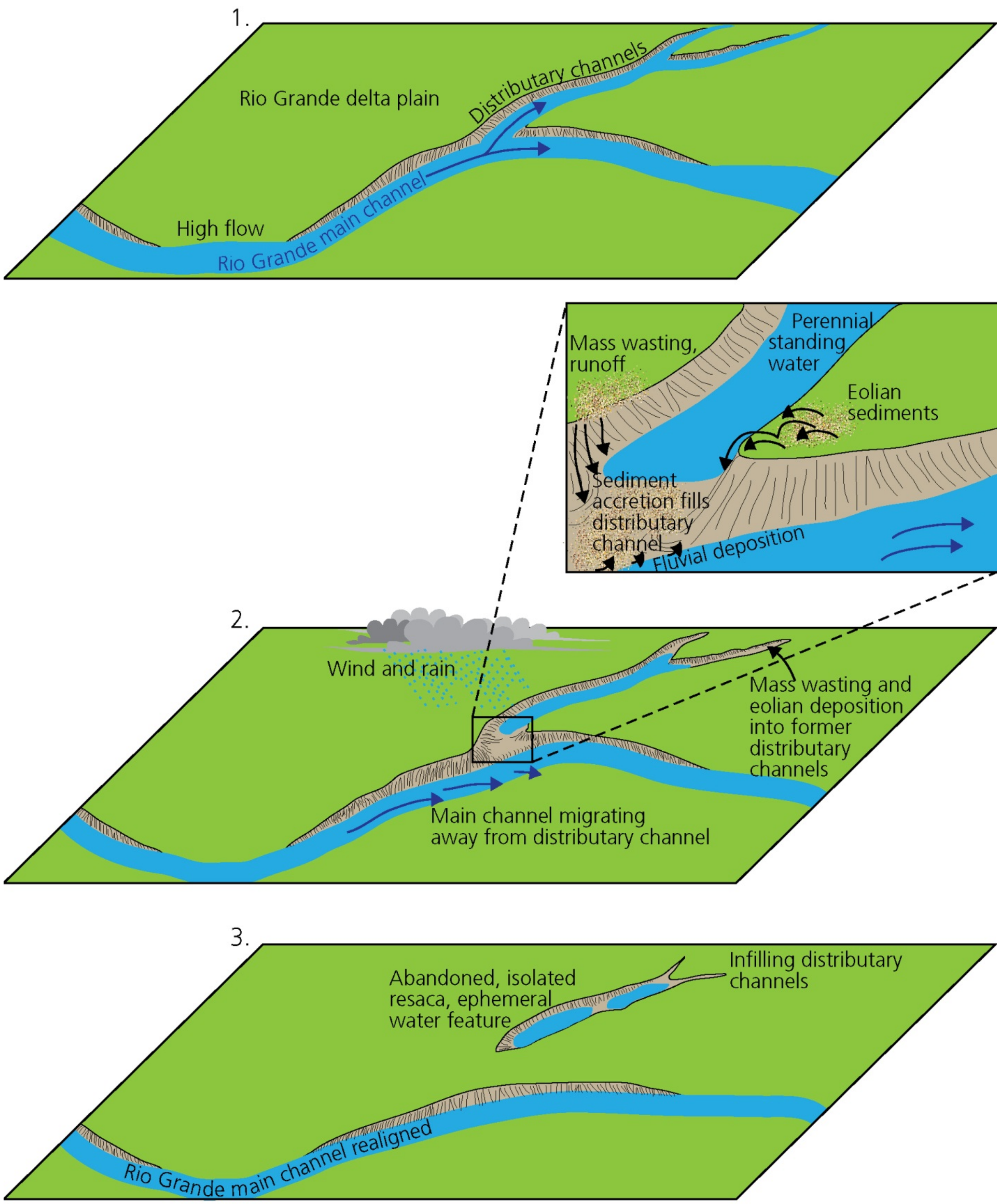


Figure 13. Formation of a resaca. River floods and distributary channels accommodate floodwater. When the main channel migrates away from the distributary channel deposition fills the channel and ultimately separates it from the main channel. The abandoned channel slowly fills in with sediment and is left abandoned as a resaca. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) with information from Caran et al. (2005).

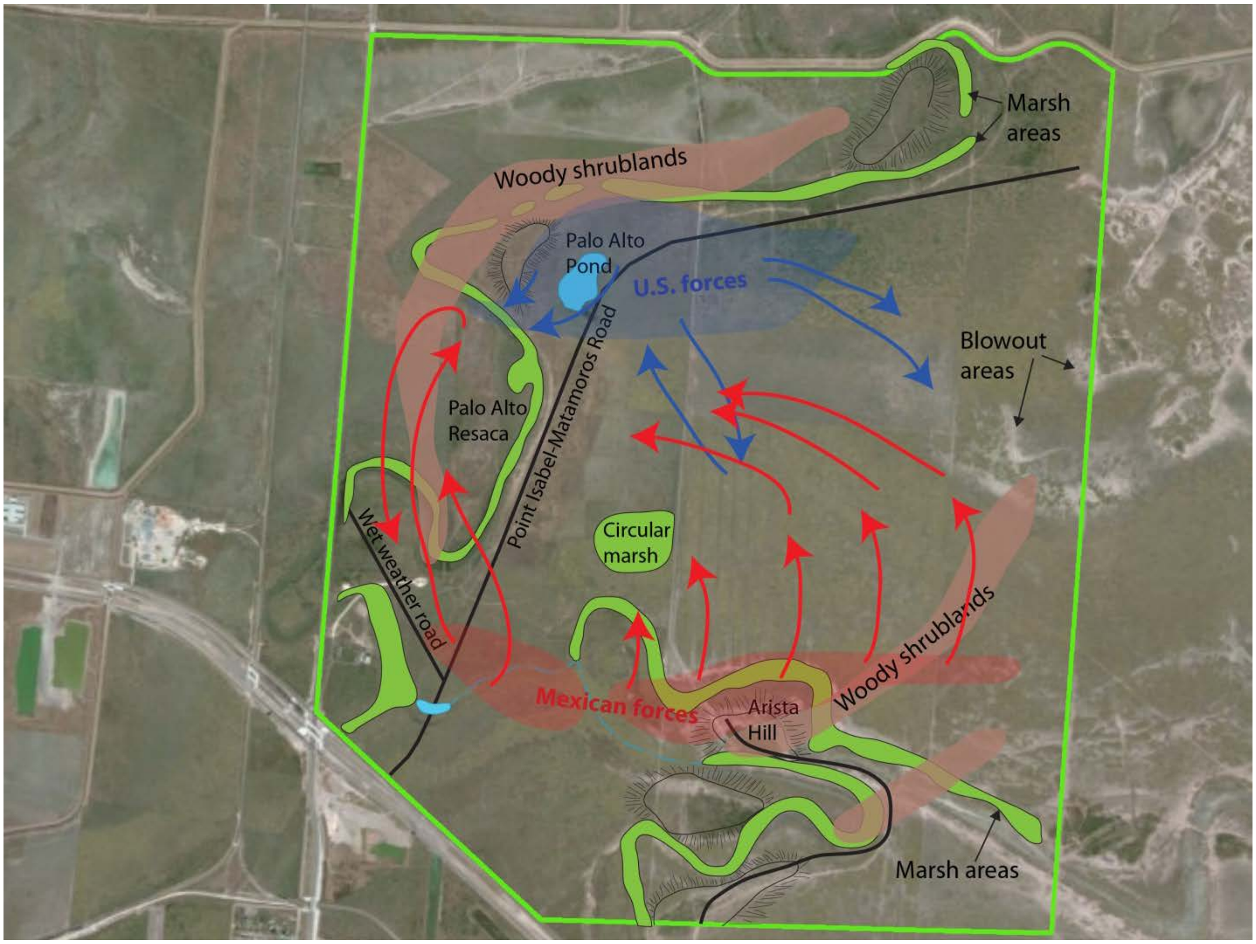


Figure 14. Map of battle setting at Palo Alto Resaca. Orange shaded areas delineate woody shrublands, green areas are marsh/wetlands, red shaded area shows approximate initial location of Mexican forces whereas blue shaded area shows the approximate initial location of U.S. forces. Graphic adapted from figure 5 in Caran et al. (2005) with information from Carney (2006) by Trista Thornberry-Ehrlich (Colorado State University). Aerial imagery from ESRI ArcMap Bing imagery basemap.

To help understand the changes to the landscape since 1846 and steps necessary to restore battle-era conditions, Caran et al. (2005) and Seramur and Ficker (2012) prepared geoarcheological investigations and paleoenvironmental histories for portions of the Palo Alto Resaca. PBS&J (2004) prepared an archeological investigation at Resaca de la Palma. The details presented in their reports are beyond the scope of this report. A summary, focused on geologic connections with the park's battle history, is presented here.

At the time of the 1846 battles, much of this part of Texas between Point Isabel and Brownsville was an upland grassland savannah with occasional mottes (clusters) of trees, and streams bordered by a dense growth of shrubs, trees, and riparian vegetation. Much of the park is underlain by Flood Basin Grading to Interdistributary Mud deposits (Hf) (Brown et al. 1980). The high clay content of the soils and low-lying resacas created very marshy, boggy areas. In 1846, the planet was experiencing the last remnants of a period of fluctuating climate known as the Little Ice Age potentially caused by volcanism and subsequent sea-ice formation (Haecker and Mauck 1997; KellerLynn 2008; Gifford et al. 2012). Haecker and Mauck (1997) reported heavy rains occurred just before the battles, which may be a reflection of the variable climate at that time. According to recent climate data, this part of southern Texas experiences an average monthly rainfall in May of about 5.6 cm (2.2 in.), with the heaviest rains in September (13.2 cm [5.2 in.]). In May 1846, the area experienced especially heavy rains (Weaver 1999). More precipitation supported more woody vegetation because trees in the park area today prefer growing in wetter substrates. The wet period immediately before and during the battles would have created alternately favorable and unfavorable conditions for troops. For example, treed areas and increases in vegetation would have provided more cover, while, on the other hand, the wet, muddy conditions would have impeded movement of heavy artillery and supplies (Caran et al. 2005).

Arista Hill, underlain by Distributary Sands and Silts (Hds) was strategically significant during the battle at Palo Alto (fig. 15) (Brown et al. 1980; Caran et al. 2005). The hill takes its name from Mexican Major General Mariano Arista. Mexican forces initially set up in an east-west configuration anchored on the eastern end by a mesquite thicket at this hill. The western edge of the line extended towards Palo Alto Resaca across the north-

Figure 15. Photograph of Arista Hill. On a landscape of very subdued topography, Arista Hill was a strategically significant feature. National Park Service photograph by Rolando Garza (Palo Alto Battlefield NHP).

south Matamoros Road. Light artillery may have been placed on Arista Hill. Historic accounts suggest thick grasses growing in the sand and silt of the Palo Alto Plain impeded the effectiveness of the artillery (Caran et al. 2005).

Palo Alto Pond and Palo Alto Resaca (PEa), were water sources for the U.S. forces. Brigadier General Taylor used the north-south Port Isabel-Matamoros Road for moving the pack train and soldiers. The American position on 8 May was just south of the pond, facing the plain, approximately 0.47 km (0.75 mi) from the Mexican forces. The lines oriented east-west from the west edge of Palo Alto Resaca (PEa), across the Matamoros Road. The pack train stayed nearest to Palo Alto Pond (Caran et al. 2005).

Boggy, marsh lands across the plains (Hf) impeded infantry marches and the battle was largely decided by a duel of artillery (Brown et al. 1980; Caran et al. 2005). The large, circular marsh in the midst of the battlefield thwarted a Mexican advance and the lighter, "flying artillery" of the American forces gave them an advantage on the landscape of alternating sandy, silty areas with clay-rich wetlands and marshes. Repeated attempts to cross the resaca and attack the Americans' western flank were thwarted by boggy conditions in the resaca. Strong winds from the Gulf of Mexico fueled a prairie grass fire

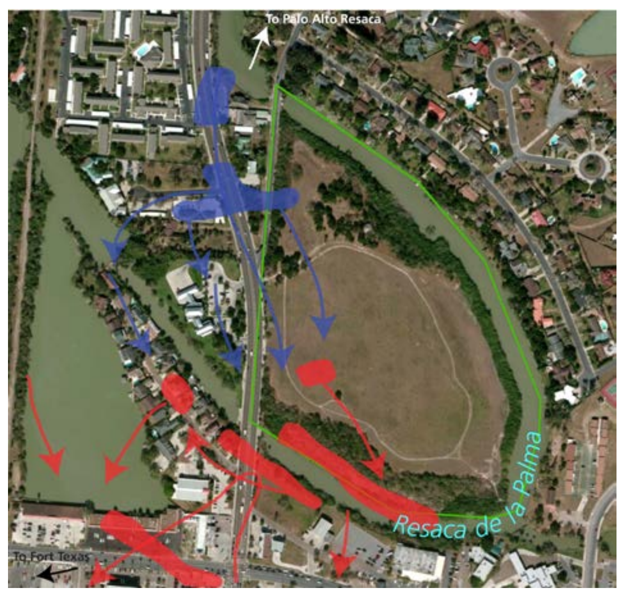


Figure 16. Map of battle setting at Resaca de la Palma over current landscape. Note the expansive, surrounding development. Red shaded area shows approximate initial location of Mexican forces whereas blue shaded area shows the approximate initial location of U.S. forces and corresponding arrows denote approximate troop movements. Green line is the approximate park boundary. Graphic adapted from an unnumbered figure Carney (2006) by Trista Thornberry-Ehrlich (Colorado State University) using aerial imagery from ESRI ArcMap Bing imagery basemap.

that created even more challenging conditions during the afternoon. By evening, the battle lines were oriented more north-south paralleling the Port Isabel-Matamoros Road. Mexican forces camped near or on Arista Hill and surrounding mesquite thickets on adjacent hills. The day after the battle, participants constructed three earthworks near Palo Alto Pond to protect the cannons and pack train (Caran et al. 2005).

Mexican forces retreated to Resaca de la Palma (fig. 16), a water-filled ravine lined with dense, thorny brush among a surrounding landscape of rolling hills covered with a thick tangle of trees and chaparral. The resaca cut a prominent 3-km-long (2-mi-long), 180-m-wide (200-yd-wide), 3.7-m-deep (12-ft-deep) furrow across the area (Carney 2006). These natural features prompted General Arista to position his troops there to limit any attack from General Taylor's advancing forces. This position also entailed blocking the Point-Isabel Matamoros Road with artillery batteries and lining troops along the banks of the resaca in cover of the heavy brush that thrived there. In this strategy, Mexican forces hoped to avoid another disastrous open-field artillery battle. When the U.S. forces arrived shortly after 3 p.m., they immediately charged, fortuitously finding a path to lead them over the marshy resaca to attach the Mexican western flank, and avoiding the most heavily fortified areas (Carney 2006; National Park Service 2013). When the U.S. troops gained control of the artillery and the roadway, the Mexican troops retreated for the safety of the Rio Grande and the battle was over—the north bank of the Rio Grande was firmly in U.S. hands (National Park Service 2013).

Geologic Influences on Ecosystems

The resacas in the park collected a comprehensive sedimentary record of environmental conditions for the past 6,000 years or so (Seramur and Ficker 2012). Stretches of Abandoned Channels (resacas, geomorphic map unit PEa) support freshwater marsh habitats (Brown et al. 1980). Pollen collected from Palo Alto Resaca reveals a decline in trees, fluctuations among grassland taxa, and an increase in chenopods (a type of plant that produces abundant pollen, frequently weeds) (Caran et al. 2005).

Soils within the resacas have higher than average gypsum contents due to poor drainage and (salt) precipitation from solution upon evaporation (Mangum and Lee 1907). This calcium sulfate ($CaSO_4$), when enriched in the soil, inhibits the growth of many plants (Caran et al. 2005). Some gypsum-tolerant chenopods have locally thrived (Caran et al. 2005). Saline soils occur within Distributary Sands and Silts (geomorphic map unit Hds) exposed within the park (Brown et al. 1980). Clay soils of the Harlingen and Benito Series occur in Flood Basin (Hfe) and Flood Basin Grading to Interdistributary Mud (Hf), both of which are locally heavily cultivated (Brown et al. 1980).Soils in the park vicinity (mostly to the south) have elevated uranium levels (KellerLynn 2008 with information from R. Page, geologist, U.S. Geological Survey). Chemical reactions involving organic sediments in the standing water of resacas and marshes (PEa and Hmf) can quickly cause anoxic conditions where sulfate-reducing bacteria can thrive and can cause high local groundwater pH (Caran et al. 2005). For more information regarding the soils and associate resource management considerations, refer to the park's Soil Resources Inventory database and map (National Park Service 2006).

This area of Texas is experiencing significant population growth and landuse change. Anthropogenic land features such as made or reclaimed land and spoil (Hml, Hse, Hsae, and Hsaq) (Brown et al. 1980) reflect a history of change that is ongoing and had far-reaching impacts to the entire coastal region of Texas. The geologic units exposed within the park: Distributary Sands and Silts (Hds); Flood Basin Grading to Interdistributary Mud (Hf); and Abandoned Channel (PEa) are the landward component of a very complex zone of interaction between a major river delta (Rio Grande) and a coastal barrier system. The "Map Unit Properties Table" included in this report details the various environments within the Bay-Estuary-Lagoon System; the Barrier-Standplain and Offshore System; and the Fluvial-Deltaic System.

Eolian Features and Processes

As discussed in the "Erosion" section, deposition and erosion by wind has significantly contributed to the evolution of the park landscape. Sand and clay mounds and ridges (dunes, geomorphic map units PEda and PEdi) generally rise less than 8 m (25 ft) high in the lower Rio Grande valley. Broad shallow depressions associated with the mounds contribute to the "blowout and dune" topography (Baker and Dale 1964). Barren areas on the east side of the Palo Alto unit (fig. 7) have potential to develop into blowouts that can contribute to the formation of dunes or Sand Sheets (PEss) (KellerLynn 2008). Portions of Flood Basin Grading to Interdistributary Mud deposits (Hf) exposed within the park include clay-sand dunes (Brown et al. 1980). Unvegetated stretches of desiccated, cracking, gypsum- and clay-rich soils in the bottoms of resacas at Palo Alto Battlefield National Historical Park produce ample source material for wind erosion; however the depressions of the resacas also collect sediment from wind sources (Caran et al. 2005; KellerLynn 2008). The moderate hilltop areas are also prone to wind erosion (KellerLynn 2008). Other local eolian units (not exposed within the park) include Gavilans (clay-sand dunes), Clay-Sand Dune Complexes, and Sand Sheets (PEda, PEdi, and PEss, respectively) (Brown et al. 1980).

The coastal areas beyond park boundaries are host to myriad eolian features influenced by nearly continuous blowing winds from the Gulf of Mexico. Detailed on the "Map Unit Properties Table", these units include beach (Hb), fore-island dunes (Hfi), sand flats (Hsf), washover fans (Hwf and Hwd), and wind-tidal flats (Htz, Hw, and Hwa) (Brown et al. 1980). In high winds and during storms, these may act as source material for eolian deposits far inland.

In the *Geological Monitoring* chapter about aeolian features and processes, Lancaster (2009) described the following methods and vital signs for monitoring aeolian resources: 1) frequency and magnitude of dust storms, 2) rate of dust deposition, 3) rate of sand transport, 4) wind erosion rate, 5) changes in total area occupied by sand dunes, 6) areas of stabilized and active dunes, 7) dune morphology and morphometry, 8) dune field sediment state (supply, availability, and mobility), 9) rates of dune migration, and 10) erosion and deposition patterns on dunes.

Paleontological Resources

Compared to Earth's long history, the underlying geologic framework at Palo Alto Battlefield National Historical Park is very young. This makes it difficult to differentiate between actual fossils and merely modern remains. The definition for a fossil put forth by the National Park Service does not place an arbitrary date to mark the cutoff between fossils and younger remains. Instead it defines a fossil as any remains of life preserved in a geologic context—"geologic context" here implies some level of antiquity (Kenworthy et al. 2007). All specimens of past life are important, nonrenewable natural resources and valuable contributors to the understanding of life on earth. The "Map Unit Properties Table" summarizes specimens and modern habitat for units (geomorphic map units Hg, Hblm, Hs, Hsb, and Hb) present in the GRI digital geologic map data.

A geoarcheological investigation of the Palo Alto resaca (PEa) unearthed fossil animal remains and traces, including burrows of fiddler crabs (*Uca subcylindrica*) and some snail shells (*Rabdotus* sp. and cf. *Gyranulus* sp.) (Brown et al. 1980; Caran et al. 2005). Another resaca, Resaca del Rancho Viejo, 3.2 km (2 mi) southeast of the park yielded a diverse Holocene assemblage including snails, clams, gastropods, insects, crabs, and some fish scales (Neck 1985). Investigators also recovered and described an extensive pollen record, which yielded radiocarbon ages ranging from 5,300 to 300 calendar years before present (Brown et al. 1980; Caran et al. 2005). The locations of the radiocarbon samples from different stratigraphic layers are part of the GRI digital geologic map data.

During the GRI scoping meeting, park staff mentioned the discovery of Pleistocene mastodon remains at the mouth of the Rio Grande (KellerLynn 2008). Hay (1924) documented this find as an "elephant [mammoth or mastodon] molar which had been found near Brownsville." There are no exposures of Pleistocene age within or adjacent to the park, but elsewhere in southern Texas these units contain a rich fossil record from that time (Kenworthy et al. 2007). Fossils washing from these units may be carried downstream and redeposited within younger deposits. The potential for future for fossil discovery is limited at the park. Pleistocene sediments may be found in the lower reaches of gullies, but most material is likely Holocene or recent in age.

Santucci et al. (2009)—the paleontological resources chapter in *Geological Monitoring*—described five methods and vital signs for monitoring in situ paleontological resources: (1) erosion (geologic factors); (2) erosion (climatic factors); (3) catastrophic geohazards; (4) hydrology/bathymetry; and (5) human access/public use. Paleontological resources within NPS units require science-based inventory, monitoring, research, protection, and interpretation as outlined by the 2009 Paleontological Resources Preservation Act. Agencies from the departments of Interior and Agriculture are currently (August 2013) finalizing the associated regulations.

Geologic History

This section describes the rocks and unconsolidated deposits that appear on the digital geologic map of Palo Alto Battlefield 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 Palo Alto Battlefield National Historical Park was shaped by the relatively recent formation of the Rio Grande deltaic system and the Texas Coastal Zone. This story was strongly influenced by the global effects of Pleistocene ice ages (within the past 2 million years), and modern climatic patterns. The geologic history reflected in sediments and landforms beneath, in, and around the park spans from the Mesozoic Era (approximately 251 million years ago) to the present (fig. 4).

Mesozoic Era (251–66 million years ago): Pangaea Separation, Gulf of Mexico Formation, and Ouachita Mountains Erosion

At the end of the Paleozoic Era, a supercontinent—Pangaea—had formed through the collisions between North America and the other continental landmasses (European, African, and South American plates). Compressive forces buckled Earth's crust along the collision zones forming mountain ranges such as the Appalachians. Locally, this event is referred to as the Ouachita orogeny and resulted in the formation of the Ouachita Mountains (fig. 17A) in central Texas, northwest Arkansas, and southeast Oklahoma (Hentz 2001; Pierson 2005).

During the early Mesozoic Era, Pangaea began to rift apart. Preexisting geologic structures, such as faults, were reactivated approximately 220–245 million years ago and opened of the Gulf of Mexico (fig. 17B) (Bureau of Economic Geology 1992; Thomas and Keller 1999). The continents pulled apart during the Triassic and Jurassic periods, forming large basins that subsequently received sediments shed from the rapidly eroding Ouachita highlands. In the early stages, a series of discontinuous rift basins developed parallel to the edge of the opening ocean basin. These basins extended from Mexico to Nova Scotia (Hentz 2001). The Gulf of Mexico originated as a small ocean basin created by seafloor spreading beginning in the Middle Jurassic (Galloway et al. 2011).

As rifting continued, thick deposits of Middle Jurassic salt buried the earlier rift basins in Texas. This accompanied the development of the East Texas and Gulf Coast basins (Hentz 2001). As the basin widened, areas in the south and east of Texas warped downwards and continued to subside under the weight of added sediments. Sediments buried marine salt from earlier basins as well as limestone shelves. This juxtaposition of rock types formed folds and hydrocarbon traps, the source of oil and gas today (Bureau of Economic Geology 1992). Much of the Coastal Plain of Texas and flanking continental shelf formed during the sedimentation of this time (fig. 17C) (Hentz 2001; Galloway et al. 2011).

Continued erosion of the Ouachita Mountains and burial of adjacent basins beveled the landscape (Pierson 2005). Orogenic events in the western United States as the Rocky Mountains formed provided more sediment to the Western Interior Seaway that bisected North America, connecting the Gulf of Mexico and the Arctic Ocean for much of the Cretaceous. Most of Texas was covered by this inland sea (Galloway et al. 2011).

Cenozoic Era (the past 66 million years): Rio Grande Evolution and Ice Age Glaciation

The Tertiary period (between 66 million and 2.6 million years ago) is marked by deposition of massive amounts of fluvial-deltaic sediments eroded from the young Rocky Mountains and transported southeastward into the widening Gulf of Mexico (Bureau of Economic Geology 1992; Hentz 2001). The Cenozoic sediments of the gulf contain a nearly continuous record of sediment supply from the North American interior (Galloway et al. 2011). The upper coastal plain formed as large, fluvial-deltaic systems along the margin advanced into the basin throughout the Paleocene (approximately 60 million years ago). Earth's crust bowed downward, subsiding under the weight of the added sediments and thus creating room for even more deposition, reaching more than 10 km (6 mi) thick in places (Galloway et al. 2011).

During the middle Tertiary period, crustal extension (pulling-apart) and igneous activity created extensive networks or normal faults and fueled volcanoes throughout the southwest. In west Texas, volcanic activity produced about 14 volcanic centers as well as thick lava-flow and ash-fall deposits between about 47 and 17 million years ago. The extensional tectonic that produces the distinctive basin-and-range topography of the southwest began about 30 million years ago in Texas (Hentz 2001). This event would have a strong influence on the development of the Rio Grande basin—one of the major contributors to sediment in the Gulf of Mexico (Galloway et al. 2011).

As the earth's crust pulls apart, basins form, including the Rio Grande rift basin. The Rio Grande River headwaters have long drained east from Arizona and south from Colorado (Galloway et al. 2011). As rifting continued, the river took advantage of the newly-formed basin, and, it now flows the length of the rift valley. This is an

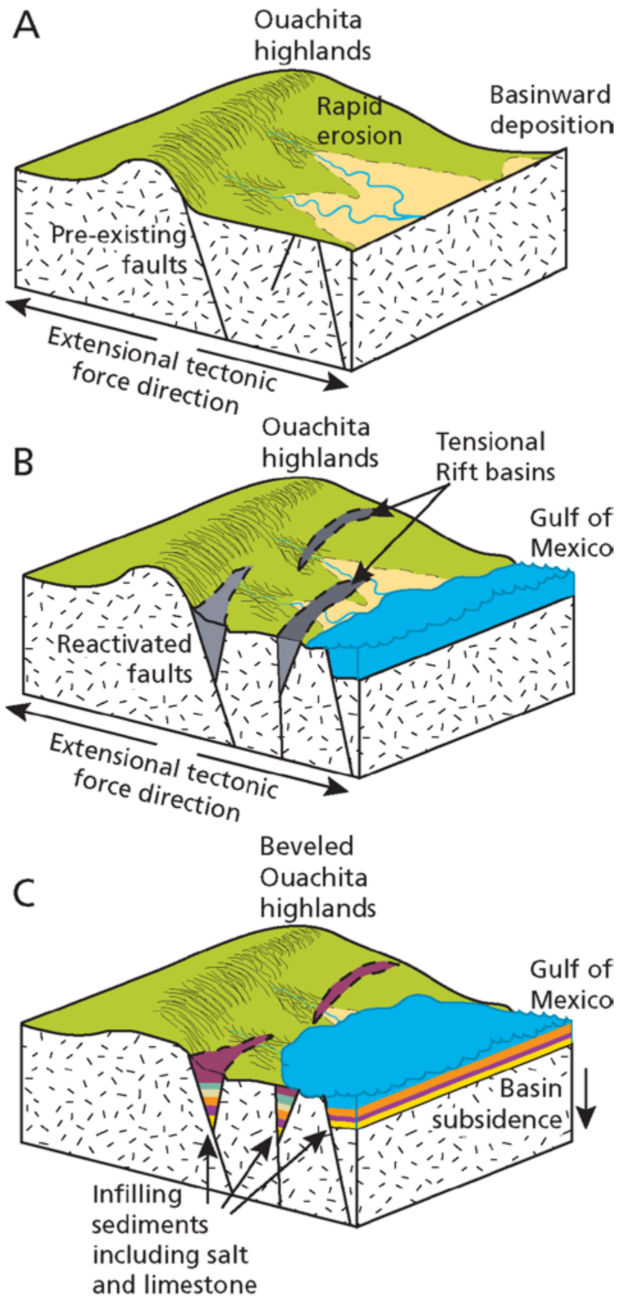


Figure 17. Schematic graphic depicting the early Mesozoic evolution of central-southern Texas. After the Ouachita Orogeny, erosion removed massive amounts of material from the highlands and transported the material toward the then-forming Gulf of Mexico, which was opening as Pangaea rifted apart. Not to scale. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University).

uncommon occurrence for a river, as the Rio Grande is now draining a valley it did not carve.

Repeated ice ages during the Pleistocene Epoch (between 2.6 million years ago and approximately 12,000 years ago) had lasting, world-wide impacts. Massive bodies of ice advanced and retreated from the northern and southern poles (continental ice sheets) and high elevations (alpine glaciers). The continental ice sheets sequestered vast amounts of water from the Earth's oceans. Global sea level dropped 90–120 m (300–400 ft) during times of maximum glacial extent (Hentz 2001).

Such a sea level drop exposed vast areas of previously submerged land, including portions of what are now continental shelves. Dust (called loess), blown from these areas and other areas of glacial disturbance, would later become fertile soils for prairies and grasslands. Glacial meltwater scoured major watersheds (Pierson 2005).

The Rio Grande delta has been a prominent feature on the south Texas continental shelf for more than 120,000 years (Banfield and Anderson 2004). During marine transgressions (highstands) wave action dominated the development of the delta geomorphology and sedimentation patterns (fig. 18). During marine regressions (lowstands), fluvial processes formed a large shelf-margin delta and slope fan (Banfield and Anderson 2004). According to Brown et al. (1980), the fluvial-deltaic sediments of the Beaumont and Lissie formations, buried deep beneath the park and the modern Rio Grande delta, were deposited over 100,000 years ago during one or more interglacial (between major glacial advances) stages. At these times, glaciers were melting and the flows in most major rivers, such as the Rio Grande were high. The swollen Rio Grande transported vast amounts of suspended sand, silt, and mud into the delta area. Between 80,000 and 60,000 years ago, sea level fell 60 m (200 ft) as glaciers again advanced, and the Rio Grande valley shifted seaward to the shelf margin (Banfield and Anderson 2004).

Approximately 30,000 years ago, sea level was around 120 m (400 ft) lower during the most recent continental glaciation, the Rio Grande eroded a broad, deep valley through the modern delta area. Its valley extended across the continental shelf to a shoreline near the present edge of the continental shelf, about 80 to 89 km (50 to 55 mi) east of South Padre Island (Brown et al. 1980; Banfield and Anderson 2004). Another significant drop in sea level occurred during the most recent ice age glacial advance, approximately between 22,000 and 17,000 years before present (Banfield and Anderson 2004).

By 18,000 years ago, the glaciers began their most recent retreat and meltwater raced toward the sea, which began its intermittent rise. As sea level rose, Holocene sediments began to fill the late Pleistocene Rio Grande Valley on the continental shelf (Brown et al. 1980). Sedimentation produced a transgressive sequence of deposits in the valley in ascending order: meandering fluvial deposits, deltaic deposits, estuarine deposits, and tidal-open marine deposits. The sea flooded the deep valley some 30 to 50 km (20 to 30 mi) west of the present shoreline creating an elongate estuary. Between 10,000 and 7,000 years ago, in the mid to late Holocene, sediments transported by the Rio Grande filled this estuary. Deposits of Holocene and Modern prograding deltaic sand and mud, and aggrading fluvial sand and mud buried the older, estuarine deposits from the marine transgression (Brown et al. 1980). By 6,000 years ago, the resaca at Palo Alto was an active distributary channel of the Rio Grande, collecting sand-rich channel and levee deposits (Seramur and Ficker 2012).

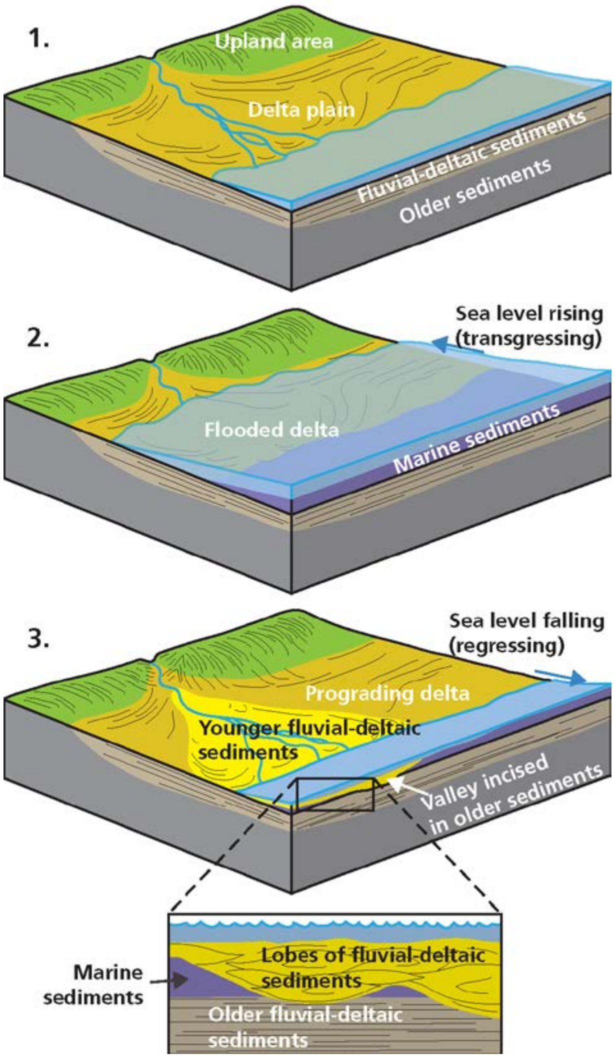


Figure 18. Schematic graphic illustrating deltaic sedimentation during changing sea level. As shoreline shifts landward and then seaward, fluvial-deltaic sediments become interlayered with marine sediments across the continental shelf. Not to scale. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University).

Approximately 4,500 to 4,000 years ago, relative sea level rise slowed in south Texas. The Rio Grande deltaic system stabilized into the open Gulf of Mexico, where a sandy, wave-dominated delta formed and a barrier island began to form. That island is now called "Padre Island" and part of the eponymous national seashore (Banfield and Anderson 2004; KellerLynn 2010). Over the past 3,400 years temperature rose and precipitation decreased making south Texas increasingly arid. As a result, the sediment supply to the Rio Grande delta and the Gulf Coast diminished and the delta began to migrate landward (Brown et al. 1980; Banfield and Anderson 2004; Weight et al. 2011). Storms and currents then reworked the sediments into discontinuous offshore shoals (Brown et al. 1980; Bureau of Economic Geology 1992). The shoals eventually coalesced to form South Padre Island. For the past several thousand years, thin coastal-barrier, delta, beach, and lagoonal sediments have been deposited along the Texas Gulf Coast (detailed in the Bay-Estuary-Lagoon System and Barrier-Strandplain and Offshore System rows in the "Map Unit Properties Table") (Brown et al. 1980; Bureau of Economic Geology 1992). As the barrier islands developed (Hsb, Hb, Hfi, Hsf, Hwf, and Hwd), Laguna Madre formed between the islands and the mainland shoreline (Brown et al. 1980). Now, Padre Island and the other Gulf Coast barriers are shifting landward as sea level continues to rise. Laguna Madre is filling with storm washover sediments (Hwf and Hwd) and eolian deposits. Broad, wind-tidal flats (Hw, Hwa, and Htz) are developing along the margins of the lagoon (Hg, Hbls, and Hblm). When the lagoon is completely filled, the Gulf the coastal plain of mainland Texas will become the shoreline (Brown et al. 1980).

The Rio Grande meandered across its broad delta for thousands of years leaving an anastomosing pattern of resacas, abandoned channels and distributaries (Hls, Hms, Hds, PEa), as well as and fluvial deposits (Hfe and Hf). The park's Palo Alto Resaca (PEa) was once part of the larger Resaca de los Cuates, one of many radiating distributary channels of the Rio Grande (Caran et al. 2005). The separation of the Rio Grande's active channel from the resaca occurred in several phases, reflected in the sedimentary record within the resaca at Palo Alto. The first phase was a transition from continual flow of water to intermittent flow as the future resaca became a flood channel, only active during high magnitude flood events. The intermittent flow through the channel was short lived and the resaca experienced standing water conditions by about 3,000 years before present as the flow of water shifted across the Rio Grande delta (Caran et al. 2005; Seramur and Ficker 2012). Marsh vegetation dominated the resaca by 1,200 years before present (Caran et al. 2005). Freshwater marshes (Hmf) now occur throughout the park area (Brown et al. 1980). Fine-grained sediment from adjacent flood plains began to fill the resaca during localized runoff (precipitation) events (Seramur and Ficker 2012).

As arid conditions prevailed in this part of southern Texas, eolian processes fueled by constant southeasterly winds produced local sand sheets and dune trains (PEda, PEdi, and PEss) from sediments derived from Pleistocene fluvial and deltaic deposits (Brown et al. 1980). Eolian deposits are present in the sediments of the resaca, which experience eolian deposition or erosion depending on whether the depression is holding water or not (Caran et al. 2005). The arid climate, sparse vegetation, persistent winds, and occasional hurricanes are the primary natural factors affecting landscape evolution (Brown et al. 1980). Accompanying natural landscape changes, anthropogenic activities have also dramatically altered the south Texas landscape. Water management and coastal engineering structures (Hml, Hsr, Hsae, and HSaq) (Brown et al. 1980) are major factors for landscape change in the park area.

The present landscape of Texas reflects a long geologic history that continues to evolve through coastal processes and erosion of the landscape. The geologic history and framework at the park contributed to the 1846 battles that shaped human history in south Texas and across two nations.

Geologic Map Data

This section summarizes the geologic map data available for Palo Alto Battlefield National Historical Park. The Geologic Map Graphic displays the geologic map data draped over a shaded relief image of the park and surrounding area. The Map Unit Properties Table summarizes this report's content for each geomorphic 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 4. Surficial geologic map data are provided for Palo Alto Battlefield National Historical Park.

Geologic maps also may show geomorphic features, structural interpretations, and locations of past geologic hazards that may be prone to future activity. Additionally, anthropogenic features such as mines and quarries may be indicated on geologic maps.

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 Palo Alto Battlefield National Historical Park. These source maps provided information for the "Geologic Issues," "Geologic Features and Processes," and "Geologic History" sections of this report.

Brown, L. F., J. L. Brewton, T. J. Evans, J. H. McGowen, W. A. White, C. G. Groat, and W. L. Fisher, with cartography by Hartmann, B., D. F. Scranton, and J. W. Macon. 1980. Environmental Geology Sheet, Environmental Geological Atlas of the Texas Coastal Zone-Brownsville-Harlingen Area (scale 1:125,000). Bureau of Economic Geology, The University of Texas at Austin, Austin, Texas, USA.

Caran, S. C., S. D. McCulloch, and J. Jackson. 2005. Report on a Geoarcheological Investigation at the Palo Alto Battlefield National Historical Park (41CF92) Cameron County, Texas. Order No. p73500-40016, Report No. 1. McCulloch Archaeological Services.

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 Palo Alto Battlefield 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 Palo Alto Battlefield National Historical Park from the unit list.

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

- Data in ESRI geodatabase and shapefile GIS formats
- Layer files with feature symbology (see table below)
- 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.
- KML/KMZ files for viewing in Google Earth™.

Table 1. Geology data layers in the Palo Alto Battlefield National Historical Park GIS data.

Data Layer	Data Layer Code	On Map Graphic?	Google Earth Layer?
Geologic Sample Localities (radiometric age date)	GSL	No	No
Eolian and Fluvial Lines (dune orientation and point bar accretion)	LIN	Yes	Yes
Geologic Contacts	GLGA	Yes	Yes
Geologic Units	GLG	Yes	Yes

Geologic Map Graphic

The Geologic Map Graphic (in pocket) displays the GRI digital geologic data draped over shaded relief imagery of the park and surrounding area. Not all GIS feature classes may be visible on the overview (table 1). Digital elevation data and geographic information, which are part of the overview graphic, 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. Connections between geologic units and park stories are also summarized.

Use Constraints

Graphic and written information provided in this section is not a substitute for site-specific investigations. 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 (1:125,000) and U.S. National Map Accuracy Standards, geologic features represented in the geologic map data are horizontally within 64 m (208 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 Geosciences 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.

abyssal plain. A flat region of the deep ocean floor, usually at the base of the continental rise.

accretion. The gradual addition of new land to old by the deposition of sediment or emplacement of landmasses onto the edge of a continent at a convergent margin.

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."

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.

anhydrite. A mineral consisting of anhydrous calcium sulfate, which is gypsum without the water in its crystal structure. Readily alters to gypsum.

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

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."

arroyo. A small, deep, flat-floored channel or gully of an ephemeral or intermittent stream in the arid and semiarid regions of the southwestern United States.

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

barchan dune. A crescent-shaped dune with arms or horns of the crescent pointing downwind. The crescent or barchan type is most characteristic of inland desert regions.

barrier island. A long, low, narrow island formed by a ridge of sand that parallels the coast.

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.

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.

berm. A low, impermanent, nearly horizontal or landward-sloping bench, shelf, or ledge on the backshore of a beach.

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

bioturbation. The reworking of sediment by organisms.

braided stream. A sediment-clogged stream that forms multiple channels which divide and rejoin.

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.

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

channel bar. An elongate deposit of sand and gravel located in the course of a stream. Common in braided streams.

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).

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

continental crust. Crustal rocks rich in silica and alumina that underlie the continents; ranging in thickness from 35 km (22 mi) to 60 km (37 mi) under mountain ranges.

continental rifting. Process by which a region of crust undergoes extension (pulling apart), resulting in the formation of many related normal faults, and often associated with volcanic activity.

continental rise. Gently sloping region from the foot of the continental slope to the deep ocean abyssal plain; it generally has smooth topography but may have submarine canyons.

continental shelf. The shallowly submerged part of a continental margin extending from the shoreline to the continental slope with water depths less than 200 m (660 ft).

continental shield. A continental block of Earth's crust that has remained relatively stable over a long period of time and has undergone minor warping compared to the intense deformation of bordering crust.

continental slope. The relatively steep slope from the outer edge of the continental shelf down to the more gently sloping ocean depths of the continental rise or abyssal plain.

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

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").

deformation. A general term for the processes 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.

depocenter. An area or site of maximum deposition; the thickest part of any specified stratigraphic unit in a depositional basin.

desert pavement. A natural residual concentration of wind-polished, closely packed pebbles, boulders, and other rock fragments, mantling a desert surface where wind action and sheetwash have removed all smaller particles. The pavement usually protecting the underlying finer-grained material from further erosion. Also called "desert armor."

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

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

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

dune. A low mound or ridge of sediment, usually sand, deposited by wind. Common dune types include "barchan," "longitudinal," "parabolic," and "transverse" (see respective listings).

eolian. Describes materials formed, eroded, or deposited by or related to the action of the wind. Also spelled "Aeolian."

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.

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.

evaporite. A sedimentary rock composed primarily of minerals produced from a saline solution as a result of extensive or total evaporation of the solvent (usually water).

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

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.

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.

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

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

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

gypsum. The most common sulfate mineral (calcium sulfate). Frequently associated with halite and anhydrite in evaporites.

highstand. The interval of time during one or more cycles of relative change of sea level when sea level is above the shelf edge in a given local area.

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.

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.

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

lag gravel. An accumulation of coarse material remaining on a surface after the finer material has been blown away by winds.

levee. Raised ridge lining the banks of a stream. May be natural or artificial.

limb. Either side of a structural fold.

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.

loess. Windblown silt-sized sediment, generally of glacial origin.

longitudinal dune. Dune elongated parallel to the direction of wind flow.

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

lowstand. The interval of time during one or more cycles of relative change of sea level when sea level is below the shelf edge.

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

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.

meander. Sinuous lateral curve or bend in a stream channel. An entrenched meander is incised, or carved downward into the surface of the valley in which a meander originally formed. The meander preserves its original pattern with little modification.

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

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

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.

oil field. A geographic region rich in petroleum resources and containing one or more wells that produce, or have produced, oil and/or gas.

orogeny. A mountain-building event.

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

overbank deposit. Alluvium deposited outside a stream channel during flooding.

oxbow. A closely looping stream meander resembling the U-shaped frame embracing an ox's neck; having an extreme curvature such that only a neck of land is left between two parts of the stream.

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.

paleosol. A ancient soil layer preserved in the geologic record.

Pangaea. A theoretical, single supercontinent that existed during the Permian and Triassic periods.

parabolic dune. Crescent-shaped dune with horns or arms that point upwind.

parent material. The unconsolidated organic and mineral material in which soil forms.

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 (compare to "active margin").

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

point bar. A low ridge of sand and gravel deposited in a stream channel on the inside of a meander where flow velocity slows.

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

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

pull-apart basin. A topographic depression created by an extensional bend or extensional overstep along a strike-slip fault.

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.

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

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.

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

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

runup. The advance of water up the foreshore of a beach or structure, following the breaking of the wave.

saltation. A mode of sediment movement, driven by wind or water, whereby materials move through a series of intermittent "leaps" or "jumps."

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).

sand sheet. A large irregularly shaped plain of eolian sand, lacking the discernible slip faces that are common on dunes.

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

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.

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).

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]).

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.

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

strand plain. A shore built seaward by waves and currents and continuous for some distance along the coast.

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.

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.

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

subaerial. Describes conditions and processes that exist or operate in the open air on or immediately adjacent to the land surface.

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

supertidal. Describes features or processes at elevations higher than normal tidal range on a give shoreface.

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

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

terrane. A large region or group of rocks with similar geology, age, or structural style.

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

terrigenous. Derived from the land or a continent.

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

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

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

transverse dune. Dune elongated perpendicular to the prevailing wind direction. The leeward slope stands at or near the angle of repose of sand whereas the windward slope is comparatively gentle.

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

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.

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

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.

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

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.

Literature Cited

This section lists references cited in this report. Contact the Geologic Resources Division for assistance in obtaining these documents.

Baker, E. T., Jr. 1995. Stratigraphic Nomenclature and Geologic Sections of the Gulf Coastal Plain of Texas. Open-File Report 94-461. U.S. Geological Survey, Austin, Texas, USA. http://pubs.usgs.gov/of/1994/0461/report.pdf (accessed 2 October 2012).

Banfield, L. A.and J. B. Anderson. 2004. Late Quaternary evolution of the Rio Grande Delta; complex response to eustasy and climate change. Pages 289–306 *in* J. B. Anderson and R. H. Fillon, editors. Special Publication 79. Society for Sedimentary Geology, Tulsa, Oklahoma, USA.

Brown, L. F., J. L. Brewton, T. J. Evans, J. H. McGowen, W. A. White, C. G. Groat, and W. L. Fisher, with cartography by Hartmann, B., D. F. Scranton, and J. W. Macon. 1980. Environmental Geology Sheet, Environmental Geological Atlas of the Texas Coastal Zone-Brownsville-Harlingen Area (scale 1:125,000). Bureau of Economic Geology, The University of Texas at Austin, Austin, Texas, USA.

Bureau of Economic Geology. 1992. Geology of Texas (scale 1:500,000). Four map sheets. Bureau of Economic Geology, University of Texas at Austin, Austin, Texas, USA.

Bush, D. M., and R. Young. 2009. Coastal features and processes. Pages 47–67 *in* R. Young and L. Norby, editors. Geological Monitoring. Geological Society of America, Boulder, Colorado, USA. http://nature.nps.gov/geology/monitoring/coastal.cfm (accessed 27 September 2012).

Caran, S. C., S. D. McCulloch, and J. Jackson, with contributions by B. M. Albert, B. M. Winsborough, and Isotope Geochemistry Laboratory of the Illinois State Geological Survey. 2005. Report on a geoarchaeological investigation at the Palo Alto National Historic Site (41CF92), Cameron County, Texas. Order P73500-40016, Report 1, January 2005. McCulloch Archaeological Services LLC, San Marcos, Texas, USA.

Carney, S. A. 2006. Guns along the Rio Grande: Palo Alto and Resaca de la Palma. Brochure CMH Pub 73-2. U.S. Army Center of Military History. http://www.history.army.mil/brochures/Resaca%20de%20la%20Palma/Palo%20Alto.htm (accessed 15 March 2013).

Ewing, T. E. 1999. Regional geologic setting of South Texas and the Santo Thomas coal deposits. Open-File Report 99-301. U.S. Geological Survey, San Antonio, Texas, USA. http://pubs.usgs.gov/pdf/of/ofr99301/chapter1.pdf (accessed 4 October 2012).

Galloway, W. E., T. L. Whiteaker, and P. Ganey-Curry. 2011. History of Cenozoic North American drainage basin evolution, sediment yield, and accumulation in the Gulf of Mexico Basin. Geosphere 7(4):938–973.

Gifford, G. H., Á. Geirsdóttir, Y. Zhong, D. J. Larsen, B. L. Otto-Bliesner, M. M. Holland, D. A. Bailey, K. A. Refsnider, S. J. Lehman, J. R. Southon, C. Anderson, H. Björnsson, and T. Thordarson. 2012. Abrupt onset of the Little Ice Age triggered by volcanism and sustained by sea-ice/ocean feedbacks. Geophysical Research Letters 39(L02708).

Haecker, C. M., and J. G. Mauck. 1997. On the prairie of Palo Alto: Historical archaeology of the U.S.-Mexican War battlefield. Texas A&M University Press, College Station, Texas, USA.

Hay, O. P. 1924. The Pleistocene of the middle region of North America and its vertebrated animals. Publication 322A. Carnegie Institution of Washington, Washington, DC, USA.

Hentz, T. F. 2001. Geology. *In* The handbook of Texas. University of Texas at Austin. http://www.tshaonline.org/handbook/online/articles/swgqz (accessed 5 October 2012).

Karl, T. R., J. M. Melillo, and T. C. Peterson (editors). 2009. Global Climate Change Impacts in the United States. Cambridge University Press, New York City, New York, USA. http://globalchange.gov/what-we-do/assessment/previous-assessments/global-climate-change-impacts-in-the-us-2009 (accessed 9 September 2013).

KellerLynn, K. 2008. Geologic Resource Evaluation Scoping Summary, Palo Alto Battlefield National Historical Park, Texas. Geologic Resources Division, National Park Service, Lakewood, Colorado, USA. http://www.nature.nps.gov/geology/inventory/publications/s_summaries/PAAL_GRE_%20scoping%20summary_2008-0922.pdf (accessed 8 October 2012).

KellerLynn, K. 2010. Padre Island National Seashore: geologic resources inventory report. Natural Resource Report NPS/NRPC/GRD/NRR—2010/246. National Park Service, Ft. Collins, Colorado. http://www.nature.nps.gov/geology/inventory/gre_publications.cfm (accessed 18 December 2012).

Kenworthy, J. P., V. L. Santucci, and C. C. Visaggi. 2007. Paleontological resource inventory and monitoring, Gulf Coast Network. TIC# D-750. Geologic Resources Division, National Park Service, Lakewood, Colorado, USA.

Lancaster, N. 2009. Aeolian features and processes. Pages 1–25 *in* R. Young and L. Norby, editors. Geological Monitoring. Geological Society of America, Boulder, Colorado, USA. http://nature.nps.gov/geology/monitoring/aeolian.cfm (accessed 27 September 2012).

Loehman, R. and G. Anderson. 2010. Understanding the science of climate change: Talking points – impacts to the Gulf Coast. Natural Resource Report NPS/NRPC/NRR—2010/210. National Park Service, Fort Collins, Colorado, USA. http://www.nature.nps.gov/climatechange/docs/GulfCoastTP.pdf (accessed 26 December 2012).

Lord, M. L., D. Germanoski, and N. E. Allmendinger. 2009. Fluvial geomorphology: Monitoring stream systems in response to a changing environment. Pages 69–103 *in* R. Young and L. Norby, editors. Geological Monitoring. Geological Society of America, Boulder, Colorado, USA. http://nature.nps.gov/geology/monitoring/fluvial.cfm (accessed 27 September 2012).

Mangum, A. W. and O. Lee, Jr. 1907. Soil Survey of the Brownsville Area, Texas. Field Operations of the Bureau of Soils, 1907:705–732. U.S. Department of Agriculture, Washington, DC, USA. http://soils.usda.gov/survey/online_surveys/texas/brownsvilleTX1907/brownsvilleTX1907.pdf (accessed 26 December 2012).

Metz, L. C. 2012. Rio Grande. Handbook of Texas Online. Texas State Historical Association. http://www.tshaonline.org/handbook/online/articles/rnr05 (accessed 9 October 2012).

Moring, J. B. and R. Setser. 2000. Historical Changes in Streamflows, Channel Morphology, and Riparian Vegetation of the Rio Grande Downstream of Brownsville, Texas. Fact Sheet 074-00. U.S. Geological Survey, Reston, Virginia, USA.

National Park Service. 2006. Soil Survey Geographic (SSURGO) for Palo Alto Battlefield National Historic Site, Texas. National Park Service Inventory & Monitoring Program, Fort Collins, Colorado, USA. https://irma.nps.gov/App/Reference/Profile/1048950 (accessed 9 September 2013).

National Park Service. 2013. Resaca de la Palma. http://www.nps.gov/paal/historyculture/resacadelapalma.htm (accessed 14 March 2013).

Neck, R. W. 1985. Paleoecological implications of a Holocene fossil assemblage, Lower Rio Grande, Cameron County, Texas. Pearce-Sellards Series 41. Texas Memorial Museum, Austin, Texas, USA.

PBS&J. 2004. Archaeological Investigations at the Resaca de la Palma Battlefield National Historic Landmark, Site 41CF3, City of Brownsville, Cameron County, Texas. Document No. 040221, prepared for City of Brownsville and U.S. National Park Service, Brownsville, Texas, USA.

Pierson, D. G. 2005. Geology of North Central Texas. *In* A Natural History of North Central Texas. http://www.nhnct.org/geology/ (accessed 5 October 2012).

Ramsey, E. III, G. Nelson, and Y. Y. Yan. 2004. Palo Alto Battlefield National Historical Park Landscape Classification and Historic Analysis. Biological Science Report Number not assigned. Biological Resources Division, U.S. Geological Survey, Reston, Virginia, USA.

Roth, D. 2009. Texas hurricane history. National Weather Service, Camp Springs, Maryland, USA. http://www.hpc.ncep.noaa.gov/research/txhur.pdf (accessed 12 October 2012).

Sanchez, J. P. 2012. Palo Alto, Battle of. Handbook of Texas Online. Texas State Historical Association. http://www.tshaonline.org/handbook/online/articles?qep01 (accessed 4 October 2012).

Santucci, V. L., J. P. Kenworthy, and A. L. Mims. 2009. Monitoring in situ paleontological resources. Pages 189–204 *in* R. Young and L. Norby, editors. Geological Monitoring. Geological Society of America, Boulder, Colorado, USA. http://nature.nps.gov/geology/monitoring/paleo.cfm (accessed 27 September 2012).

Saunders, S., T. Easley, J. A. Logan, and T. Spencer. 2006. Losing ground: Western national parks endangered by climate disruption. The Rocky Mountain Climate Organization, Louisville, Colorado; Natural Resources Defense Council, New York, New York, USA. http://www.nrdc.org/land/parks/gw/gw.pdf. (accessed 28 September 2012).

Seramur, K. C. and E. E. Ficker. 2012. Interpretation of the Paleoenvironmental History of Resaca de Palo Alto at the Palo Alto Battlefield National Historic Park, Brownsville, TX. Contract Number: P7580100152. Unpublished.

Stanley, J.-D. 1999. Deltas in arid settings; water, dams and lessons learned in the Nile and Rio Grande systems. Geological Society of America Abstracts with Programs 31(7):480.

Stanley, J.-D. and A. G. Warne. 2001. Consequences of water diversion in arid coastal systems within the Rio Grande, Colorado, and other world deltas. Geological Society of America Abstracts with Programs 33(6):41–42.

Thomas, W. A., and G. R. Keller. 1999. Cambrian rifting and subsequent structures in eastern Texas. American Association of Petroleum Geologists Annual Meeting Expanded Abstracts A138.

Weaver, K. S. 1999. Pre-European Texas: Vegetation change on Palo Alto Battlefield National Historical Park. M.S. Thesis. Texas A&M University at Corpus Christi, Corpus Christi, Texas, USA.

Weight, R. W. R., J. B. Anderson, and R. Fernandez. 2011. Rapid mud accumulation on the central Texas shelf linked to climate change and sea-level rise. Journal of Sedimentary Research 81(10):743–764.

Wermund, E. G. 1996. Physiographic map of Texas. State Map 5. Texas Bureau of Economic Geology, Austin, Texas, USA. http://www.beg.utexas.edu/UTopia/images/pagesizemaps/physiography.pdf (accessed 8 October 2012).

Wermund, E. G. and T. A. Tremblay. 1998. Surface geology of the Rio Grande delta, United States-Mexico, a GIS layer. AAPG Bulletin 82(9):1795.

Additional References

This section lists additional references, resources, and websites that may be of use to resource managers. Web addresses are current as of September 2013.

Geology of National Park Service Areas

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

NPS Geologic Resources Inventory: http://www.nature.nps.gov/geology/inventory/gre_publications.cfm

Harris, A. G., E. Tuttle, and S. D. Tuttle. 2003. Geology of national parks. Sixth Edition. Kendall/Hunt Publishing Co., Dubuque, Iowa, USA.

Kiver, E. P. and D. V. Harris. 1999. Geology of U.S. parklands. John Wiley and Sons, Inc., New York, New York, USA.

Lillie, R. J. 2005. Parks and plates: The geology of our national parks, monuments, and seashores. W.W. Norton and Co., New York, New York, USA.

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

NPS Views Program (Geology-themed modules are available for Geologic Time, Paleontology, Glaciers, Caves and Karst, Coastal Geology, Volcanoes, and a wide variety of geologic parks): http://www.nature.nps.gov/views/layouts/Main.html#/Views/.

NPS Resource Management Guidance and Documents

1998 National Parks Omnibus Management Act: http://www.gpo.gov/fdsys/pkg/PLAW-105publ391/pdf/PLAW-105publ391.pdf

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. 2009. Geological monitoring. Geological Society of America, Boulder, Colorado, USA. http://nature.nps.gov/geology/monitoring/index.cfm

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

Geological Surveys and Societies

Bureau of Economic Geology, University of Texas at Austin: http://www.beg.utexas.edu/

U.S. Geological Survey Texas Water Science Center: http://tx.usgs.gov/

US Geological Survey: http://www.usgs.gov/

Geological Society of America: http://www.geosociety.org/

American Geosciences Institute: http://www.agiweb.org/

Association of American State Geologists: http://www.stategeologists.org/

US Geological Survey Reference Tools

National Geologic Map Database (NGMDB): http://ngmdb.usgs.gov/

Geologic Names Lexicon (GEOLEX; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/geolex_home.html

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

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

Publications Warehouse (USGS publications, many available online): http://pubs.er.usgs.gov

Tapestry of Time and Terrain (descriptions of physiographic provinces): http://tapestry.usgs.gov/Default.html

Appendix: Scoping Meeting Participants

The following people attended the GRI scoping meeting for Palo Alto Battlefield National Historical Park, held on 23 April 2008. Discussions during this meeting supplied a foundation for this GRI report. The scoping summary document is available on the GRI publications website (http://www.nature.nps.gov/geology/inventory/gre_publications.cfm).

Name	Affiliation	Position
Jeff Bracewell	Gulf Coast Network	GIS Specialist
Eddie Collins	Texas Bureau of Economic Geology	Geologist
Andrea Croskrey	Geologic Resources Division	Geologist/GIS Specialist
Rolando Garza	Palo Alto Battlefield National Historical Park	Resource Manager
Bruce Heise	Geologic Resources Division	Geologist/GRE Program Coordinator
Katie KellerLynn	Colorado State University	Research Associate
Ric Page	U.S. Geological Survey	Geologist
Martha Segura	Gulf Coast Network	Network Coordinator

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

NPS 469/122361, September 2013

National Park Service
US Department of the Interior

Natural Resource Stewardship and Science
1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525

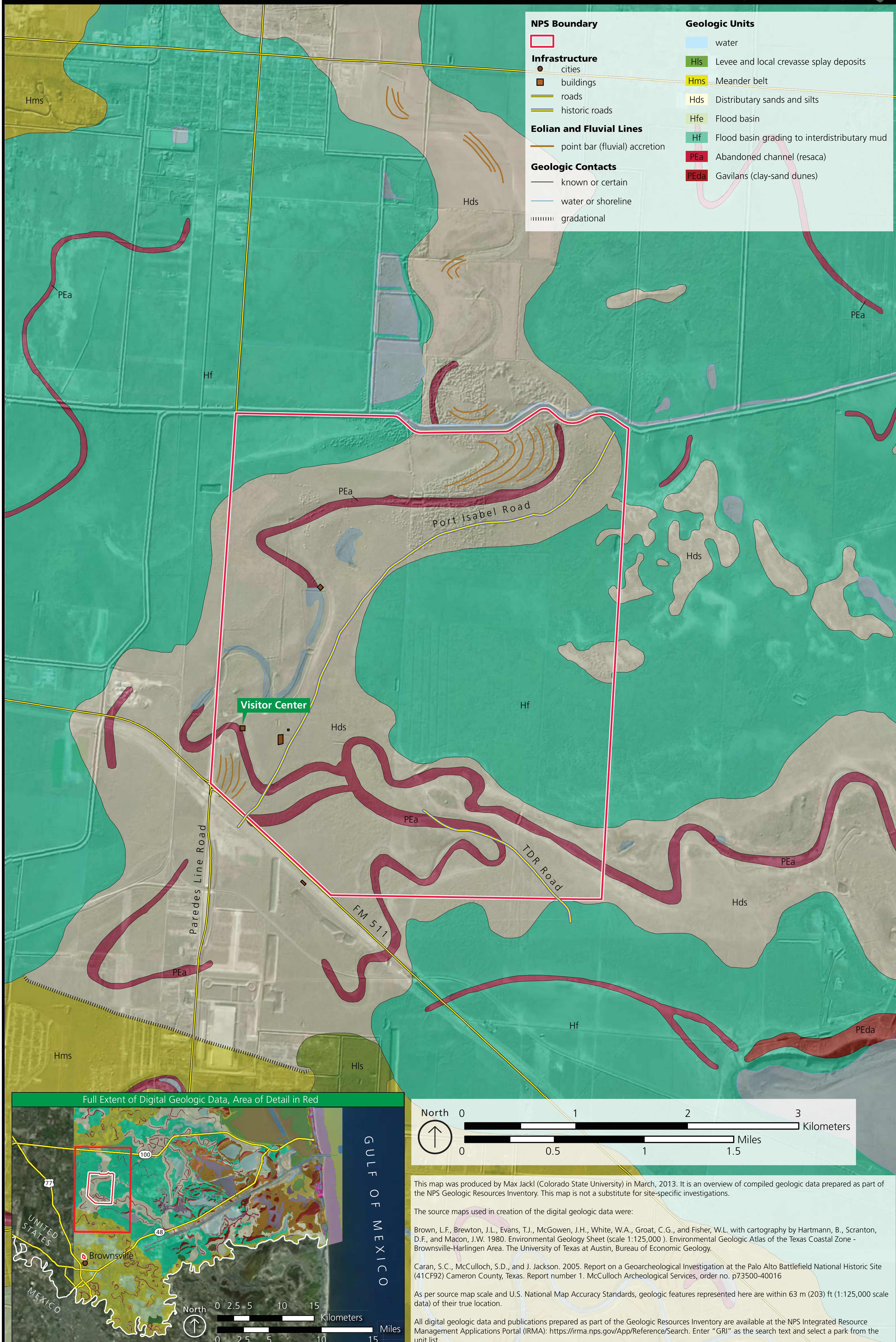
www.nature.nps.gov

Geologic Map of Palo Alto Battlefield NHP

Texas

National Park Service
U.S. Department of the Interior

Geologic Resources Inventory



This map was produced by Max Jackl (Colorado State University) in March, 2013. It is an overview of compiled geologic data prepared as part of the NPS Geologic Resources Inventory. This map is not a substitute for site-specific investigations.

The source maps used in creation of the digital geologic data were:

Brown, L.F., Brewton, J.L., Evans, T.J., McGowen, J.H., White, W.A., Groat, C.G., and Fisher, W.L. with cartography by Hartmann, B., Scranton, D.F., and Macon, J.W. 1980. Environmental Geology Sheet (scale 1:125,000). Environmental Geologic Atlas of the Texas Coastal Zone - Brownsville-Harlingen Area. The University of Texas at Austin, Bureau of Economic Geology.

Caran, S.C., McCulloch, S.D., and J. Jackson. 2005. Report on a Geoarcheological Investigation at the Palo Alto Battlefield National Historic Site (41CF92) Cameron County, Texas. Report number 1. McCulloch Archeological Services, order no. p73500-40016

As per source map scale and U.S. National Map Accuracy Standards, geologic features represented here are within 63 m (203) ft (1:125,000 scale data) of their true location.

All digital geologic data and publications prepared as part of the Geologic Resources Inventory are available at the NPS Integrated Resource Management Applications Portal (IRMA): https://irma.nps.gov/App/Reference/Search. Enter "GRI" as the search text and select a park from the unit list.

Map Unit Properties Table: Palo Alto Battlefield National Historical Park

Colored rows indicate units mapped within Palo Alto Battlefield National Historical Park.

<table>
<tr><th>Age</th><th colspan="2">Map Unit
(Symbol)</th><th>Geologic Description</th><th>Geologic Issues</th><th>Geologic Features and Processes</th><th>Geologic History and Unit Location</th></tr>
<tr><td rowspan="4">Modern</td><td rowspan="4">Artificial Units</td><td>Made Land
(Hml)</td><td>Unit consists of anthropogenic land at boat basins and dikes.</td><td rowspan="4">Sea level rise and hurricanes—Anthropogenic units were created primarily via dredging to facilitate boat navigation and access along the coast. Tidal currents and wave action rework spoil deposits. Units are vulnerable to damage or inundation from sea level rise and hurricanes.

Erosion—Dredged spoil is commonly piled along the margin of the cut channel. This creates local artificial relief which then exposes the spoil to erosion processes. The local relief also acts as a tidal dam in places. The spoil is naturally reworked and redistributed by rainfall sheetwash, gullying and subsequent alluvial fan development, tidal currents, and waves. This redistribution increases the areas of wind-tidal flats and lagoon bottom that are covered by spoil.

Disturbed lands—Dredging channels interrupts groundwater flow.

Oil and gas exploration and development—Spoil deposits occur along small channels dredged into shallow water and wind-tidal flats (Hw, Hwa) to provide access to oil and gas well drill sites.</td><td rowspan="4">Geologic influences on ecosystems—the artificial units represent the modern developments occurring along the Texas gulf coast in recent decades.</td><td rowspan="4">Hml is limited in area to the boat basins at Port Mansfield and Port Isabel, extending almost 10 km (6 mi) of the western side of the southernmost stretch of South Padre Island. A dike extends across Bahia Grande. Spoil units Hsr, Hsae, and Hsaq were originally derived from excavation and maintenance of the Intracoastal Waterway, extending along the entire length of Laguna Madre and interconnected ship channels (Port Mansfield, Arroyo Colorado Cutoff, Brownsville Ship, and Port Isabel Ship channels).</td></tr>
<tr><td>Reworked Spoil, Subaerial
(Hsr)</td><td>Spoil is reworked from old dredge deposits. Dredging of the Intracoastal Waterway, ship channels, small channels, and access channels yields churned deposits of sand, muck, and organics.</td></tr>
<tr><td>Spoil, Subaerial
(Hsae)</td><td>Spoil from dredging that is not covered with water.</td></tr>
<tr><td>Spoil, Subaqueous
(Hsaq)</td><td>Spoil that occurs below water on the bay bottom.</td></tr>
</table>

Colored rows indicate units mapped within Palo Alto Battlefield National Historical Park.

Age		Map Unit (Symbol)	Geologic Description	Geologic Issues	Geologic Features and Processes	Geologic History and Unit Location
QUATERNARY (Holocene)	Bay-Estuary-Lagoon System	Berm, Vegetated (Hblv)	Berms form as bay or lagoon-margin sand or shell debris accretes along the shores. This unit is relatively stable with abundant vegetation.	**Sea level rise and hurricanes**—Wind-tidal flats can flood rapidly. **Hg** areas are expanding with relative sea-level rise in north Laguna Madre. **Hg** is spreading into **Hbls** with rising seas. Water table fluctuations strongly impact areas of **Htz**. When water is high, salt-tolerant grass species stabilize the area. When water is low, eolian processes of deflation dominate. **Erosion**—berms that are no longer actively accreting are subject to erosion and incorporation into adjacent wind-tidal flats or subaqueous lagoon-margin sand. **Disturbed lands**—Construction of islands and shoals has reduced the fetch of winds blowing across Laguna Madre and thus the wave energy that can build up natural berms. As anthropogenic construction and sea-level rise increase water depth, salinity, and/or turbidity, flora and fauna compositions of **Hg** may change rapidly.	**Fluvial Features and Processes**—**Hsp** is a surface water unit. Some surface water features formed in association with sand and loess sheet deflation and are flanked on their leeward side by clay-sand dunes (**PEda** and **PEdi**).Others developed from relict drainage systems (pirated or diverted by the Arroyo Colorado), or from the damming effect of levees deposited along distributary channels. **Geologic influences on ecosystems**—**Hsp** can support fairly dense vegetation growth. In the tidal flats areas around Bahia Grande, **Hsp** is barren flats with areas of spare to dense vegetation including marshes. Small areas of saltwater marsh can occur behind and along the bay and lagoon-margin berms of **Hble** and **Hblv**. **Hg** composes lagoon-margin and lagoon-center environments of less than 1 m (4 ft) depth. Five species of marine grass thrive in **Hg**: *Halodule* (*Diplanthera*) *wrightii* (shoalgrass), *Cymodocea manatorum* (manatee-grass), *Ruppia maritima* (widgeongrass), *Thalassia testudinum* (turtlegrass), and *Halophila engelmannii* (clovergrass). Grass distribution is changing with salinity fluctuations, turbidity, and water depth. Algae (including leafy calcareous *Acetabularia)* thrive in **Hg**, which also provides food and protection for a variety of invertebrates and fish to spawn. **Hg** is locally replacing areas of **Hbls**. **Hg** provides habitat for modern mollusks, such as the pelecypods (clams) *Cumingia*, *Tellina*, *Tagelus*, and *Mysella* and the gastropods (snails) *Bittium*, *Caecum*, and *Mitrella*. Burrowing organisms such as clams (*Laevicardium, Chione*, *Anadara*, *Mulinia, Tellina, Tagelus Ensis*, and *Anomalocardia* [in hypersaline areas]) bioturbate **Hblm**. South Bay contains the only significant occurrence of the oyster *Crassostrea* south of Corpus Christi Bay; these particular oysters may be a new physiological race adapted to higher-than-normal salinities (in excess of 40%). **Hblm** requires areas of low wave and current energy to accumulate and supports sparse marine grass. Many wet areas of **Htz** have become vegetated and are currently stabilized with salt-tolerant grasses such as *sacahuista*. When drought conditions return, eolian processes resume active deflation of the flats. Four environments compose the spectrum of wind-tidal flats: 1) firm sand and mud flats which extend from frequently flooded low elevations to higher elevations; 2) sand and mud flats that are alternately emergent-submergent, contributing to the development of extensive algal mats; 3) firm gypsiferous mud and sand with algal-bound mud; and 4) soft mud and sand with extensive algal mats that are frequently wet because of locally depressed relief. **Eolian features and processes**—a berm at Bahia Grande has accreted in part through eolian processes, active when wind-tidal flats are dry thereby providing a source of sediment to the winds. **Htz**, when not inundated by wind tides, is the site of wind deflation, winnowing of airborne sediment, windward accretion of small eolian clay dunes, and large landward-trending blowout depressions intermittently inundated by wind tides. Wind-driven tides (or drops in barometric pressure) inundate **Hw** and **Hwa**. Winds from the east and southeast drive water off the flats. Prolonged subaerial exposure of wind-tidal flats causes severe desiccation that fragments the surface sediment into sand- and silt-sized particles, which are blown to the northwest where these particles accumulate to form clay-sand dunes.	Mud-filled coastal lakes and ponds occur northwest of El Jardin and in the area of Bahia Grande. **Hg** covers almost 65% of the subaqueous area in the bay-estuary-lagoon system. **Hg** extends the length of Laguna Madre. **Hbls** is derived principally from eroded Modern-Holocene deposits along the mainland shore. **Hw** and **Hwa** occur along lagoon margins adjacent to the mainland and South Padre Island. They vary in width from 0.2 to 11 km (0.1 to 7 mi) along the mainland and from 0.4 to 6 km (0.2 to 4 mi) on South Padre Island for a length of 63 km (39 mi). **Htz** is related to **Hw** and **Hwa** of the Texas coastal region. It marks the area of transition between the wind-tidal flats (remnants of deflated sand sheets, clay dunes, and blowout depressions) and the South Texas eolian system. Wind-tidal flats containing extensive algal mats (blue-green algae) are present throughout the central part of the flats (middle flats) associated with South Padre Island and on the mainland flats between Fourmile Slough and Stover Cove among other areas.
		Berm, Occasionally Emergent (Hble)	Typically bare sand or mud and shell debris from bay or lagoon marginal areas. Locally **Hble** is covered by sparse marine grass. Berms are narrow, elongate features only 1 m (2 to 3 ft) above mean sea level.			
		Grass Flat (Hg)	Grass flats are saline to hypersaline subaqueous areas of muddy sand with abundant shell debris.			
		Bay and Lagoon Sand (Hbls)	Sparse marine grass grows in the muddy bay and lagoon sand in water depths between 0.3 and 1 m (1 and 3 ft). Tides driven by wind cause these areas to be subaerially exposed occasionally. Southeasterly and northerly winds move **Hbls** landward into shallow subaqueous bars and berms. Accretion only occurs during high-energy wave events. Longshore transport continues to redistribute the winnowed sediment of **Hbls**.			
		Bay and Lagood Mud (Hblm)	**Hblm** consists of mottled bay and lagoon mud mixed with abundant shell debris. This unit occurs in water depths of less than 1 m (3 ft) as wide, parallel bands, and narrow sinuous channels.			
		Wind-tidal Flat, Rarely Flooded (Hw)	**Hw** is firm sand and mud that forms part of a wind-tidal flat. Much like **Hwa**, **Hw** is broad, flat, barren, and virtually featureless. Different from the other two units, **Hw** is rarely inundated. It is less than 1 m (3 ft) above mean sea level. Wind-tidal flats form from sediments derived from the shoreface, beach, and dune areas transported to the flats by hurricane storm surge and prevailing southeast winds.			
		Wind-tidal Flat, Algal Mats, Emergent-submergent (Hwa)	**Hwa** consists of sand and mud with extensive algal mats that are frequently inundated with wind-driven tides. Surfaces of the flats are always near the water table; the upper few inches of the wind-tidal flat deposits are oxidized light brown (above the water table), whereas the sediment beneath the water table is light green. Secondary gypsum deposits are common for these units.			
		Transitional Zone (Htz)	**Htz** marks the transition from wind-tidal flat to eolian sand sheet with wind deflation, concentrated clay-sand dunes, and blowing sand.			

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Age		Map Unit (Symbol)	Geologic Description	Geologic Issues	Geologic Features and Processes	Geologic History and Unit Location
QUATERNARY (Holocene)	Barrier-Standplain and Offshore System (continues on next sheet)	Shelf Mud (Hs)	**Hs** consists of mud and sand, shell, and mottles (patchy/blotch texture caused by bioturbation). These components make up the area just seaward of the fore-beach (see **Hsb**). Deposits are thin and patchily distributed throughout the map area. **Hs** is part of the offshore system (shoreface and inner continental shelf). The transition between the inner continental shelf and shoreface occurs at a depth of 13 m (42 ft) where there is a decrease in slope.	**Sea level rise and hurricanes**—Many years of sand deposition blowing from the beach may be necessary to restore the former dune position after a storm. The fore-island sand ridge protects the barrier island from the full impact of storm surge. As relative sea level rises, barrier island systems will continue to migrate landward. The configuration and stratified layers of fore-island dunes (**Hfi**) may record long-term climatic changes. **Erosion**—beaches (**Hb**) are eroding on South Padre Island. This is due to: (1) a sand deficit, (2) storm conditions on a thin sand body, (3) strong longshore drift northward, (4) dominant winds and storms move sand into Laguna Madre and out of the buffer zone, and (5) Rio Grande deltaic mud continues to compact causing a relative rise in sea level. Current rates of erosion are about 6 m (21 ft) per year based on a fixed well location that was 100 m (330 ft) from the beach in 1956, but was in the swash zone by 1972. The beach is repeatedly eroded by storm-surge floods in areas where the dunes (**Hfi**) are absent. **Hfi** may be eroded many meters during storms or hurricanes. **Disturbed lands**—In areas where there are fore-island dunes (**Hb** and **Hfi**), no sharp line exists between the beach and other barrier island depositional environments. Activities such as 19th and early 20th century ranching on Padre Island reduced vegetation cover, which in turn led to the destruction of fore-island dunes (**Hfi**) and promoted an increase in large back-island dune fields. **Hsf** currently occupies areas of the island previously occupied by **Hfi**. Jetty systems largely prevent the accumulation of **Hi** in active inlets. Two jettied inlets—Port Mansfield Channel to the north and Brazos Santiago Pass to the south—cut through South Padre Island. The jetties associated with these artificial inlets reroute sand that would otherwise be transported into south Laguna Madre through the inlets.	**Fluvial features and processes**—Channels of unit **Htc** share features similar to traditional fluvial systems including meanders and scour features. **Geologic influences on ecosystems**—In areas where vegetation is disturbed, either through drought or anthropogenic causes, fore-island dunes (**Hfi**) experience erosion. In areas of sufficient precipitation to promote vegetation, areas of **Hsf** have developed into small fore-island dunes (**Hfi**). Without the tidal exchange facilitated by **Htc**, salinity and circulation patterns would be substantially different. The flora and fauna (mainly marine grasses and oysters) would also change resulting in a substantial reduction in biologic productivity. Restricted circulation leads to the development of hypersaline basins. **Eolian features and processes**—fore-island dunes are a major component of **Hb**. The vegetation line coincides with the gulfward side of the fore-island dune ridge. Eolian crossbeds within **Hfi** records a complex history of dune deflation and deposition. **Hsf** includes low coppice and wind-shadow sand dunes, and broad sandflats. Between storm events, eolian processes erode and redistribute sands of **Hwf** and **Hwd**. This nourishes back-island dune fields, wind-tidal flats (**Hw**, **Hwa**), and vegetated transverse dunes. **Hb** contains lag, or wind-deflation deposits composing shell pavements left behind when the wind removes finer particles. **Paleontological resources**—**Hs** contains abundant shelly remains. **Hsb** is burrowed. **Hb** contains large clams *Eontia*, *Mercenaria*, and *Echinochama*. There may be a relationship between high, well-developed, fore-island dunes and abundant shell content on adjacent beaches. **Hb** contains abundant shell pavements. Oysters are the primary fauna in lagoonal basins.	Accumulation of modern sediment (**Hs**) is rather slow offshore from South Padre Island. **Hsb** accumulated atop Pleistocene and Holocene Rio Grande fluvial-deltaic deposits. The Gulf shoreline of South Padre Island is rapidly eroding; a continuous fore-island dune ridge (**Hfi**) will likely never develop again. There are 12–16 active areas of **Hsf** on South Padre Island. The broadest areas of the island, up to 7.2 km (4.5 mi) are associated with **Hsf**. At least 12 distinct washover channels are recognized locally.
		Shoreface (Hsb)	**Hsb** consists of sand and muddy sand deposited in the shoreface zone. **Hsb** forms in a high energy environment along the shore. Breaking waves occur along the upper shoreface, less than 5 m (15 ft) deep. Storm waves mold **Hsb** into a series of breaker bars en echelon or parallel to the shoreline. Prevailing southeast winds and northeast winds accompanying polar fronts create a zone in the upper shoreface (sea level down to 4 to 5 m [12 to 15 ft]) where waves touch bottom and break. This forms several lines of breakers in water above the upper shoreface.			
		Beach (Hb)	**Hb** contains sorted sand and shell fragments. Bedding of beach deposits generally dips towards the Gulf of Mexico at angles of 5°—accentuated by dense, dark heavy minerals concentrated by swash and backwash. **Hb** occurs between low tide and the first inland line of vegetation. **Hb** consists of a forebeach (the seaward-sloping smooth part of the beach where the waves wash up) and a back-beach (separated from the forebeach by a berm). The backbeach slopes gently seaward or may slope the opposite way forming a backbeach trough or runnel.			
		Fore-island (Hfi)	**Hfi** is a discontinuous sandy dune ridge. The sand is well sorted and arranged in steeply dipping eolian crossbeds. The highest island elevations occur within this unit ranging from 2 to 9 m (5 to 30 ft). **Hfi** forms as sands are blown from the backbeach toward Laguna Madre. This represents a delicate balance between onshore winds that deflate backbeach sands and vegetative cover that stabilizes the dunes.			

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Age		Map Unit (Symbol)	Geologic Description	Geologic Issues	Geologic Features and Processes	Geologic History and Unit Location
QUATERNARY (Holocene)	Barrier-Standplain and Offshore System (continued from previous sheet)	Sand Flats (Hsf)	**Hsf** is sand flats, coppice sand-dune fields, and/or wind-shadow dunes. **Hsf** covers broad flat areas about 1 m (4 ft) above mean sea level with a mixture of fine-grained sand and shell. The broadest areas of the island, up to 7.2 km (4.5 mi), are associated with **Hsf**. **Hsf** is associated with several active or potentially active washover areas—places where sand is transported during hurricanes from the shoreface onto the backside of the island, where the sand may form dunes.	**Sea level rise and hurricanes**—Many years of sand deposition blowing from the beach may be necessary to restore the former dune position after a storm. The fore-island sand ridge protects the barrier island from the full impact of storm surge. As relative sea level rises, barrier island systems will continue to migrate landward. The configuration and stratified layers of fore-island dunes (**Hfi**) may record long-term climatic changes. **Erosion**—beaches (**Hb**) are eroding on South Padre Island. This is due to: (1) a sand deficit, (2) storm conditions on a thin sand body, (3) strong longshore drift northward, (4) dominant winds and storms move sand into Laguna Madre and out of the buffer zone, and (5) Rio Grande deltaic mud continues to compact causing a relative rise in sea level. Current rates of erosion are about 6 m (21 ft) per year based on a fixed well location that was 100 m (330 ft) from the beach in 1956, but was in the swash zone by 1972. The beach is repeatedly eroded by storm-surge floods in areas where the dunes (**Hfi**) are absent. **Hfi** may be eroded many meters during storms or hurricanes. **Disturbed lands**—In areas where there are fore-island dunes (**Hb** and **Hfi**), no sharp line exists between the beach and other barrier island depositional environments. Activities such as 19th and early 20th century ranching on Padre Island reduced vegetation cover, which in turn led to the destruction of fore-island dunes (**Hfi**) and promoted an increase in large back-island dune fields. **Hsf** currently occupies areas of the island previously occupied by **Hfi**. Jetty systems largely prevent the accumulation of **Hi** in active inlets. Two jettied inlets—Port Mansfield Channel to the north and Brazos Santiago Pass to the south—cut through South Padre Island. The jetties associated with these artificial inlets reroute sand that would otherwise be transported into south Laguna Madre through the inlets.	**Fluvial features and processes**—Channels of unit **Htc** share features similar to traditional fluvial systems including meanders and scour features. **Geologic influences on ecosystems**—In areas where vegetation is disturbed, either through drought or anthropogenic causes, fore-island dunes (**Hfi**) experience erosion. In areas of sufficient precipitation to promote vegetation, areas of **Hsf** have developed into small fore-island dunes (**Hfi**). Without the tidal exchange facilitated by **Htc**, salinity and circulation patterns would be substantially different. The flora and fauna (mainly marine grasses and oysters) would also change resulting in a substantial reduction in biologic productivity. Restricted circulation leads to the development of hypersaline basins. **Eolian features and processes**—fore-island dunes are a major component of **Hb**. The vegetation line coincides with the gulfward side of the fore-island dune ridge. Eolian crossbeds within **Hfi** records a complex history of dune deflation and deposition. **Hsf** includes low coppice and wind-shadow sand dunes, and broad sandflats. Between storm events, eolian processes erode and redistribute sands of **Hwf** and **Hwd**. This nourishes back-island dune fields, wind-tidal flats (**Hw**, **Hwa**), and vegetated transverse dunes. **Hb** contains lag, or wind-deflation deposits composing shell pavements left behind when the wind removes finer particles. **Paleontological resources**—**Hs** contains abundant shelly remains. **Hsb** is burrowed. **Hb** contains large clams *Eontia*, *Mercenaria*, and *Echinochama*. There may be a relationship between high, well-developed, fore-island dunes and abundant shell content on adjacent beaches. **Hb** contains abundant shell pavements. Oysters are the primary fauna in lagoonal basins.	Accumulation of modern sediment (**Hs**) is rather slow offshore from South Padre Island. **Hsb** accumulated atop Pleistocene and Holocene Rio Grande fluvial-deltaic deposits. The Gulf shoreline of South Padre Island is rapidly eroding; a continuous fore-island dune ridge (**Hfi**) will likely never develop again. There are 12–16 active areas of **Hsf** on South Padre Island. The broadest areas of the island, up to 7.2 km (4.5 mi) are associated with **Hsf**. At least 12 distinct washover channels are recognized locally.
		Washover Distributary Channel (Hwc)	**Hwc** consists of washover channels where sandy slurries are washed from one side of the island towards the other during periods of high tides and storms. **Hwc** contains shells and sand. The sand and shells of **Hwc** moves as dunes and sand waves during a storm surge. The washover channel moves water from the gulf to the back-island lagoon. Then, as the storm moves inland, ebb flows move water the opposite direction from the lagoon toward the gulf through channels. Within a few weeks, the channels are sealed on the gulf side by sand transported via longshore drift. When the channel is sealed, clay and fine-grained material settles to the floor of the former channel.			
		Washover Fan (Hwf)	Deposits of **Hwf** may be vegetated or barren (see **Hwd**). Vegetated fans resemble eolian deposits and may rise to heights greater than 2 m (6 ft). **Hwf** and **Hwd** occur where channels (**Hwc**) open onto the wind-tidal flats.			
		Washover Distal Fan (Hwd)	Barren fans (**Hwd**) contain sandy shell, shelly sand, and sand lobes in subaerial deposits. **Hwd** is part of an active environment. **Hwf** and **Hwd** occur where channels (**Hwc**) open onto the wind-tidal flats.			
		Tidal Channel (Htc)	**Htc** consists of active, sand-lined channels with pockets of muddy sand and shells. Units of **Htc** facilitate tidal exchange between bay, estuary, lagoon, and gulf environments. The channels are commonly located within a complex network of wind-tidal flats (**Hw**, **Hwa**) and lakes. **Htc** channels may function as drainage channels when rain floods inland basins.			
		Inlet-related Shoal (Hi)	**Hi** includes the sand that accumulates within natural or dredged inlets and is transported by longshore currents within the shoreface (**Hsb**).			

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Age	Map Unit (Symbol)		Geologic Description	Geologic Issues	Geologic Features and Processes	Geologic History and Unit Location
QUATERNARY (Holocene)	Fluvial-Deltaic System (continued on next sheet)	Levee and Local Crevasse Splay Deposits (Hls)	**Hls** consists of silty, muddy, and locally sandy deposits covered with sparse grass. Levees form elevated berms flanking stream channels. Crevasse splays are fan-shaped lobes of sediment that spread out onto the floodplain beyond a break or breach in a levee.	**Fluvial system**—The low elevation of the park area, including areas of **Hds**, and **Hf,** are particularly susceptible to drought, storm, and flood cycles. Precipitation patterns will change as climate continues to change. The fluvial system has been altered to control flooding and store water for agriculture. **Sea level rise and hurricanes**—As sea level continues to rise, the barrier system is migrating landward burying features such as former river deltas beneath the transgressive shelf. **Disturbed lands**—Many areas of **Hf** are now cultivated, but were once elongate, grass-covered areas underlain by mud and clay. **Oil and gas exploration and development**—An oil pipeline and access road at the park crosses portions of **Hds** and **Hf**.	**Fluvial features and processes**—The meander loops or scrolls, abandoned channels, and accretionary point bars of **Hms** document the fluvial processes that constructed these distinctive depositional units. In an area with little relief, meander belts and levees (**Hms** and **Hls**) stand in stark contrast to the surrounding lowlands. **Hls** occurs along the Rio Grande and is only active during periods of major flooding during major storms and hurricanes. **Hls** forms when floodwaters breach levees and discharge into adjacent floodplains, floodbasins, or interfluve depressions. Most of **Hms** is inactive with a few small, active point bars along the present Rio Grande channel. The anastomosing pattern of sandy point bars, silty levees and splays, and mud-filled oxbow lakes of **Hms** formed by fluvial processes of fluvial meandering and channel abandonment. **Hds** is transitional landwards with **Hms** and includes sandy point bars, silty/sandy levees and splays, and abandoned mud-filled channels with finer grained compositions than **Hms**. **Hfe** and **Hf** are contains within an entrenched valley. **Hf** consists of the following fluvial features: floodbasins, abandoned channels, and interfluve (interdistributary—areas between channels) areas with small abandoned channels. Portions of **Hf** may flood following intense rainfall. **Hmf** is part of a small, headward-eroding stream system. **Geologic influences on May 1846 battles**—**Hds** underlies some of the high ground within the park including Arista Hill used by Mexican forces during the battle. **Hf** underlies the majority of the battlefield at Palo Alto. The high clay content of **Hf** can cause low-lying areas of this unit to hold water. This likely impeded troop movements in 1846. **Geologic influences on ecosystems**—Saline soils occur within **Hds**, including the Jackass Prairies where the salinity limits agricultural activity. Saline silty clay loams of the Laredo and Sejita series support salt-tolerant grasses, alkali invasives, and thorny shrubs. **Hfe** and **Hf** are characterized by predominantly nonsaline clay soils of the Harlingen and Benito series—these are heavily cultivated locally. During dry years, freshwater influx is reduced and freshwater marsh assemblages (**Hmf**) are replaced by assemblages adaptable to brackish water conditions. **Eolian features and processes**—**Hf** includes some clay-sand dunes.	**Hls** occurs mostly along the present Rio Grande channel (the international border). Meander belts (**Hms**) record the passage of former channels of the Rio Grande River across the landscape throughout its evolution. **Hds** records the presence of a subsiding and inactive San Benito Rio Grande delta plain where nearly 195 km^2 (75 mi^2) of relict distributary channels crisscross the landscape in sinuous patterns. Delta lobes of **Hds** are now buried beneath the transgressive shelf as the barrier system continues to migrate landward. **Hf** and **Hfe** once covered 360 km^2 (140 mi^2) of the mapped area and much of this area is now cultivated. **Hmf** and **Hmb** may not include smaller freshwater marsh features including perennial ponds, lakes, and abandoned channels that are too small to be mapped at the 1:125,000 scale of the source map. **Hds** occurs within park boundaries adjacent to the resacas (see **PEa**). **Hf** occurs within park boundaries in the northwestern corner and the center of the C-shaped pattern of **PEa** along the eastern side.
		Meander Belt (Hms)	**Hms** contains belts of sand and silt, some of which are grass- and shrub-covered. Individual belts average about 3 to 5 km (2 to 3 mi) wide and up to 48 km (30 mi) long. Each belt may reach 2 to 3 m (5 to 10 ft) high and 20 m (65 ft) thick. Most have a sharp base eroded into older floodplain muds. Relict point bars contain coarse, basal gravels and coarse-grained sand that fines upward.			
		Distributary Sands and Silts (Hds)	**Hds** contains sands and silts in relict meandering to sinuous bodies. **Hds** occurs where meander belts (**Hms**) become smaller and split apart (bifurcate) gulfward across a gradational transition.			
		Flood Basin (Hfe)	**Hfe** is gradational with **Hf** and consists of overbank mud and silt.			
		Flood Basin Grading to Interdistributary Mud (Hf)	**Hf** consists of overbank mud and silt in a variety of depositional environments including fluvial, lacustrine, and eolian.			
		Fresh-water Marsh (Hmf)	**Hmf** consists of marshy areas of mud and sand inundated by fresh water.			

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Age		Map Unit (Symbol)	Geologic Description	Geologic Issues	Geologic Features and Processes	Geologic History and Unit Location
QUATERNARY (Pleistocene)	Fluvial-Deltaic System (continued from previous sheet)	Abandoned Channel (PEa)	**PEa** (resaca) consists of mud-filled channels and stream courses.	**Fluvial system**—The low elevation of the park area, including **PEa,** are particularly susceptible to drought, storm, and flood cycles. Precipitation patterns will change as climate continues to change. The fluvial system has been altered to control flooding and store water for agriculture. **Erosion**—**PEss** results from the mass removal of sands from dunes. **Disturbed lands**—Water control and storage infrastructure, as well as agricultural activity, altered areas of **PEa** and **PEss**. **Oil and gas exploration and development**—An oil pipeline and access road at the park crosses portions of **PEa**. Access is limited to where the road and pipeline cross a resaca	**Rio Grande resacas and other fluvial features and processes**—**PEa** records the process by which rivers change their courses in response to changes in the flow characteristics of the stream system (meandering and channel cutoff). Remnants of the Rio Grande levees or delta plain concentrate accretion of clay-sand dunes (**PEda** and **PEdi**). Units of **PEdi** occur around erosional remnants of meander belts (**Hms**). **Geologic influences on May 1846 battles** —Areas within the park of **PEa** (resacas) played significant roles during the 1846 battle. Marshy lowlands impeded repeated attacks on the U.S. western flank by Mexican forces trying to cross the resaca. **Eolian features and processes**—Wind-blown sediment fills depressions (**PEcl**). **PEda** occurs as active dunes formed of clay and sand. These hawk-shaped dunes are the products of windward accretion of salty clay and silt particles against a nucleus of levee remnants left exposed on wind-tidal flats. **PEss** are inactive elongate dune fields or trains that resulted from wind-caused deflation of relict fluvial (associated with rivers) and deltaic sediments. **Paleontological resources**—Channels of **PEa** may contain additional fossil animal remains and/or traces. **Geologic influences on ecosystems**—Some areas of **PEa** support fresh-water marshes. Sediments within **PEa** support gypsum-tolerant vegetation. Low permeability clays flooring depressions (**PEcl**) support local marshes in areas where precipitation allows. These areas support aquatic plants (hydrophytes) during periods of higher rainfall.	The complex pattern of filled channels (**PEa**) records the shifting, meandering nature of the Rio Grande fluvial system through time. Resacas (**PEa)** cover 340 km^2 (130 mi^2) of the mapped area. Coastal lakes or ponds (**PEcl)** are relicts of Pleistocene fluvial systems throughout the area. They total approximately 8 km^2 (3 mi^2) of the mapped area. Active clay-sand dunes cover approximately 16 to 21 km^2 (6 to 8 mi^2) of the mapped area. Sand sheets (**PEss**) cover nearly 105 km^2 (40 mi^2) of the mapped area. Gavilans (**PEda**) takes its name from Mesa del Gavilan (a dune complex shaped like the head of a hawk). **PEa** occurs in sinuous low-lying resacas predominantly in a C-shaped curve across the northern, western, and southern areas of the park.
		Coastal Lake or Pond (PEcl)	**PEcl** is a mud-filled depression.			
		Gavilans (clay-sand dunes) (PEda)	Gavilans occur in dune fields that occur on or border extensive wind-tidal flats (**Hw**, **Hwa**). These dunes are linear to crescent in shape.			
		Clay-sand Dune Complexes (PEdi)	Units of **PEdi** are primarily grass- or brush-covered dunes. Vegetation renders them inactive (see **PEda**).			
		Sand Sheets (PEss)	**PEss** is primarily grass-covered, base-leveled dune areas composed of sand. **PEss** areas have sharp boundaries.			