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San Antonio Missions National Historical Park

Geologic Resources Inventory Report

Mission San José’s primary building material is a coarse, porous limestone tufa. The portico and famed Rose Window were carved from Austin limestone.

COLORADO STATE UNIVERSITY / MATTHEW HARRINGTON

San Antonio Missions National Historical Park: Geologic resources inventory report

Science Report NPS/SR—2024/146

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Acknowledgements

The GRI team thanks the participants of the 2008 scoping meeting and 2023 follow-up meeting for their assistance in this inventory. The lists of participants are in alphabetical order by last name and reflect the names and affiliations of these participants at the time of the meeting and call. Because the GRI team does not conduct original geologic mapping, the team is particularly thankful for the Texas Bureau of Economic Geology and the Texas Water Development Board for their maps of the area. This report and accompanying GIS data could not have been completed without them. The GRI team thanks Denny Capps (NPS Geological Resources Division) for his review of the Erosion and Hillslope Features and Processes and Geologic Hazards sections of this report, Tony Gallegos and Forrest Smith (NPS GRD) for their review of the Oil and Gas Exploration and Development section, Patricia Seiser (NPS GRD) for her review of the Karst Features and Processes section, and Justin Tweet (NPS GRD) for his review of the Paleontological Resources section. The GRI team also thanks Amani Canada and Joel Osborne (San Antonio Missions National Historical Park) for reviewing the Geologic Heritage section.

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Executive Summary

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

San Antonio Missions National Historical Park, hereafter also referred to as the "park" in this report, is located in south-central Texas and preserves the largest concentration of Spanish colonial-era cultural resources in the United States. The park, established in 1978, preserves four Spanish missions, Mission San José, Mission Concepción, Mission San Juan, and Mission Espada, along with Mission Espada's historic ranch, Rancho de las Cabras. A cooperative agreement unlike any other in the National Park System exists between the NPS and the Catholic Archdiocese of South Texas, allowing religious history and tradition to continue under the Catholic Archdiocese of South Texas while allowing the NPS to provide preservation, restoration, and interpretation of park buildings and structures to visitors.

Long before humans settled the San Antonio River Valley, most of Texas was submerged beneath the Western Interior Seaway during the late Cretaceous Period, roughly 100 million years ago. From the late Cretaceous to the end of the Paleogene 23 million years ago, south-central Texas experienced alternating marine transgressions (sea level rises) and regressions (sea level retreats), and eventually, the retreat of the sea toward its modern location in the Gulf of Mexico. Evidence of these alternating marine cycles can be found in the rock layers, with transgressions associating with geologic units such as the Midway Group (geologic map unit **Emi**; see "GRI GIS data" and "GRI Poster"), with fine-grained clays, silts, and marine-derived sands, and regressions associating with units such as the Carrizo Sand (**Ec**), with course-grained, poorly sorted sandstones. Most of the exposed units in the park are Quaternary-aged gravels, floodplain deposits, and tufas.

Although there are only a few rock outcrops within the park's boundaries, a strong geologic heritage exists in the building stones that were used to construct the missions and their compounds. What is left of the original missions, dams, and aqueducts was constructed from locally quarried tufas, limestones, sandstones, and claystones, most notably from the Austin Chalk (**Kau**), Midway Group (**Emi**), and Wilcox Group (**Ewi**). This report makes connections among park resources—historic, cultural, and geologic—and is the most comprehensive, park-specific geologic report known for the park. GRI reports (1) are based on the most accurate, up-to-date geologic mapping known at the time of writing; (2) compile and summarize park-specific, geologic information and research; (3) are written from the perspective of park management; and (4) incorporate a park's significance as expressed in its foundation document. This report contains the following chapters:

Introduction—This chapter is divided into two sections: "Park Background and Establishment" and "Introduction to the GRI." It provides a historical context, orients the readers to the location and physiographic setting of the park, and highlights its operation as a series of missions as well as its establishment as part of the National Park System. Additionally, the chapter provides background information about the GRI, highlights the GRI process and products, and recognizes GRI collaborators. A geologic map in geographic information system (GIS) format (referred to as the “GRI GIS data”) is the principal deliverable of the GRI. This chapter provides specific information about the use of the GRI GIS data. The source maps used to compile the GRI GIS data were originally produced by the Texas Bureau of Economic Geology and the Texas Water Development Board. The GRI GIS data was compiled in 2010 and updated in 2022. Both data sets and the geologic information and interpretations associated with them were used in preparing this report. The chapter also calls attention to the poster, which illustrates the GRI GIS data.

Geologic Heritage—This chapter highlights the significant geologic features, landforms, landscapes, and stories of the park preserved for their heritage values. It also draws connections between geologic resources and other park resources and stories, such as the use of locally quarried stone in mission construction and the importance of aquifer-fed springs in the settling of the region by both indigenous people and the Spanish missionaries.

Geologic History—This chapter describes the chronology of geologic events that formed the present landscape. The geologic events are discussed in chronological order, starting in the Cretaceous Period (145.0 million–66.0 million years ago) with the formation of the Austin Chalk and ending with the modern landscape. The chapter also includes a geologic time scale and a table describing the geologic units in the GRI GIS data, their location in the park, and any associated paleontological resources.

Geologic Features, Processes, and Management Issues—This chapter describes the geologic features and processes of significance for the park as well as active and potential management issues related to the park’s geologic resources. Features, processes, and issues include fluvial features and processes, erosion and hillslope features and processes, climate change, karst features and processes, disturbed lands, geothermal features and processes, paleontological resources, oil and gas exploration and development, seismic features and processes, and geologic hazards.

Guidance for Resource Management—This chapter is a follow up to the “Geologic Features, Processes, and Management Issues” chapter. It provides resource managers with a variety of ways to find and receive management assistance with geologic resources. It also contains lists of park-specific resource management documents, NPS resource management documents, and geologic resource laws, regulations, and policies.

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

In addition to these chapters, “Literature Cited” provides a bibliography of all the references cited in this GRI report. It serves as a source of park-specific geologic information applicable to the protection, management, and interpretation of the park’s geologic resources.

Introduction

The Geologic Resources Inventory (GRI), which is administered by the Geologic Resources Division (GRD) of the National Park Service (NPS) Natural Resource Stewardship and Science Directorate, provides geologic map data and pertinent geologic information to support resource management and science-informed decision making in more than 270 natural resource parks throughout the National Park System. The GRI is funded by the NPS Inventory and Monitoring Program.

Park Background and Establishment

San Antonio Missions National Historical Park (referred to as the "park" throughout this report) preserves the largest concentration of Spanish colonial-era cultural resources in the United States (Allen et al. 2016). The enabling legislation to form the park was signed into law on 10 November 1978, in order to "provide for the preservation, restoration, and interpretation of the Spanish Missions of San Antonio, Texas" (P.L. 95-629). That same year, the park was expanded to include a greater portion of the mission compounds and historic acequias (Amdor et al. 1994). The park was expanded on 28 November 1990, and later expanded again in 1995 to acquire the Rancho de las Cabras unit, associated with Mission Espada (OCULUS 1998). In 2013, Congress approved another expansion, which led to the acquisition of land around Missions San José, San Juan, and Espada (H.R.885). On 20 May 2021, the National Park Trust acquired 44 acres (0.178 km^2) of land east of the San Antonio River adjacent to the original San Juan Acequia and transferred the property to the park (National Park Trust 2021) On 5 July 2015, the park was designated a World Heritage Site by the United Nations Educational, Scientific, and Cultural Organization (UNESCO) in recognition of the park's "outstanding universal value and importance to all humankind" (National Park Service 2016).

The park is separated into two units, the Missions unit and the Rancho de las Cabras unit (Figure 1). The Missions unit, the primary unit of the park, is located directly south of downtown San Antonio along a 7.7-mile (12.4 km) stretch of the upper San Antonio River (National Park Service 2016). It is predominantly situated along the river terraces and floodplains of the San Antonio River, with little bedrock exposed (Figure 2). The unit consists of four missions, each located 1 to 2.5 miles (4 km) away from the next mission. Due to intense urbanization across the sites of the historic missions, the Missions unit is broken down into a series of small subunits, all connected by the Mission Trail driving tour and/or the River Walk trail. Some subunits of the Missions unit, including the San Juan Dam and the Labores de Espada, contain limited access to the general public. The smaller and more rural unit, Rancho de las Cabras, is located approximately 32 miles (51.5 km) southeast of the Missions unit near the town of Floresville. Since the early 1990s, annual visitation numbers have typically fallen in the range of 1.1 to 1.4 million (National Park Service n.d.).

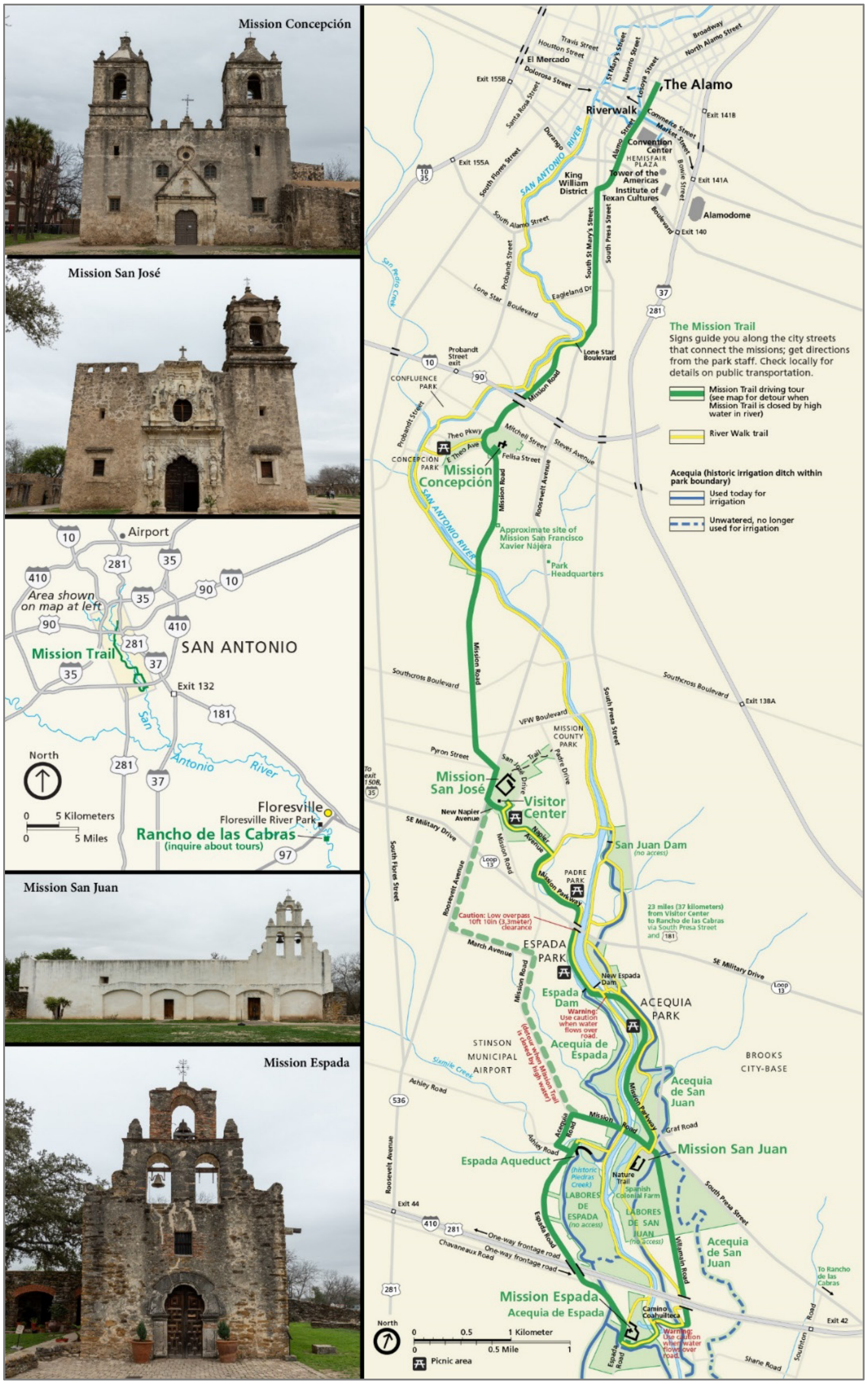

Figure 1. Maps of San Antonio Missions National Historical Park. San Antonio Missions is split into two primary units, the Missions unit and the Rancho de las Cabras unit. The Missions unit follows the San Antonio River south of downtown San Antonio where it is intersected by many driving and walking trails. The Rancho unit is located south of Floresville, Texas. National Park Service (NPS) maps are available at www.nps.gov/carto. Photographs by Matthew Harrington (Colorado State University).

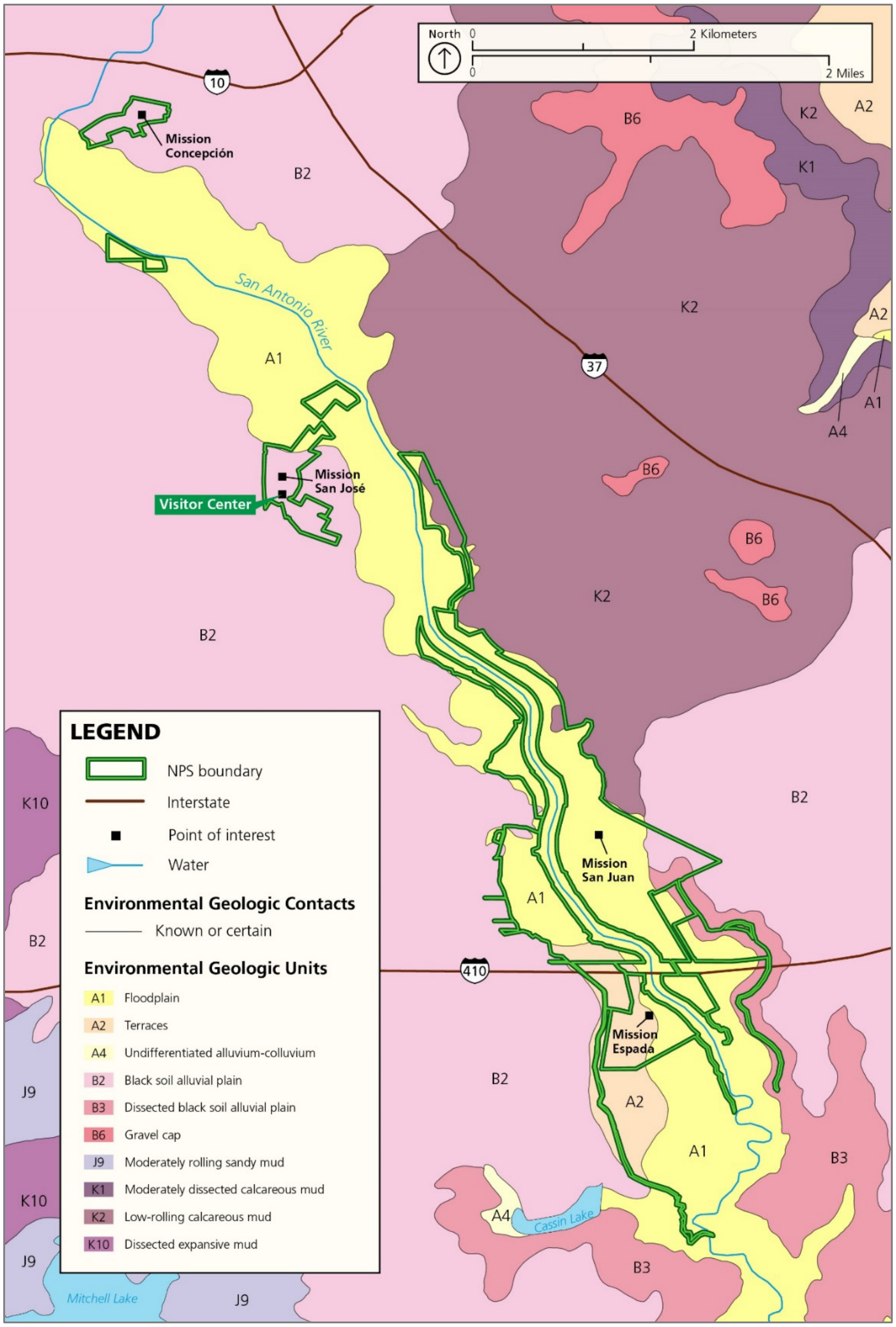

Figure 2. Surficial geologic map of the park. The map identifies the materials overlaying the bedrock. Environmental geology, or surficial geology, deals with the sediments that overlay bedrock on a landscape. This figure showcases the surficial geology around the Missions unit within the park. For more detailed information on each unit and broader coverage (including the Rancho unit), refer to the environmental GIS data. The surficial geologic units in this figure were sourced from nine 7.5’ quadrangle maps produced by the Texas Bureau of Economic Geology (1985). For a more detailed citation, refer to the Introduction chapter.

In 1983, a cooperative agreement unlike any other in the National Park System was formed between the NPS and the Catholic Archdiocese of South Texas (National Park Service 2016). This agreement enables the NPS to engage in the preservation, restoration, and interpretation of the four missions, allowing access to the mission grounds and secular buildings for public use and education, as long as such use does not interfere with religious and church purposes. On the other end of the agreement, the archbishop is tasked with maintaining and preserving the nonsecular structures within the park and is not allowed to alter or remove historic features without the approval of the NPS. The park also partakes in agreements fundamental to the park's mission with the San Antonio River Authority, the city of San Antonio, and Bexar County (National Park Service 2016).

The park is located on the border of two physiographic provinces in Texas: the Blackland Prairies and the Interior Coastal Plains, with the Missions unit located in the Blackland Prairies, and the Rancho de las Cabras unit located in the Interior Coastal Plains (Figure 3). The Blackland Prairies are composed of low rolling topography with chalk and marl beds tilted toward the south and east (Wermund 1996). The Environmental Protection Agency (EPA) Level III Ecoregions describe the region as possessing "fine-textured, clayey soils and predominantly prairie potential natural vegetation" (Environmental Protection Agency 2013). Grasslands dominated the landscape before Spanish colonization, but less than one percent of the original grassland vegetation remains, and within the boundaries of San Antonio National Historical Park, these former prairies are now scrublands or agricultural fields (Cooper et al. 2005, Allen et al. 2016). From Austin to Del Rio, the Blackland Prairie province backs up against the Balcones Escarpment, a topographic feature of cliffs that is often used as an ecological demarcation between drier climates to the north and west, and wetter climates to the south and east (see "Geologic History" for more information on the Balcones Escarpment).

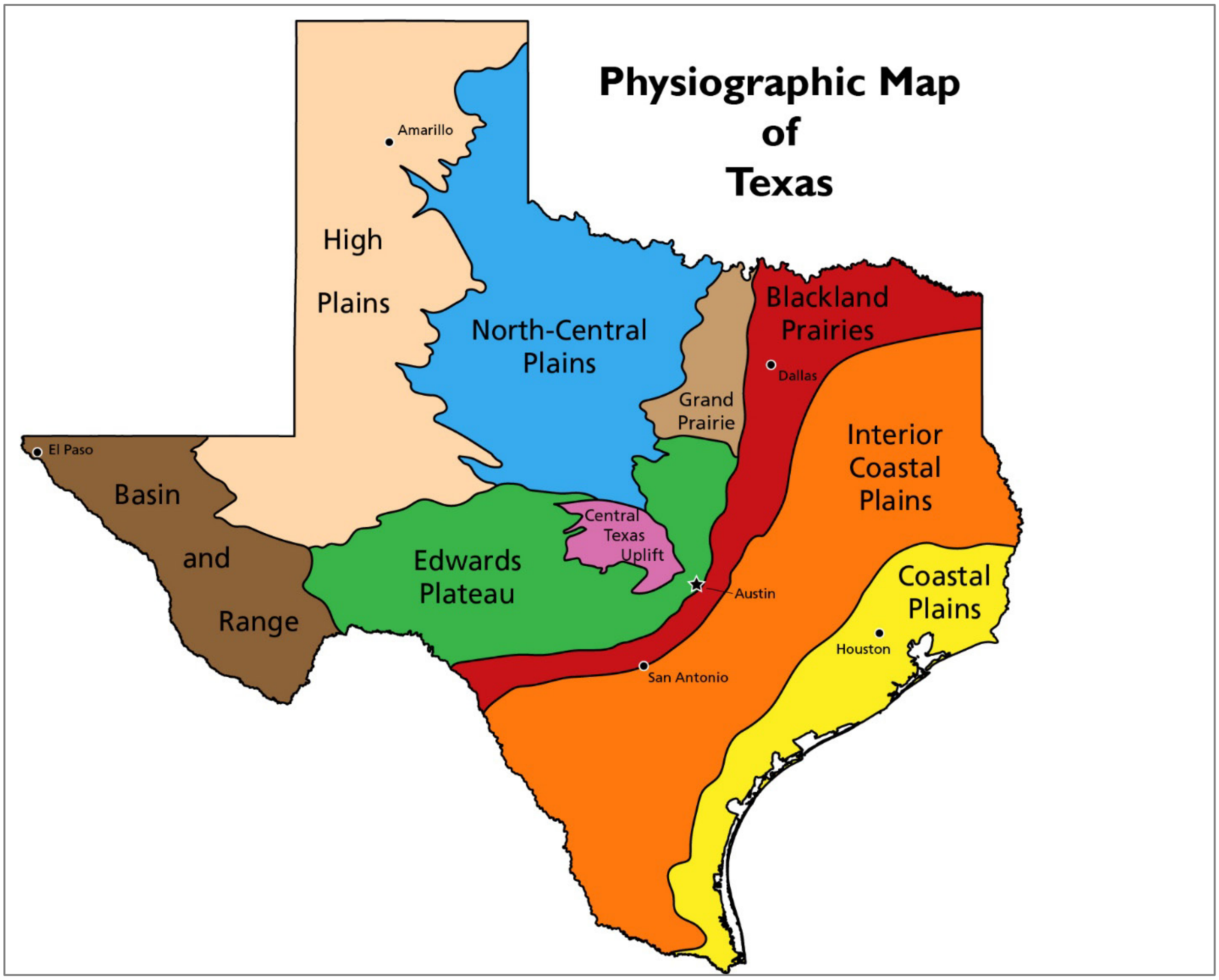

Figure 3. Physiographic provinces of Texas. This map depicts the physiographic provinces of Texas based upon the map created by Wermund (1996). The park is located in San Antonio along the boundary of the Blackland Prairies and the Interior Coastal Plains, just south of the Balcones Escarpment.

The Interior Coastal Plains consist of cuestas (ridges with a gentle slope on one side and a steeper slope on the other side) formed by sandstones, mudstones, and sediments with beds tilted toward the Gulf of Mexico (Wermund 1996). Historically, this region consisted of post oak savannas but is now dominated by pastures and range (Environmental Protection Agency 2013). The climate at the park is characterized as subtropical, with mild winters and high humidity and heat in the summer (Segura et al. 2007, National Park Service 2021). The San Antonio River Valley, home to all five of the missions, is characterized by the San Antonio River and the San Pedro Creek, both of which allowed the missions (and the city of San Antonio) to survive (Department of History at Southwest Texas State University 2000).

The park's foundation document (National Park Service 2016) provides the following significance statements that express why the park's resources and values are important enough to merit designation within the National Park System:

The Spanish Empire’s efforts to colonize, evangelize, and defend the northern frontier of New Spain—reflected by the architecture, landscapes, and functioning acequias and agricultural systems—are preserved as the most complete, geographically concentrated, and intact group of Spanish Colonial mission complexes in the world.

The park’s resources are the result of the complex interweaving of peoples and cultures from Indigenous groups, central and northern New Spain, and the Spanish settlers that precipitated a rapid, fundamental, and permanent change most dramatically among the Indigenous groups. This new society, neither wholly Indigenous nor wholly Spanish, has continually evolved to become the predominant culture of South Texas.

In partnership with the NPS, the Archdiocese of San Antonio and local parishes preserve and provide public access to the park’s four historic mission churches, all of which are active today. This is the only park unit in the National Park System that has this type of partnership.

Introduction to the GRI

The GRI team—which is primarily a collaboration between GRD staff and research associates at Colorado State University, Department of Geosciences and University of Alaska Museum of the North—completed the following tasks as part of the GRI process for the park: (1) conduct a scoping meeting and provide a scoping summary, (2) provide geologic map data in a geographic information system (GIS) format (referred to as the “GRI GIS data”), (3) create a poster to display the GRI GIS data, and (4) provide a GRI report (this document). GRI products are available on the “Geologic Resources Inventory—Products” website and through the NPS Integrated Resource Management Applications (IRMA) DataStore portal (see “Access to GRI Products”).

Information provided in GRI products is not a substitute for site-specific investigations. Ground-disturbing activities should neither be permitted nor denied based on the information provided in GRI products. Minor inaccuracies may exist regarding the locations of geologic features relative to other geologic or geographic features in the GRI GIS data or on the poster. Based on the source map scale (Barnes 1982, Texas Water Development Board 2007; 1:250000) and *Map Accuracy Standards* (US Geological Survey 1999), geologic features represented in the GRI are horizontally within 127 meters (417 feet) of their true locations.

Scoping Meeting

On 22 April 2008, the NPS held a scoping meeting at the park. The scoping meeting brought together park staff and geologic experts, who reviewed and assessed available geologic maps, developed a geologic mapping plan, and discussed geologic features, processes, and resource management issues to be included in the final GRI report. A scoping summary (KellerLynn 2008) summarizes the findings of that meeting.

GRI GIS Data

Following the 2008 scoping meeting, the GRI team compiled the GRI GIS data for the historical park. The GRI GIS data was updated in 2022 and may be updated again if new, more accurate geologic maps become available or if software advances require an update to the digital format.

These data are the principal deliverable of the GRI. The GRI GIS data is available on the NPS DataStore (see "Access to GRI Products").

The GRI team did not conduct original geologic mapping but compiled existing geologic information (i.e., paper maps and/or digital data) into the GRI GIS data (Figure 4). Scoping participants and the GRI team identified the best available source maps based on coverage (area mapped), map scale, date of mapping, and compatibility of the mapping to the current geologic interpretation of an area.

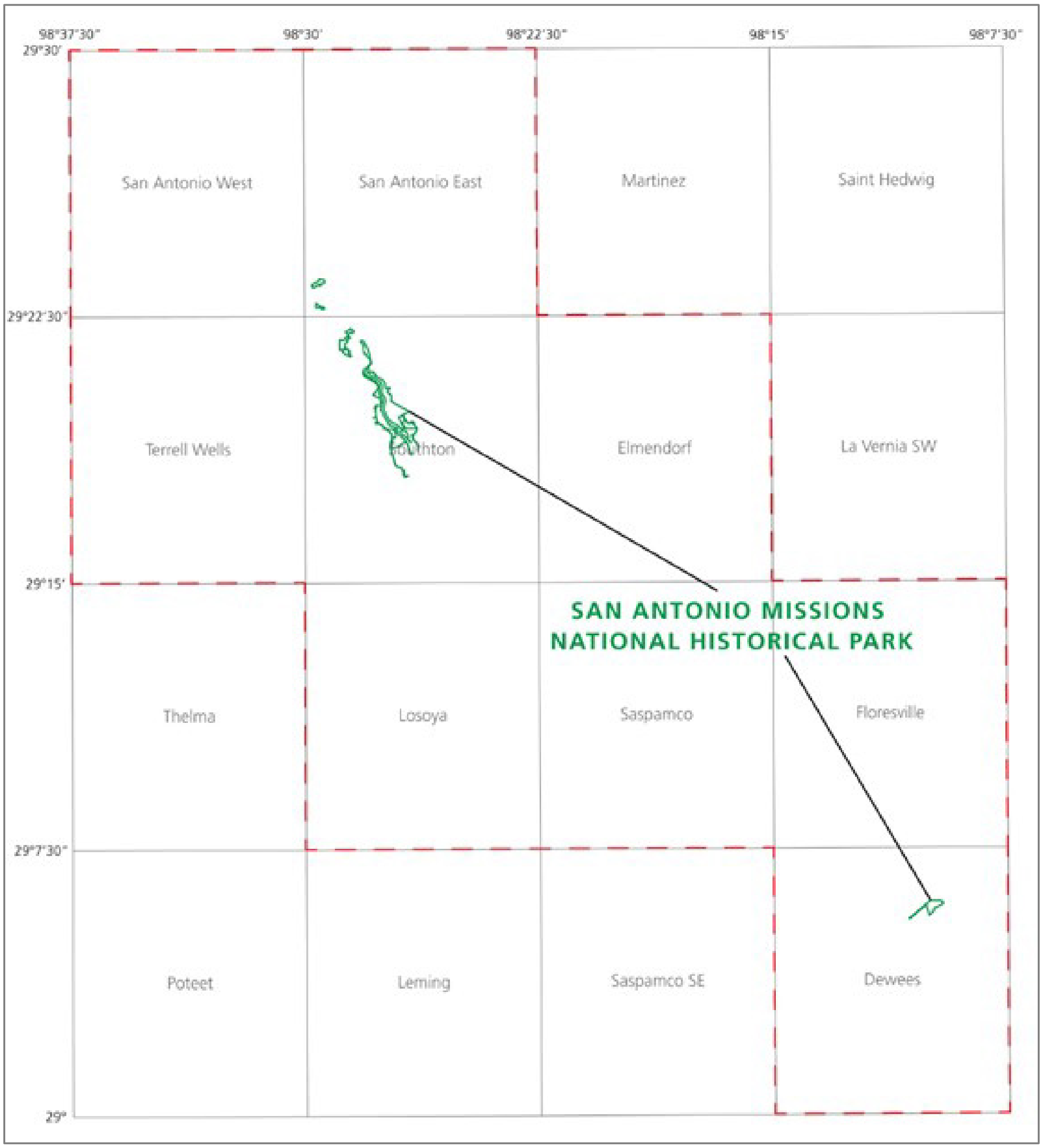

Figure 4. Index map of the GRI GIS data. This map shows the GRI GIS data in the context of 7.5-minute quadrangles. The extent of the data is outlined with a red dashed line. The boundary of the park (as of February 2022) is outlined in green. Index map by James Winter (Colorado State University).

More information about the GRI GIS data can be found in the files accompanying the data on the NPS DataStore. The "GIS readme file" explains the available file formats for the GRI GIS data, how to use the different file formats, and where to find more information about the GIS data model. The "ancillary map information document" lists the geologic maps or GIS data used to produce the GRI GIS data, the map units and map unit descriptions (including descriptions from all source maps), and additional information about the source maps.

Both bedrock and surficial geologic datasets were compiled for this report. The GRI poster produced for this report utilizes the bedrock dataset. A map of the surficial geology is included in the report as a figure (see Figure 2).

The GRI GIS data for the bedrock geology of the park was compiled from the following two source maps:

- Geologic Atlas of Texas: San Antonio Sheet (Barnes 1982)
- Geologic Database of Texas: 1:250000 Geologic Data for Beaumont Sheet (Texas Water Development Board 2007)

The GRI GIS data for the surficial geology of the park was compiled from the following nine source maps:

- Dewees 7.5' Quadrangle: San Antonio East Llano East Environmental Geology Sheet (Texas Bureau of Economic Geology 1985a)
- Elmendorf 7.5' Quadrangle: San Antonio East Llano East Environmental Geology Sheet (Texas Bureau of Economic Geology 1985b)
- Floresville 7.5' Quadrangle: San Antonio East Llano East Environmental Geology Sheet (Texas Bureau of Economic Geology 1985c)
- Losoya 7.5' Quadrangle: San Antonio East Llano East Environmental Geology Sheet (Texas Bureau of Economic Geology 1985d)
- San Antonio East 7.5' Quadrangle: San Antonio East Llano East Environmental Geology Sheet (Texas Bureau of Economic Geology 1985e)
- San Antonio West 7.5' Quadrangle: San Antonio East Llano East Environmental Geology Sheet (Texas Bureau of Economic Geology 1985f)
- Saspamco 7.5' Quadrangle: San Antonio East Llano East Environmental Geology Sheet (Texas Bureau of Economic Geology 1985g)
- Southton 7.5' Quadrangle: San Antonio East Llano East Environmental Geology Sheet (Texas Bureau of Economic Geology 1985h)
- Terrell Wells 7.5' Quadrangle: San Antonio East Llano East Environmental Geology Sheet (Texas Bureau of Economic Geology 1985i)

The GRI used the following source map for unit descriptions for the surficial geology of the park:

- San Antonio East Llano East Environmental Geology Sheet (Wermund 1985)

GRI Poster

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

GRI Report

This report is a culmination of the GRI process. It synthesizes discussions from the scoping meeting in 2008, a follow-up meeting in 2023, reviewers' comments in 2023, and additional geologic research. The selection of geologic features discussed in the report was guided by the previously completed GRI GIS data and discussions during the scoping meeting and follow-up meeting. Notably, the writing reflects the geologic interpretation provided by the author(s) of the source map(s) (see "GRI GIS Data"). Information from the park's foundation document (National Park Service 2016) was also included as applicable to the park's geologic resources and resource management.

The GRI report links the GRI GIS data to the geologic features and processes discussed in the report using map unit symbols; for example, the Wilcox Group mapped in the park has the map symbol **Ewi**. Capital letters indicate age, followed by lowercase letters that symbolize the unit name. For example, "**E**" represents the Eocene Epoch (~56.0 million–33.9 million years ago) and "**wi**" represents the Wilcox Group. A geologic time scale and a list of all the map units in the GRI GIS data are provided as tables in this report (see "Geologic History").

Geologic Heritage

Geologic heritage (also called "geoheritage") evokes the idea that the geology of a place is an integral part of its history and cultural identity. This chapter highlights geologic features, landforms, landscapes, and stories of the park valued for their geologic heritage qualities. It also draws connections between geologic resources and other park resources and stories.

In 2015, in cooperation with the American Geosciences Institute, the NPS Geologic Resources Division, which administers the GRI (see "Introduction to the GRI"), published, America's Geologic Heritage: An Invitation to Leadership (National Park Service and American Geosciences Institute 2015). That booklet introduced the American experience of geologic heritage and outlined key principles and concepts, including the following five big ideas:

- America's geologic landscape is an integral part of its history and cultural identity, and Americans have a proud tradition of exploring and preserving geologic heritage.
- America's geologic heritage, as shaped by geologic processes over billions of years, is diverse and extensive.
- America's geologic heritage holds abundant values—aesthetic, artistic, cultural, ecological, economic, educational, recreational, and scientific—for all Americans.
- America's geologic heritage benefits from established conservation methods developed around the world and within the United States.
- America's geologic heritage engages many communities, and involvement by individuals will ensure its conservation for future generations.

Geoheritage sites are conserved so that their lessons and beauty will remain as a legacy for future generations. Such areas generally have great potential for scientific studies, use as outdoor classrooms, and enhancing public understanding and enjoyment. Geoheritage sites are fundamental to understanding dynamic earth systems, the succession and diversity of life, climatic changes over time, evolution of landforms, and the origin of mineral deposits. Currently, the United States does not have a comprehensive national registry of geoheritage sites. Though park units are not currently established specifically for geoheritage values, any geologic component of a park's enabling legislation, planning, and management documents can be considered a part of America's geoheritage.

Native American Culture

The San Antonio region has been home to Indigenous people for at least 11,000 years, providing a moderate climate, fertile soil, and rich hydrologic features that nourished the local population (Department of History at Southwest Texas State University 2000). Although dry today (except during flash floods), upper San Antonio possesses hundreds of springs emanating from the Edwards Aquifer that used to freely flow into local tributaries, the San Pedro Creek, and the San Antonio River (Department of History at Southwest Texas State University 2000; Eckhardt n.d.). The springs provided year-round, actively available, fresh water and a suitable habitat for local wildlife and plant communities. In the typically arid region of south-central Texas, this landscape proved to be an attractive home for the first inhabitants and all those to follow.

By the mid-1600s, numerous groups of Indigenous people inhabited the region, many of whom were part of small, family-based hunter-gatherer groups (Campbell and Campbell 1985; Department of History at Southwest Texas State University 2000). The collective name often given to describe these people, Coahuiltecans, is based on cultural assumptions and fractured documentation, and it remains unknown if they all spoke various dialects of the same language or unique languages (Torres 1993).

Spanish-American Culture

Spanish colonialism reached Mexico by 1521, and over the following three centuries, it slowly expanded north, displacing Native American groups along the way (Campbell and Campbell 1985). Further intensifying the displacement of local tribes was the southeastern expansion of the Apache (and later Comanche) from the southern high plains in the mid-1600s (Campbell and Campbell 1985). This dual-pressure displacement led many of the fractured groups to enter Spanish mission life, where they were converted to Catholicism and a European way of life centered around agriculture and ranching.

Southern-central Texas existed as one of the frontiers of Spain's colonial empire, with the San Antonio River's headwaters a full two-week ride beyond the closest Spanish settlement (Torres 1993). The initial Franciscan missionaries arrived in 1718 to establish the first of the five San Antonio Missionaries, Mission San Antonio de Valero (more commonly known as the Alamo; present-day, the site is under the management of the Daughters of the Republic of Texas as a living shrine to Texas patriotism and is not a part of the park), along with a presidio and the villa of San Antonio de Béxar (Torres 1993).

When selecting a new site for a mission, the highest priority for missionaries was access to water (Ivey 2018). After selecting an appropriate site near accessible water, a dam was created to push water into an irrigation ditch system, or acequia. This system allowed the natural flow of the river to continue over the top of the dam while diverting enough water into the engineered acequia (Ivey 2018). Franciscans were aware of the San Antonio River's (and others) tendency to have serious floods, so missions were never established within a floodplain (Ivey 2018).

Geoheritage of the Missions

Mission San José

In 1719, Friar (Fr.) Antonio Margil de Jésus encountered multiple Indigenous groups in the area who were open to joining the mission system but refused to enter Mission Valero, as they were fierce rivals with some of the Indigenous groups already there (Torres 1993). Seeing the potential of a second mission, Fr. Margil drafted a proposal for a new mission despite opposition from the Friar at Mission Valero. On 23 February 1720, Mission San José y San Miguel de Aguayo (Mission San José) was founded in a formal ceremony on the east bank of the San Antonio River (Torres 1993). However, within a few years, the missionaries decided to relocate the mission to its present location on the western bank of the river for unknown reasons (Ivey 2018).

By the 1740s, the first permanent stone buildings were under construction at Mission San José (Torres 1993; Habig 1968). Construction on the mission church started in 1768 and was completed in 1782. The primary building stone used at Mission San José (and Mission Concepción) is a course, porous limestone tufa (a calcareous rock formed by the precipitation of carbonate minerals from unheated freshwater sources) (**Qle** or **Qt**) containing numerous holes (3–4 cm in diameter) lined with a fine calcite that possesses a flowstone (thin sheets of calcite or carbonates formed where water flows along a floor or wall, often in caves) appearance (Figure 5) (Ewing 2008). Small vermicular (worm-like) tubes (5–10 mm) and cavities, some possibly formed around plant roots, are common within the rock (Ewing 2008). The tufa was likely deposited by calcite-rich water emerging from a former spring (Ewing, 2008). The tufa used at Mission San José was quarried near Mission Concepción (Ewing 1997).

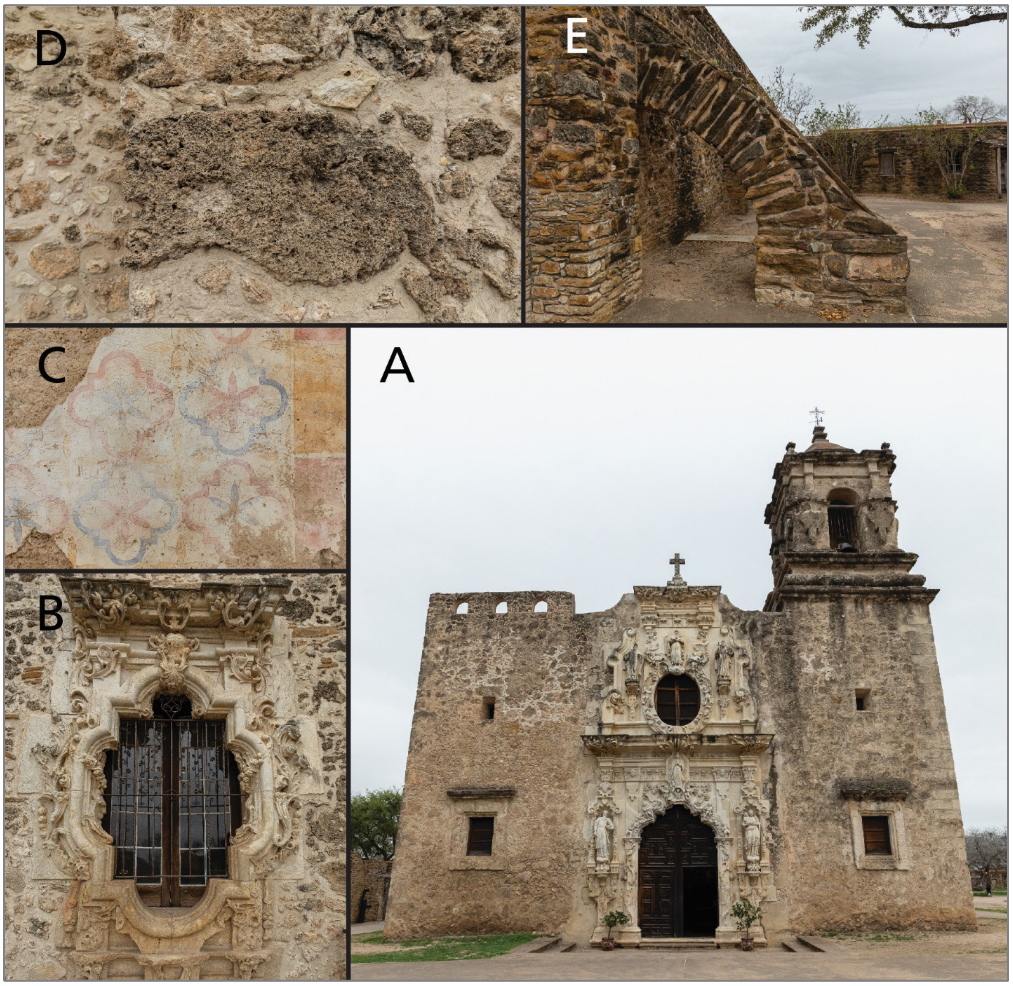

Figure 5. Photographs of Mission San José. A) The façade of Mission San José, showcasing the expertly carved stone used in construction. B) The iconic Rose Window, added sometime after the church's initial completion, is carved out of Austin Limestone. C) Remnants of the bright frescos that once adorned the exterior of the mission. The frescos were colored by oxides acquired from local sandstones and painted over the tufa foundations on wet lime plaster. The infusion of oxide pigments into limey plaster allowed the frescos to survive for over two centuries. D) An example of the rough nature of the large tufa blocks that were used as building stones at Mission San José. E) The walls of the compound were originally composed of Wilcox sandstone but were lost to time and decay. They were reconstructed in the 1930s and reflect what the original walls and materials would have looked like. Photographs by Matthew Harrington (Colorado State University).

The rough, coarse nature of the local tufa deposits allowed for only rough-hewn masonry (Ewing 1997). For the more detailed structures of the church, including the carved portico and the iconic Rose Window (added later after the church's completion in 1782), a higher quality building stone was preferred. The Austin Limestone (**Kau**), imported from quarries north of the mission near San Antonio Springs, possessed a unique property of softness when initially extracted from the quarry, where it was purported to be cuttable by a knife (Roemer 1849). After its initial extraction and exposure to air, the limestone would harden, making the Austin Limestone well-adapted for sculpting (Roemer 1849).

The San José church was expertly constructed, so much so that it has been called the "Queen of the Missions" (Torres 1993). During an inspection of New Spain's frontier missions in 1777, Fr. Juan Agustín Morfi noted that Mission San José was "in truth, the first mission in America, not in point of time, but in point of beauty, plan, and strength, so that there is not a presidio [sic] along the entire frontier line that can compare with it." (Torres 1993, p. 21). Frescos were painted onto limey plasters over the tufa foundations, utilizing oxide pigments from local sandstone exposures (potentially **Emi** or **Ewi**) as sources for reds and yellows (NPS 2024). The pigments were painted onto the wet limey plaster, solidifying into permanence as the plaster hardened into limestone.

The convento at Mission San José was constructed with a blend of tufa and Wilcox Formation sandstone (**Ewi**); brickwork was added by Benedictine monks in the mid-19th century (Ewing 1997; Allison Young, San Antonio Missions National Historical Park, Division Lead, Resource Management [Natural and Cultural], personal communication, 24 February 2023). The quadrangle walls of Mission San José were primarily composed of Wilcox platy sandstones that were likely sourced from exposures one to two miles south–southeast, near Mission San Juan (Ewing 1997). The modern walls, reconstructed in the 1930s, do not contain original materials. Blocks of original tufa and Wilcox sandstone were uncovered alongside colonial artifacts within a section of the San José Acequia just southeast of the mission quadrangle (Henderson and Clark 1984).

Mission San José was very productive during the peak of its operation, producing enough crops to not only supply itself but the other San Antonio missions, the nearby presidio, and other presidios in East Texas (Torres 1993). The final report on the mission in 1815, 21 years after the partial secularization of 1794, listed a population of 109 people living in the mission (Torres 1993). However, the mission complex began to fall into a state of decay and disrepair, exacerbated by the occupation of the mission by United States troops during the American–Mexican War (1846–1848), where stationed soldiers entertained themselves by using the façade and statues of the mission as target practice (Torres 1993).

During the next 50 years, the mission underwent heavy dilapidation and ruin. In 1868, the north wall of the church collapsed; the dome and most of the roof fell in 1874; and the main doors of the church were stolen in the 1890s (Torres 1993). By 1900, every building except the sacristy was in ruins, and the perimeter walls and adjoining Indigenous quarters had disappeared (Torres 1993). The first preservation efforts began in 1917, and in 1934, the Archdiocese of San Antonio signed an agreement with the federal government's Work Projects Administration (WPA) to completely reconstruct and restore Mission José's complex (Torres 1993). While much of Mission San José today is a reconstruction, it provides a tangible example of what the mission looked like during its operation and allows visitors to appreciate the architecture and layout of the mission compound.

Mission Concepción

Mission Nuestra Señora de la Purísima Concepción de Acuña (Mission Concepción) was originally established in present-day Nacogdoches County in 1716 to work with the Tejas (Torres 1993). The mission faced multiple hardships at its initial site, including difficulties convincing the Tejas to abandon their traditional lifestyle and convert to missionary life (Torres 1993). By 1719, the mission was forced to relocate to its second site after the French threatened it. In 1731, the Viceroy of New Spain and Marqués de Casafuerte Juan de Acuña (to whom Mission Concepción was rededicated) approved the relocation of Mission Concepción, Mission San Juan Capistrano, and Mission San Francisco de la Espada to the banks of the San Antonio River (Department of History, Southwest Texas State University 2000).

By 1740, Mission Concepción was running successfully, but still operating with temporary buildings and structures (Torres 1993). The construction of permanent stone buildings began shortly after, under the supervision of Fr. Francisco Xavier Ortiz (Torres 1993). By 1745, the mission complex contained a two-story house for the missionaries, three houses for soldiers, a granary, and the beginning of a new stone church, all surrounded by a stone wall (Torres 1993). By 1755, the construction of the church had finished, and it was officially dedicated on 8 December 1755 (Torres 1993)

As with Mission José, locally sourced tufa (**Qle** or **Qt**) was the primary building stone for Mission Concepción (Figure 6). The tufa was quarried on site, just outside the west and south walls of Mission Concepción, and although much of the quarry has been filled in, remnants of the quarry are still visible near the parking lot (Ewing 2008). The church walls, 45 inches (1.1 m) thick, were composed of adobe mixed with small stones and an external facing of tufa that was subsequently plastered and painted (Torres 1993; Ewing 2008). Carvings around the front portico were created from blocks of Austin Limestone (**Kau**), and chert fragments were used artistically around the blocks for decorative purposes (Ewing 2008).

Figure 6. Photographs of Missions Concepción. A) The façade of Mission Concepción. B) A close-up photo of the texture of the remnant plaster covering the tufa used in construction of the mission. The plaster was also created using locally available geologic resources. C) A close-up photo of the Austin Limestone carved for the portico on the mission along with the decorative chert placed in chiseled-out lines. D) Texture of the Concepción tufa. E) The location of one of the historic quarries that was utilized during the construction of Mission Concepción. Photos by Matthew Harrington (Colorado State University).

At its peak, Mission Concepción had a productive mission farm that utilized the acequia system to irrigate its croplands for bountiful harvests (Torres 1993). When the partial secularization decrees went into place in 1794, only 38 people inhabited the mission (Torres 1993). The population had one last peak of 53 people by 1809, and by 1819, the mission had been completely abandoned and had begun to deteriorate (Torres 1993).

During the Texas Revolution (1835–1836), a volunteer Texan army and a Mexican cavalry unit engaged in battle a mile from the Concepción complex, resulting in a win for the Texan army (Torres 1993). After the engagement, the Texans used Mission Concepción as a camp and staging area

(Torres 1993). Mission Concepción was used as a supply depot during the Mexican–American War (1846–1848), where it deteriorated further (Torres 1993). The mission was turned over to the Brothers of Mary in 1855, who cleaned up, restored, and reopened the church for services in 1861 (Torres 1993). The church building and part of the convento are the only remaining structures from Mission Concepción, but what remains is almost entirely original.

Mission San Juan

Mission San Juan Capistrano (Mission San Juan), originally established in Nacogdoches County in 1716 for the Nazoni and Nadaco Indigenous people, was relocated to San Antonio alongside Mission Concepción and Mission Espada in 1731 (Torres 1993). Smaller than the missions to the north (Mission San Juan was 3 miles away from San José), Mission San Juan experienced more difficulties than the larger missions. Apache raids around the mission made travel to and from the mission dangerous, and discontent amongst the converted Indigenous people led to mass abandonments (Torres 1993).

The construction of stone buildings within Mission San Juan was also laced with difficulties. The original thatch-roofed chapel wasn't replaced by a stone chapel until 1756, and construction on a larger stone church was started but never completed (Torres 1993). Interestingly, Austin Limestone (**Kau**) was not used in the construction of any of the Mission San Juan buildings or carved porticos (Ewing 1997). Furthermore, Concepción tufa is not present in any construction materials, unlike those at Missions Concepción and San José. Roughly 30% to 40% of the building stones within Mission San Juan were platy, ferruginous (iron-bearing rocks split into thin, flat, and sometimes even flaky sheets) Wilcox Formation sandstone (**Ewi**), and many had good small-scale cross-bedding (inclined layers of sediment within a horizontal bed, typically formed from deposition along dunes or ripples) (Figure 7; Ewing 2008). These blocks of Wilcox sandstone are similar to the Wilcox blocks at Mission San José. While the precise locality of where the Wilcox sandstone was quarried remains unknown, it was likely quarried from either the hills to the northeast of San Juan or from the exposed outcrops near the Espada Aqueduct (Ewing 1997).

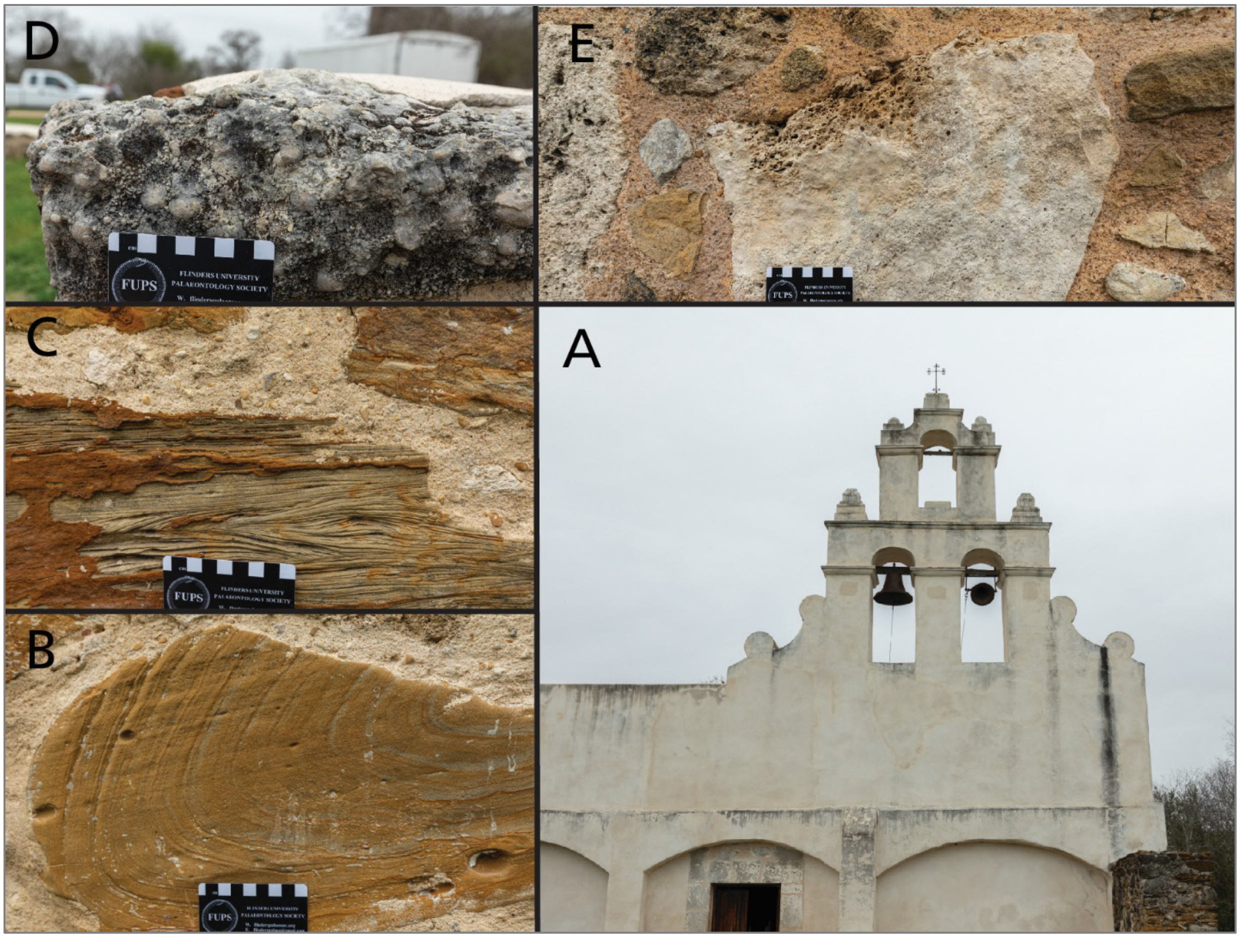

Figure 7. Photographs of Mission San Juan. A) A frontal view of Mission San Juan and its bells. B/C) Close-up photos of some of the unique textures preserved within the Wilcox sandstone, including cross-bedding. D) A close-up photo of the calcite-cemented conglomerate used within Mission San Juan. E) An example of the tufa (different from Concepción tufa) used at Mission San Juan. Note the difference in texture from the tufas in Figures 5 and 6. Photographs by Matthew Harrington.

The remainder of the building stones used at Mission San Juan were a wide variety of tufas (**Qle** or **Qt**) and calcite-cemented conglomerate (sedimentary rock composed of large, rounded clasts cemented together) sourced from the area (Ewing 1997). The tufa at Mission San Juan, used for cornerstones and other precise stone masonry, was fine-grained, even-textured, and porous with millimeter-sized holes (Ewing 1997). Texturally very different than the Concepción-area tufa, the source of Mission San Juan's tufa is unknown. The conglomerates used within Mission San Juan are common across the Leona Formation (**Qle**), recognizable by their characteristic pisolitic (rounded pebble) composition (Ewing 1997). Many filled-in pits have been recorded around the area, and large pits in what is now Stinson Field may have been a historic source for the stone (Ewing 1997).

By 1894, Mission San Juan's population had shrunk to only 36 Indigenous converts and to a small fraction of the once sizable mission livestock herds (Torres 1993). Unlike at Mission San José and Mission Concepción, the church remained in good condition through 1815, as the final missionary for the San Antonio missions was stationed there (Torres 1993). Eventually, the chapel roof collapsed in 1890, but the overall layout of the mission remained intact in contrast to the larger missions to the north (Torres 1993). Restoration efforts at Mission San Juan began in the early 1900s and were in full force by the 1960s.

Mission Espada

Mission San Francisco de la Espada, originally established near the Neches River in present-day Houston County in 1690, was reestablished in San Antonio in 1731. Mission Espada was located the furthest away from town and the presidio, established on the western bank of the San Antonio River, roughly 1.5 miles south of Mission San Juan (Torres 1993).

No permanent structures existed until the 1740s, when the first stone church was completed (Torres 1993). By 1762, work had begun on a larger, second church, but access to good building stone was limited, and Mission Espada's worsening financial situation made it impossible to import stone from quarries closer to the upper San Antonio missions (Ewing 1997). Of the permanent buildings that were completed, around 80 to 85% of the stone used was Wilcox sandstone (**Ewi**) (Figure 8; Ewing 2008). The remaining stone used in the mission structures was Quaternary carbonate-rich rocks (**Qle** or **Qt**) derived from local terraces along the San Antonio River (Ewing 2008). These rocks were primarily fine-grained tufa (texturally distinct from Concepción tufa) and pisolitic conglomerate (pea-sized spherical grains cemented together to form a conglomerate). Tufa was used in the carved trefoil arch on the church door at the mission (Ewing 2008).

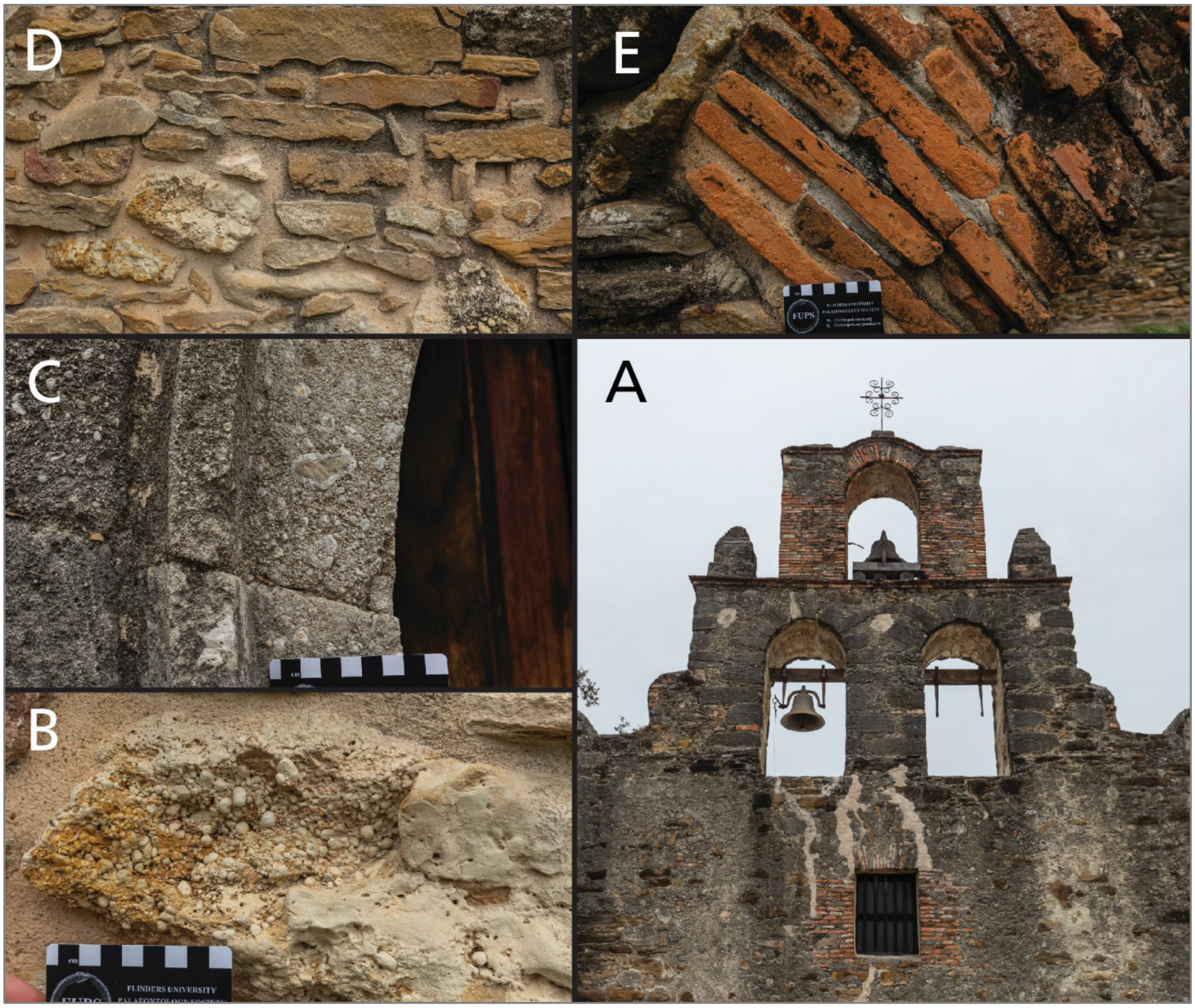

Figure 8. Photographs of Mission Espada. A) A frontal view of Mission Espada and its bells. B) Pisolitic conglomerate used in the construction of Mission Espada. C) Fine-grained tufa used in the trefoil arch on the front of Mission Espada. D) Platy Wilcox sandstone slabs used heavily across Mission Espada. E) Across Mission Espada, bricks sourced from the local Midway claystone are commonly utilized. Photos by Matthew Harrington (Colorado State University).

Many of the bricks used in Mission Espada's construction were sourced from local Midway claystone (**Emi**), which outcrops near the mission complex (Ewing 2008). Historic quarries for the Midway claystone have not been located but were likely in proximity to Mission Espada (Ewing 1996). The local abundance of Midway claystone led to a flourishing brick manufacturing industry in late colonial times (Ewing 1997). The Espada Aqueduct, the only remaining (and functioning) Spanish aqueduct in the United States, was built between 1731 and 1740 to allow the Espada Acequia to cross the historic San Piedras Creek in order to irrigate the mission's fields to the south (Ewing 2008). Nice outcrops of thickly laminated Wilcox limestone (**Ewi**) are exposed beneath the aqueduct. The Espada Aqueduct is supported by two stone arches—12 feet (3.7 m) and 16.5 feet (5 m) in diameter—and stretches 195 feet (59.5 m) long (Baker et al. 1974).

As with Mission San Juan, the population of people at Mission Espada had dwindled down to 45 by the time of its partial secularization, with only a remnant of the former livestock herds (Torres 1993). The passage of final secularization was accompanied by neglect, and during the Texas Revolution in 1836, American soldiers took over the complex (Torres 1993). A Mexican attack on the mission was repelled due to the Americans' strategically defensive position within its walls (Torres 1993). The first restoration of Mission Espada began in 1858, when Fr. Francis Bouchu began rebuilding the church, of which only the façade and rear wall were still standing (Torres 1993). Additional reconstructions occurred throughout the 1900s.

Associated with Mission Espada, Rancho de las Cabras was built in the 1750s after San Antonio residents complained that the mission livestock were trampling crops (Texas Beyond History 2006). It was located 32 miles southeast of Mission Espada along the San Antonio River and initially consisted of four jacals (structures built with upright poles and thatched roofs), pens, corrals, and a field. It was upgraded in the 1770s to include a full sandstone wall (likely composed of **Ew** sandstone; possibly **Eqc** or **Es** sandstones), a chapel, and defensive towers (Figure 9) (Taylor and Fox 1985). The rocks used in the construction of the stone structures are believed to have been quarried on site (Allison Young, San Antonio Missions National Historical Park, Division Lead, Resource Management [Natural and Cultural], personal communication, 24 February 2023). All that remains at the site today are ruins and artifacts from when the ranch was active.

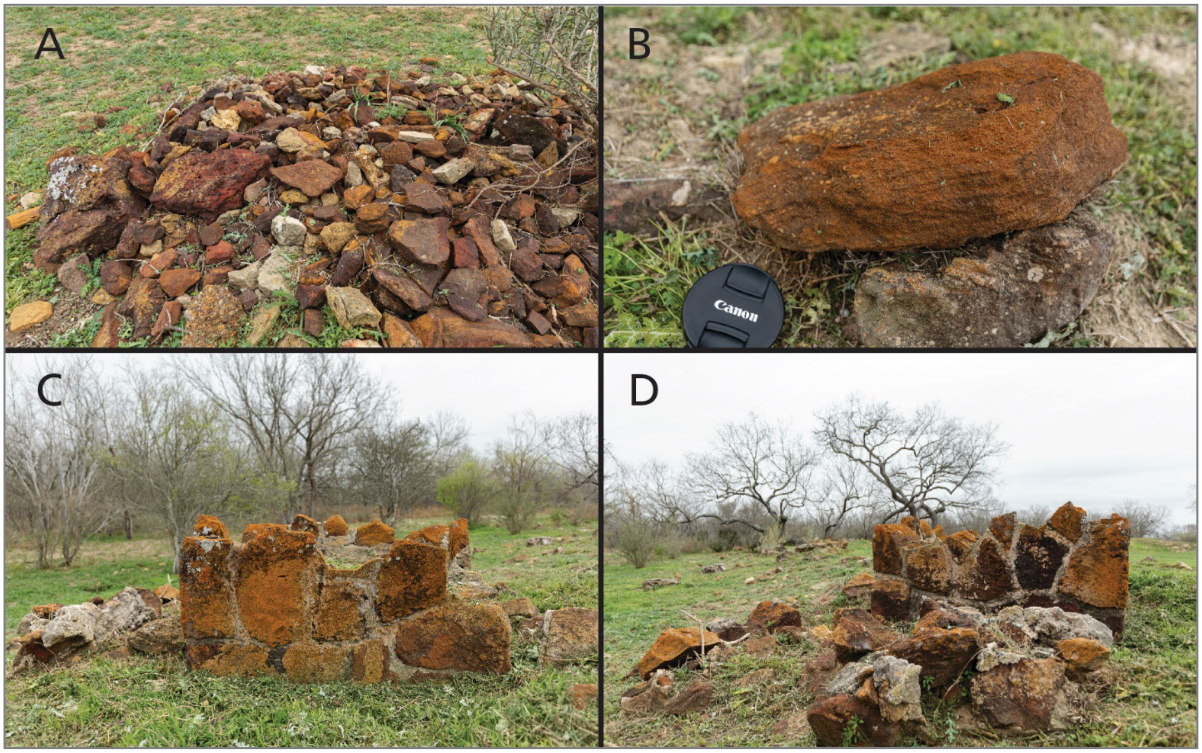

Figure 9. Photographs of Rancho de las Cabras. A) A pile of rocks, primarily sandstones, which were created when community members who had taken them from the site later returned them after learning of their significance. B) A close-up photo of one of the sandstone blocks, likely quarried from the Weches Formation. C/D) The ruins of some of the former structures at Rancho de las Cabras, composed of sandstone. Photographs by Matthew Harrington (Colorado State University).

Geologic History

This chapter describes the geologic events that formed the present landscape. Events are discussed more-or-less in order of geologic age (oldest to youngest). Table 1 shows the divisions of geologic time. The geologic events that led to the park's present-day landscape began more than 90 million years ago during the Cretaceous Period.

Table 1. Geologic time scale. The geologic time scale puts the divisions of geologic time in stratigraphic order, with the oldest divisions at the bottom and the youngest at the top. Cell colors correspond to USGS suggested colors for geologic maps. Items in parentheses include GRI map abbreviations for geologic time units. For example, "K" in a map unit symbol means that a map unit was deposited during the Cretaceous Period. Where no geologic time subdivision exists, "n/a" indicates not applicable. Boundary ages are millions of years ago (MYA) and follow the International Commission on Stratigraphy (2022).

Eon	Era(s)	Period(s)	Epoch(s)	MYA
Phanerozoic	Cenozoic	Quaternary (Q)	Holocene (H)	0.0117–today
	Cenozoic	Quaternary (Q)	Pleistocene (PE)	2.6–0.0117
	Cenozoic	Neogene (N)	Pliocene (PL)	5.3–2.6
	Cenozoic	Neogene (N)	Miocene (MI)	23.0–5.3
	Cenozoic	Paleogene (PG)	Oligocene (OL)	33.9–23.0
	Cenozoic	Paleogene (PG)	Eocene (E)	56.0–33.9
	Cenozoic	Paleogene (PG)	Paleocene (EP)	66.0–56.0
	Mesozoic	Cretaceous (K)	Upper, Lower	145.0–66.0
	Mesozoic	Jurassic (J)	Upper, Middle, Lower	201.3–145.0
	Mesozoic	Triassic (TR)	Upper, Middle, Lower	251.9–201.3
	Paleozoic	Permian (P)	Lopingian, Guadalupian, Cisuralian	298.9–251.9
	Paleozoic	Pennsylvanian (PN)	Upper, Middle, Lower	323.2–298.9
	Paleozoic	Mississippian (M)	Upper, Middle, Lower	358.9–323.2
	Paleozoic	Devonian (D)	Upper, Middle, Lower	419.2–358.9
	Paleozoic	Silurian (S)	Pridoli, Ludlow, Wenlock, Llandovery	443.8–419.2
	Paleozoic	Ordovician (O)	Upper, Middle, Lower	485.4–443.8
	Paleozoic	Cambrian (C)	Furongian, Miaolingian, Series 2, Terreneuvian	538.8–485.4
Proterozoic	Neoproterozoic (Z)	Ediacaran, Cryogenian, Tonian	n/a	1,000–538.8
	Mesoproterozoic (Y)	Stenian, Ectasian, Calymmian	n/a	1,600–1,000
	Paleoproterozoic (X)	Statherian, Orosirian, Rhyacian, Siderian	n/a	2,500–1,600
Archean	Neo-, Meso-, Paleo-, Eo-archean	n/a	n/a	4,000–2,500
Hadean	n/a	n/a	n/a	~4,600–4,000

Table 2 shows the geologic units in the GRI GIS data for the park, and it provides information on each unit's lithology, spatial location, age, and fossil resources. Each geologic unit is represented by a map symbol (series of letters) and color in the GRI GIS data and on the GRI poster. The map symbol consists of an uppercase letter indicating age (e.g., **Q** for Quaternary) and lowercase letters indicating the rock formation's name or the type of deposit (e.g., **al** for alluvium).

Table 2. Geologic units in the San Antonio Missions National Historical Park GRI GIS data.

Map Unit [A]	**Age**	**Description and Spatial Distribution**	**Fossils**
Alluvium (**Qal**)	Holocene	Floodplain deposits **Qal** can be found near Mission Concepción, particularly in Concepción Park.	No fossils within park boundaries
Fluviatile Terrace Deposits (**Qt**)	Pleistocene	Fine calcareous silt grading down into coarse gravel **Qt** is the dominant unit within the park's boundaries, accounting for 90% of the park's surface	Mammoth fossils in low abundance; terrestrial gastropods fossils; no fossils within park boundaries
Leona Formation (**Qle**)	Pleistocene	Gravel, sand, silt, and clay; adjacent to Edwards Plateau, predominantly gravel, limestone and chert; southeastward increasing amounts of sand, silt, and clay **Qle** is located east/southeast of Mission San Juan and beneath Mission Concepción	Mammoth fossils in low abundance; terrestrial gastropods fossils; no fossils within park boundaries
Uvalde Gravel (**QTu**)	Pleistocene or Pliocene	Caliche-cemented gravel; some boulders up to one foot in diameter; well-rounded cobbles of chert, some cobbles of quartz, limestone, and igneous rock; occupies topographically high areas not associated with present drainage **QTu** is not found within the park boundary, but is located just east of the San Juan Dam	No fossils within park boundaries
Yegua Formation (**Ey**)	Eocene	Sandstone: mostly quartz (some chert), fine-grained, indurated to friable, calcareous, glauconitic, massive and laminated, crossbedded; clay is lignitic, sandy, bentonitic, silty, mostly well laminated, chocolate brown to reddish brown, lighter colored upward **Ey** is not found within the park boundary	Fossil wood; no fossils within park boundaries
Cook Mountain Formation (**Ecm**)	Eocene	Clay: gypsiferous, slightly silty and lignitic, minor glauconite, brown to brownish gray, weathers brownish gray to yellowish gray; sandstone near top and at base, very fine-grained, calcareous, glauconitic, gray to yellowish brown **Ecm** is not found within the park boundary	Marine megafossils and microfossils abundant; no fossils within park boundaries

[A] Cell colors correspond to geologic unit colors in the GRI GIS Data and poster. Letters in parentheses are the map symbols from the GRI GIS data and poster.

Table 2 (continued). Geologic units in the San Antonio Missions National Historical Park GRI GIS data.

Map Unit [A]	Age	Description and Spatial Distribution	Fossils
Sparta Sand (**Es**)	Eocene	Quartz sand: very fine- to fine-grained, well sorted, micaceous, some silty clay partings and interbedded siltstone, light gray to pale orange to grayish brown; weathers yellowish brown to reddish brown **Es** is not found within the park boundary, but is located just east of Ranchos de las Cabras across the San Antonio River	No fossils within park boundaries
Weches Formation (**Ew**)	Eocene	Greensand: mostly glauconite, in part marly; quartz sand common, pale green to yellowish brown; interbedded clay, silty, glauconitic, dark brown to chocolate brown; weathers light to dark reddish brown **Ew** comprises the western half of the Rancho de las Cabras unit	No fossils within park boundaries
Queen City Sand (**Eqc**)	Eocene	Sandstone: fine to medium grained, well sorted, noncalcareous, friable to indurated, commonly massive, may be finely laminated, crossbedded, light gray to yellow-orange; siltstone, light gray, friable, thin interbeds of clay, sandy, silty, light gray to olive green; weathers mottled red and white **Eqc** is not found within the park boundary	No fossils within park boundaries
Reklaw Formation (**Er**)	Eocene	Sandstone: fine to medium grained, abundant hematite, muscovite, and glauconite, friable to highly indurated, thin bedded to massive, well-developed cross-bedding; clay, silty, lignitic, chocolate brown to light gray, weathers moderate brown and dark yellowish orange **Er** is not found within the park boundary	Pelecypod casts; no fossils within park boundaries
Carrizo Sand (**Ec**)	Eocene	Sandstone: medium to very coarse grained up to size of rice, finer grained toward top, poorly sorted, friable to locally indurated, noncalcareous, thick bedded, light yellow to orange and brown; weathers yellowish brown, locally iron-oxide banded; characterized by ridges thickly forested with oak in eastern part of sheet **Ec** is not found within the park boundary	Fossils are rare; Wilcox-aged leaf fossils in the middle section; no fossils within park boundaries

[A] Cell colors correspond to geologic unit colors in the GRI GIS Data and poster. Letters in parentheses are the map symbols from the GRI GIS data and poster.

Table 2 (continued). Geologic units in the San Antonio Missions National Historical Park GRI GIS data.

Map Unit [A]	**Age**	**Description and Spatial Distribution**	**Fossils**
Wilcox Group (**Ewi**)	Eocene	Mostly mudstone with varying amounts of sandstone and lignite; in uppermost and lowermost parts commonly glauconitic; mudstone. massive to thin bedded, some silt and very fine sand laminae, pale brown to yellowish brown in upper part, medium to dark gray, weathering yellowish gray in lower part; sandstone in upper part, medium to fine-grained, light gray to pale yellowish brown, in lower part very fine-grained, yellowish brown to moderate brown, lignite mostly near middle; lower boundary not readily mappable because of gradation into Midway Group **Ewi** can be found along parts of the Acequia de San Juan and beneath the Espada Aqueduct	Marine invertebrates and plant fossils in low abundance; no fossils within park boundaries
Midway Group (**Emi**)	Paleocene	Clay and sand: clay, silty, sandy, silt and sand more abundant upward grading to mudstone and sand of Wilcox Group, light gray to dark gray; sand, glauconitic to very glauconitic in lower part, argillaceous, poorly sorted, phosphatic nodules and pebbles common in lowermost part, weathers to yellow and yellowish-brown soil **Emi** can be found along the eastern outskirts of the San Juan Dam and New Espada Dam and just outside park boundaries east of Mission San Juan and west of the Labores de Espada	Marine fossils present, but rarely abundant; fossil plants can be found; no fossils within park boundaries
Navarro Group and Marlbrook Marl, undivided (**Knm**)	Upper Cretaceous	Upper part—marl and clay, glauconitic, contain concretions of limonite and siderite; sandstone, fine-grained, and siltstone, yellow brown, contain concretions of hard bluish-gray siliceous limestone 2 to 10 feet in diameter; sandstone beds have little lateral continuity and become more abundant westward; thickness up to 580 feet. Lower part—clay, dominantly montmorillonitic, unctuous, greenish gray to brownish gray; weathers to a very thick, black, clayey soil **Knm** is not found within the park boundary	Locally abundant; oysters can be common; shark teeth have been found; no fossils within park boundaries

[A] Cell colors correspond to geologic unit colors in the GRI GIS Data and poster. Letters in parentheses are the map symbols from the GRI GIS data and poster.

Table 2 (continued). Geologic units in the San Antonio Missions National Historical Park GRI GIS data.

Map Unit [A]	Age	Description and Spatial Distribution	Fossils
Pecan Gap Chalk (**Kpg**)	Upper Cretaceous	Chalk and chalky marl, more calcareous westward, very light yellow to yellowish brown, weathers to form moderately deep soil, seldom exposed; Exogyra ponderosa common; thickness 100–400 feet, thins westward to eastern Medina County where it is overlain by Anacacho Limestone, beyond this point included with Austin Chalk **Kpg** is not found within the park boundary	No fossils within park boundaries
Austin Chalk (**Kau**)	Upper Cretaceous	Chalk: mostly microgranular calcite with minor foraminifera tests and Inoceramus prisms, averages about 85 calcium carbonate, ledge forming, grayish white to white; alternates with marl, bentonitic seams locally, recessive, medium gray, sparsely glauconitic, pyrite nodules in part feathered to limonite common, occasional beds with large-scale cross-stratification; locally highly fossiliferous **Kau** is not found within the park boundary	Locally highly fossiliferous; used as building stone in Missions San José and Concepción

[A] Cell colors correspond to geologic unit colors in the GRI GIS Data and poster. Letters in parentheses are the map symbols from the GRI GIS data and poster.

Cretaceous Period

The oldest exposed rocks both within and around the park are late Cretaceous in age (**Kau**, **Kpg**, and **Knm**; see Table 2 for more information on all geologic units). Older Mesozoic and Paleozoic rocks are exposed north of the park but are deeply buried and inaccessible within the modern park boundary. During the Cretaceous Period, a shallow sea labeled the Western Interior Seaway stretched from western Iowa to western Wyoming and from the Arctic Ocean to the Gulf of Mexico. With the seaway fully bisecting North America, the majority of what is now Texas was fully submerged throughout the late Cretaceous (Figure 10). Three large marine transgressions (sea level rises) within the Western Interior Seaway occurred during the late Cretaceous; the last of the three transgressions occurred during the Coniacian-Santonian stages (89.8 million–83.6 million years ago) of the late Cretaceous and led to the maximum expanse of the sea across Texas (Udden et al. 1916; Kauffman 1977). This last transgression also formed the Austin Chalk (**Kau**), a chalky, fossiliferous limestone that is the oldest exposed bedrock unit within the vicinity of the park (Rose 2016).

Figure 10. Paleogeography of the Western Interior Seaway of North America during the Late Cretaceous Period. Roughly 92 million years ago, most of Texas was completely submerged beneath an epeiric sea that bisected the continent of North America. This sea, named the Western Interior Seaway, went through multiple pulses of marine transgressions and regressions, eventually depositing the Austin Chalk during the final and largest pulse at the end of the Cretaceous. Paleogeographic map by Ron Blakey, North American Key Time Slices © 2014 Colorado Plateau Geosystems Inc.

With a depositional sea depth of approximately 300 to 600 feet (90 to 180 meters), the Austin Chalk (**Kau**) formed in quiet, clear-water marine-shelf conditions with little influx of clay or silt (Rose 2016). The Austin Chalk consists of primarily calcium carbonate sourced from the death assemblages of tiny marine invertebrates known as foraminifera and marine algae known as coccoliths. The warm, shallow sea during the late Cretaceous was full of abundant marine life and facilitated the abundant deposition of calcareous remains.

Following the large marine transgression of the Coniacian-Santonian stages, a substantial marine regression (sea level retreat) occurred during the Campanian and Maastrichtian stages (83.6 million–66.0 million years ago) of the late Cretaceous, almost completely draining the Western Interior Seaway by the end of the Maastrichtian (Rose 2016). The exception to this regressive cycle was the deposition of the Pecan Gap Chalk (**Kpg**), considered to be a final “last gasp” invasion of the seaway (Rose 2016). As the seaway continued to recede, the Navarro Group and Marlbrook Marl (**Knm**) were deposited primarily as marine mudstones and marls (an unconsolidated sedimentary rock or soil consisting of clay and lime) but trending sandier toward the upper parts of the Navarro, representing the gradual marine regression that was occurring (Rose 2016).

Paleocene and Eocene Epochs

By the beginning of the Cenozoic Era, the Western Interior Seaway had closed, and the mass extinction of dinosaurs, marine reptiles, pterosaurs, and countless other species had opened ecological niches that had been occupied for millions of years. Following the large marine regression that ended the Cretaceous, a short transgressive period in the early Paleocene deposited the Midway Group (**Emi**), a relatively thin marine mudstone representing the furthest western extent of the Gulf Coast during the Cenozoic (Rose 2016).

The upper Paleocene and early Eocene are represented by the Wilcox Group (**Ewi**), a terrigenous (material derived from the land or a continent) clastic unit deposited during a regression from the early Paleocene coastlines (Rose 2016). By the end of the Paleocene, the coastline had receded 100 miles from its early Paleocene position in the San Marcos Platform Region (a subsurface feature of Texas sometimes referred to as the San Marcos Arch; Rose 2016). Unlike the lower Wilcox Group (**Ewi**), which represents shallow marine deposition, the upper Wilcox Group (**Ewi**) consists of coastal plain and marsh sediments that were deposited on shore (Udden et al. 1916).

Throughout the Eocene, seas continued to fluctuate between advances and retreats, depositing units including the Reklaw Formation (**Er**), Weches Formation (**Ew**), and Cook Mountain Formation (**Ecm**) during transgressions, as well as the Carrizo Sand (**Ec**), Queen City Sand (**Eqc**), Sparta Sand (**Es**), and Yegua Formation (**Ey**) during regressions. Many of the regressional units were deposited in a deltaic environment in the Eocene coastal plain. By the end of the Eocene, the maximum regressional shoreline was only 50 miles inland from the modern shoreline and would not advance over San Antonio again (Rose 2016).

Oligocene and Miocene Epochs

Throughout the Oligocene and Miocene, the shoreline of the Gulf continued to recede, even dropping below the modern shoreline during the Miocene (Rose 2016). No units from the Oligocene or

Miocene are represented in the San Antonio area, but heavy deposition occurred throughout the two epochs along the entire Gulf Coastal Plain to the southeast. Starting in the Oligocene and accelerating into the Miocene, tectonic stress from mass accumulation of sediment along the Gulf Coastal Plain paired with upward forces along the San Marcos Platform led to faulting along the Balcones Fault Zone (Rose 2016).

As the Balcones Fault Zone formed high-angle faults, the Gulf Coastal Plain was lowered relative to the Edwards Plateau (a region bounded by the Balcones Escarpment to the south and east; the Llano Uplift and the Llano Estacado to the north; and the Pecos River and Chihuahuan Desert to the west), which was simultaneously uplifted (Udden et al. 1916). The Edwards Plateau (along with the Hill Country and Llano Uplift) block was uplifted over 1600 feet (490 meters) in the San Antonio to Austin section of the fault (Rose 2016). The main length of the Balcones Escarpment runs from Del Rio in the southwest to San Antonio, where it curves north toward Austin.

The abrupt uplift of the Edwards Plateau and adjoining highlands led to increased erosion, supplying heavy loads of sediment into newly forming wide alluvial fans across the coastal plains of the late Oligocene and Miocene. While the late Mesozoic and early Cenozoic were times of deposition in San Antonio, the middle Cenozoic is defined by heavy and almost continuous erosion (Udden et al. 1916). Using formation thickness projections, Rose (2016) projected that the Edwards Plateau, Llano Uplift, and Hill Country region eroded away an estimated 8000 cubic miles (33,000 km^3) of rock. Following the Balcones faulting, an additional 1300 cubic miles (5400 km^3) of Upper Cretaceous, Paleocene, and Eocene sediments that were uplifted along the gulfward side of the escarpment were also eroded away (Figure 11; Rose 2016). In a cross section starting at the Balcones Escarpment and ending at the Gulf of Mexico, rock units dip toward the southeast (toward the Gulf) in successive chronological order, with exposed Mesozoic-aged units in the high country and along the fault and Quaternary sediments along the Gulf (Figure 12).

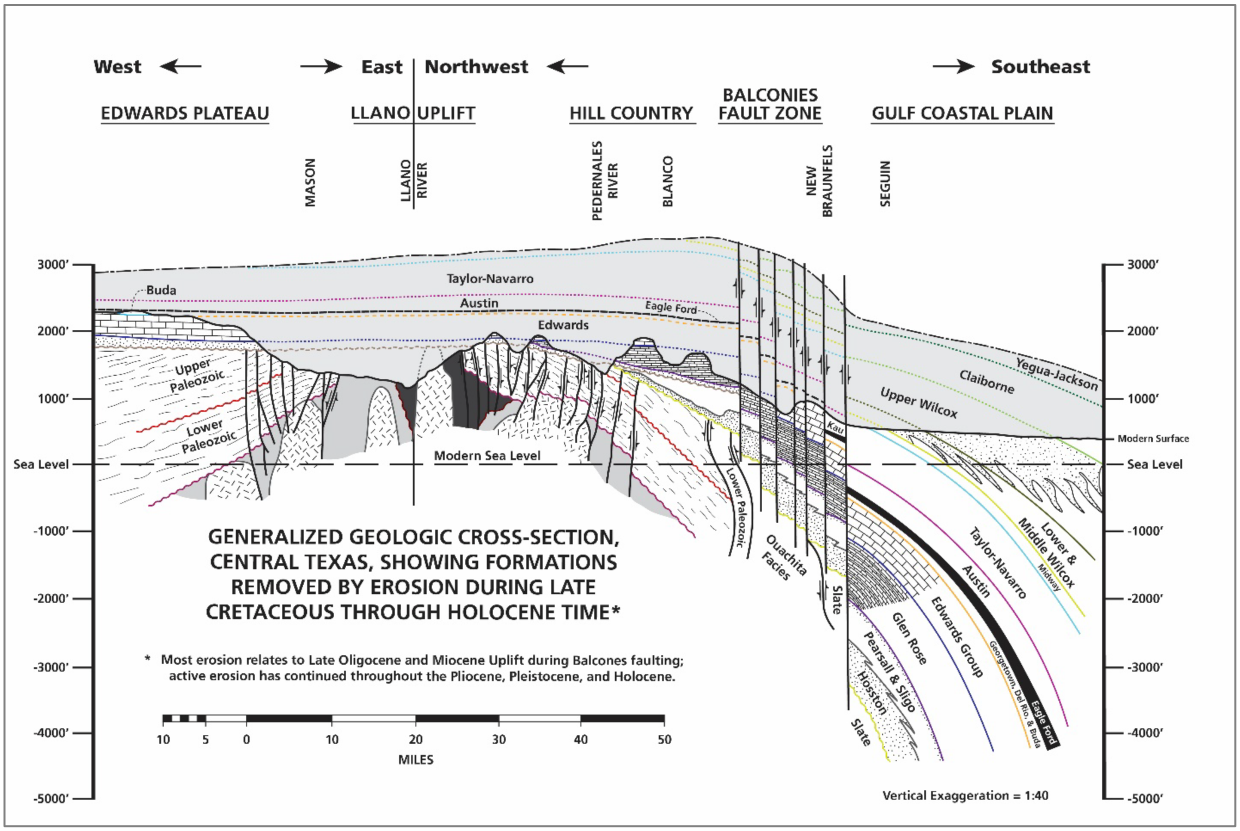

Figure 11. A geologic cross section of south-central Texas. San Antonio is located near New Braunfels (shown in figure). This cross section demonstrates how the geologic formation of the area spans from west to east until it reaches the Llano River, where it shifts to span northwest to southeast. The shaded area represents rock units that have been eroded away. The period of heavy erosion following the Balcones faulting in the Miocene led to the deposition of massive loads of sediment toward the Gulf. The weight of this sedimentation across the coastal plains aided in the downward dip seen in the cross section. Rocks dip toward the southeast in successive chronological order, capping off with exposed Mesozoic-aged rocks in the Hill Country north of San Antonio. Exposed rock formations become younger in age toward the southeast. Figure adapted from Rose (2016).

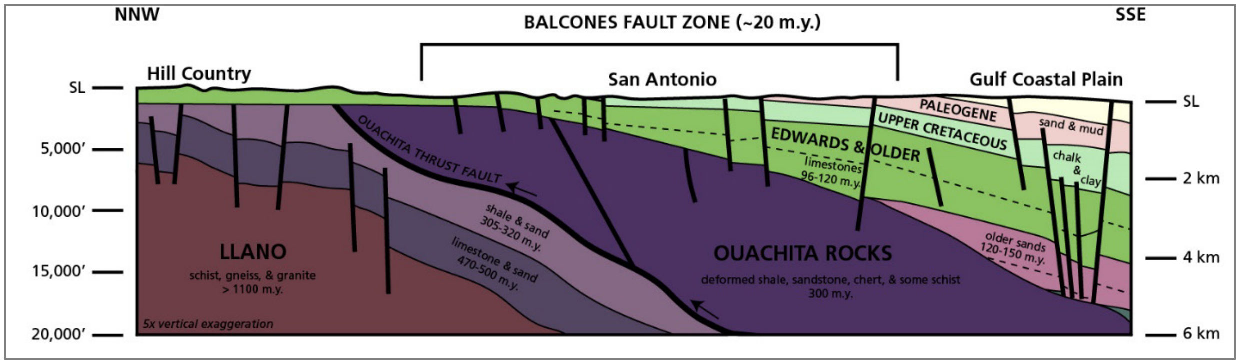

Figure 12. A simplified geologic cross section of Texas centered on San Antonio. This cross section highlights the major groupings of rocks underlying San Antonio and the park. Younger rocks crop out toward the south and southeast and older rocks lie to the north and northwest. Figure adapted from Ewing 2008).

The Balcones faulting also allowed the Edwards Aquifer to begin forming, a critical aspect of San Antonio's history. Meteoric waters (water from precipitation) were able to enter the exposed Edwards Group (not on the geologic map) underlying the Austin Chalk (**Kau**) and initiate the aquifer system (Rose 2016). The Edwards Aquifer and its relation to the springs of San Antonio and the San Antonio River will be discussed in more detail in the "Geologic Features, Processes, and Management Issues" section.

Pliocene, Pleistocene, and Holocene Epochs

The Pliocene and Pleistocene boundary in the San Antonio region is difficult to distinguish, and the Uvalde Gravel (**QTu**) is aged to be either late Pliocene or early Pleistocene in formation, or potentially both. The Pleistocene consisted of intense glacial-interglacial cycles that strongly affected the geology and landscape of North America. While the expansive ice sheets of the Pleistocene never reached Texas, the region was affected by the ice sheets to the north. During glacial cycles in the Pleistocene, Texas possessed a milder and more humid climate than today, with cooler summers and winters (Hentz 1952).

River and natural spring activity in the San Antonio region covered the landscape in Quaternary deposits, including river terraces, flood plains, gravel bars, and alluvium. The end of the Pleistocene saw the retreat of the massive ice sheets and the continental extinctions of most of the large megafaunal animals that roamed Texas during the Pleistocene. The Pleistocene-aged Leona Formation (**Qle**) consists of floodplain and terrace deposits that accumulated between the Uvalde Gravel (**QTu**) and late Pleistocene river terrace deposits (**Qt**; Sayre 1936). Floodplain deposits have been accumulating across the entirety of the Holocene (**Qal**).

Geologic Features, Processes, and Management Issues

This chapter highlights geologic features and processes significant to the park's landscape and history. Selection of these features and processes was based on input from scoping and conference-call participants, analysis of the GRI GIS data, and research of the scientific literature and NPS reports. Some geologic features, geologic processes, or human activities may require management for human safety, protection of infrastructure, or preservation of natural and cultural resources. The NPS Geologic Resources Division provides technical and policy assistance for these issues (see "Guidance for Resource Management"). The issues are ordered with respect to management priority.

At the beginning of each of the following sections, map units corresponding to the poster are listed; these indicate which map units are discussed in each section. Map units are referenced directly in the text as well. Some sections may not be directly related to a map unit on the poster, in which case no unit is listed at the start of the section. The map units can also be viewed in the GRI GIS data.

Fluvial Features and Processes

Map Units: **Kau**, **Kpg**, **Knm**, **Qal**, **Qt**

Edwards Aquifer

The Edwards Aquifer, which today supplies water for over 1 million people across an area of 8,000 square miles, fueled the many springs that first made the region enticing to early human populations (Ewing 2008). The aquifer itself exists within the Edwards Group, a collection of limestones ideal for hosting and transmitting water through underground conduits and caverns (Eckhardt n.d.). The Edwards Group sits on top of older impermeable rock and underlies younger, less permeable rocks, including the Austin Chalk (**Kau**), Pecan Gap (**Kpg**), and Navarro Group and Marlbrook Marl (**Knm**).

The aquifer is broken down into three primary zones, the contributing zone, the recharge zone, and the artesian zone (Eckhardt n.d.). The contributing zone catches rainfall and runoff, carrying the water in streams across relatively impermeable layers into the recharging zone (Eckhardt n.d.). In the Edwards Aquifer, the recharge zone is located along the Balcones Fault, where the Edwards Group is exposed (Ewing 2008). In this zone, streams and rivers flow over the Edwards Group and enter the permeable limestones, migrating underground (Figure 13). Because the limestones here have no overlaying rock, this zone is considered unconfined and possesses a water table that fluctuates based on precipitation levels (Ewing 2008; Eckhardt n.d.).

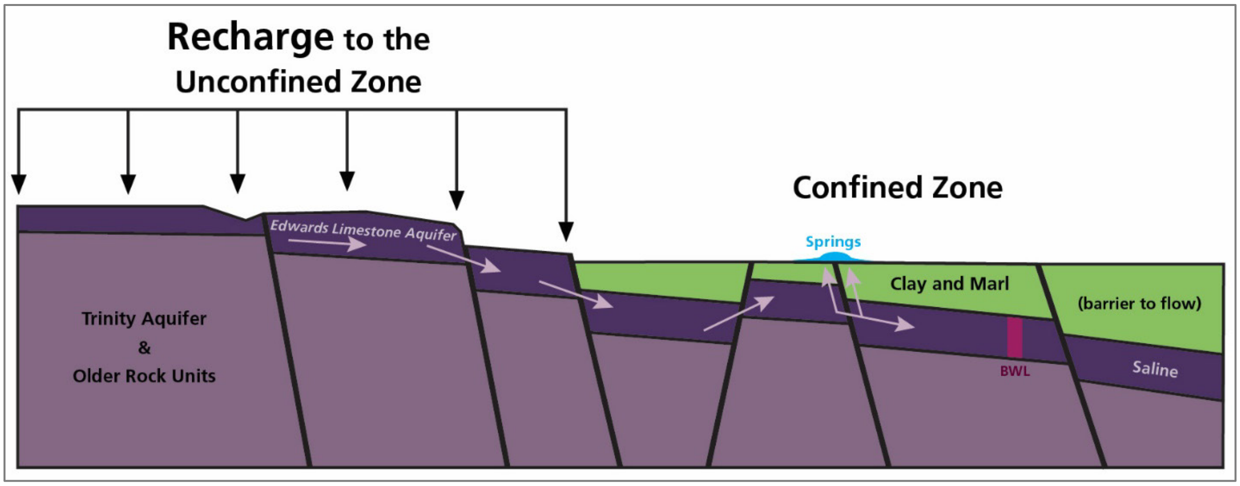

Figure 13. The Edwards Aquifer cross section. The Edwards Aquifer has played an integral role in the occupation of the greater San Antonio area for millennia. The aquifer, which recharges in the unconfined zone north of San Antonio, used to release large quantities of water in the form of springs. While most of these springs are dry today due to heavy water extraction from the aquifer, the Edwards Aquifer continues to provide essential water to the inhabitants of San Antonio. The bad water line (BWL) marks the transitional zone where freshwater becomes saline. Graphic adapted from Ewing (2008).

After entering the Edwards Group, the water has a residence time of 35 years, as it moves anywhere from 3 to 30 feet (1 to 9 meters) per day through the artesian zone (Ewing 2008). The artesian zone is a confined zone where the aquifer is contained between two impermeable layers. This zone can be up to 1500 feet (460 meters) beneath overlying claystone, chalk, and marl (Ewing 2008). The tremendous pressure from overlying rock and the weight of incoming recharge generate enough hydraulic pressure to force water up through faults and wells and onto the surface in the form of springs (Eckhardt n.d.). The major springs of the Edwards Aquifer are Comal Springs and San Marcos Springs, but smaller springs, including San Antonio Springs and San Pedro Springs, occur in faults across the Austin Chalk (Ewing 2008).

The bad water line forms where the highly transmissible water flows within the aquifer encounter more saline, less transmissible water flows that have a considerably higher residence time (Eckhardt n.d.). When the quantity of dissolved solids within the aquifer reaches 1000 ppm or greater, the water is considered saline (Eckhardt n.d.). During levels of low water and low recharge, it is possible for the bad water line to migrate deeper into the freshwater zone. As water extraction has increased to support San Antonio's growing population, monitoring the water levels of the aquifer has become a critical issue.

In the 1870s, when deep artesian wells were first drilled into the aquifer, water levels began to decline (Eckhardt n.d.). Since then, increasing amounts of water have been extracted from the aquifer, limiting, and all but prohibiting the once active spring flows of the San Antonio springs. Today, the springs in San Antonio only release water after severe flash flood-level rainstorms. Despite the lack of spring activity today in San Antonio, the hydrogeology and history of the springs are critical aspects of the park's landscape and history.

The San Antonio River

The San Antonio River and its springs were the lifeblood of both the Indigenous people who inhabited the region and the Spanish mission complexes. Historically, the San Antonio River's headwaters originated from a cluster of springs located north of present downtown San Antonio. Today, most of the water that flows in the San Antonio River is recycled water, runoff after precipitation, and water from the artesian well inside the San Antonio Zoo (Eckhardt n.d.). After decades of water extraction from the Edwards Aquifer, the springs are mostly dry year-round, apart from heavy precipitation events (Eckhardt n.d.).

Prior to historic modifications, the San Antonio River channel was sinuous (having many curves and turns) and flowed through a broad but fairly steep valley, where it deposited gravels and sediments in the flood plain (**QTu**, **Qle**, **Qt**, and **Qal**; Osburn et al. 2007). The modern San Antonio River in the Mission Reach area, which extends from Lonestar Boulevard south to Loop 410 South (approximately 8 miles), is almost unrecognizable from its historic form, with countless modifications and rechannelizations through bank stabilization, damming, filling, dredging, and flood control development projects (Osburn et al. 2007). These heavy modifications, spanning over two centuries, make identifying former channel patterns difficult to almost impossible.

The earliest modifications were made during the Spanish colonial period, when up to 15 miles of acequias were constructed around the five missions, the presidio, and the early town of San Antonio (San Antonio River Authority n.d.; Osburn et al. 2007). The Espada Acequia and a portion of the San Juan Acequia are still fully operational and in active use. The Spanish also constructed dams at the headwaters of each acequia, further altering the original flow of the river. The original Espada Dam still functions and is one of the oldest Spanish dams in North America.

Anglo American modifications to the San Antonio River began in the 1800s and continue to this day. Mills and millrace structures were built throughout the 1800s, followed by the construction of more modernized dams, such as the Olmos Dam in 1927, located north of the missions (Osburn et al. 2007). Bypass channels have also been excavated, most notably, cutting off the horseshoe bend in the San Antonio River near the Alamo, completed in 1929 (Osburn et al. 2007). The famous San Antonio Riverwalk, in the downtown area of the river, consists of stabilized riverbanks, bridges, sidewalks, and parks. The initial creation of the Riverwalk occurred between 1938 and 1941 (San Antonio River Authority n.d.).

The largest impacts on the San Antonio River channel occurred between the 1960s and 1980s, when major work to mitigate flooding issues was undertaken (Osburn et al. 2007). Across these decades, culverts, dams, and flood control facilities were built; the river channel was widened, straightened, and stabilized; adjacent soil and vegetation were removed; and massive amounts of fill were placed along the riverbanks (Osburn et al. 2007). These river channel modifications created the trapezoidal river channel seen today that allows reduced flooding through more efficient and enhanced floodwater discharge (San Antonio River Authority n.d.).

Drill cores taken from various river terraces indicate that the San Antonio River bedload (the part of the total stream load that is moved on or immediately above the stream bed), prior to modification, was predominantly sand and gravel, with silts and clays composing most of the overbank flood deposits (map units **Qal** and **Qt**). Natural terraces (abandoned floodplains) are very challenging to identify within the mission area. River modifications, including the deposition of significant construction fill adjacent to the channel and contouring, have removed or hidden most of the natural terraces (Osburn et al. 2007).

In recent years, the San Antonio River Authority has done extensive restoration work on the San Antonio River in the Mission Reach area (San Antonio River Authority n.d.). The San Antonio River floodplain has been widened; native riparian corridors have been restored; aquatic habitat features, including riffles and embayments, have been recreated; and native species of birds, fish, insects, and more have recovered (San Antonio River Authority n.d.). These projects, still ongoing, have helped return the river segment near the park to a healthier and less artificial state.

Riverine and Flash Floods

River basins in Texas are primarily impacted by four major precipitation mechanisms: tropical cyclones, westerly migrating cyclones (fronts), anomalous positions of the subtropical jet stream, and convectional thunderstorms (Hudson and Heitmuller 2008). Although the timing and location of cyclones originating in the Gulf of Mexico can vary, these storms often produce high intensity and long-lasting rainfall that can generate dangerous flooding (Slade and Patton 2002; Hudson and Heitmuller 2008). Westerly migrating cyclones, the dominant precipitation mechanism from late fall to spring, occur as cooler air masses from Canada or the Pacific Ocean clash with the warm, moist air of the Gulf of Mexico and deliver widespread precipitation along the contact boundaries (Hudson and Heitmuller 2008).

In the summer months, subtropical jet streams can route Gulf of Mexico moisture over Texas, producing sizable and persistent precipitation (Hudson and Heitmuller 2008). Convectional storms (thunderstorms) are smaller in scale, generally occurring in late spring and early summer, where moisture, gathered from local soil evaporation or the Gulf of Mexico, creates short but intense precipitation events (Hudson and Heitmuller 2008). These precipitation mechanisms, paired with Texas's high temperatures and runoff rates, create conditions for numerous and intense flash floods.

Topography has an impact on the four main precipitation mechanisms, especially along the Balcones Escarpment. The proximity of San Antonio to the Balcones Escarpment places it in a region prone to intense and extreme flash floods, as seen during major storms in 1998 and 2002, among others (Nielsen-Gammon et al. 2005; Hudson and Heitmuller 2008). The park brochure warns of flash flooding, and localized floods occur during rainfall events greater than 6 inches in the San Juan area (KellerLynn 2008; David Vekasy, San Antonio Missions National Historical Park, Chief, Facility Management, personal communication, 24 February 2023).

Flooding and runoff are also problems for maintaining the historic Mission-era buildings within the park. Limestone buildings absorb water, leading to instability, and excessive runoff from flash floods can lead to flooding and pooling around historic structures (KellerLynn 2008). Park staff have had to cut swales to channel pooling water away from historic structures in various locations (KellerLynn 2008). Sheetwash produces a large buildup of sediments within the acequias at Mission San José, which require periodic cleanup from park staff (KellerLynn 2008). For more information on the erosion and management concerns for the acequias, see the "Erosion and Hillslope Features and Processes" section.

Within the Rancho de las Cabras unit, Picosa Creek, which is natural and not channelized, flows through the center of the unit and creates an arroyo system (a steep-sided gully) through flooding. A portion of the unit is a floodplain for both Picosa Creek and the San Antonio River. The Spanish colonial-era ruins at the unit are located well above the flood plain and arroyo, and they are not at immediate risk for flooding damage.

Erosion and Hillslope Features and Processes

Most erosional issues at the park stem from heavy precipitation that leads to slumping along the creeks and acequias. Heavy rain (see "Fluvial Features and Processes" for more information) leads to high runoff. The density of urbanization around the missions, particularly at Missions Concepción and San José, causes increased peak runoff because of lower permeability surfaces (e.g., roads and parking lots) and more focused drainage (e.g., ditches). Increased peak runoff exacerbates the sloughing of sediments along river terraces (KellerLynn 2008).

Slumping also occurs within the acequias, threatening their structure and function. As acequias are still used as both agricultural and interpretive features, their preservation is of the utmost importance to the park. At the Espada Aqueduct, there are concerns that upstream modifications and disturbances could potentially threaten the structural integrity of the aqueduct and the flow path of Piedras Creek, which runs beneath the aqueduct (Figure 14; Carufel 2020).

Figure 14. The Espada Aqueduct in 1936 and 2023. Originally constructed in the 1730s, the Espada Aqueduct is the oldest Spanish aqueduct in the United States. Although most of the missions have seen considerable change since their initial construction, the Espada Aqueduct has successfully survived over 275 years of floods, storms, and urban expansion. The first photo shows the Espada Aqueduct in 1936. The second photo shows the Espada Aqueduct as it looked in 2023. In both photos, Piedras Creek, which flows beneath the aqueduct, has a similar pattern of flowing under the right arch of the aqueduct. The first photo was taken by an unknown Historic American Buildings Survey photographer, courtesy of David Vekasy, NPS. The second photo was taken by Matthew Harrington (Colorado State University).

In the late 1970s and early 1980s, a bypass channel was constructed to divert flood waters away from Piedras Creek and the Espada Aqueduct after storm flows were said to overtop the aqueduct by up to 6 feet (2 meters) (Baker et al. 1974). The new channel diverted all storm flows and high-water levels while allowing normal and low flows to continue into Piedras Creek (Carufel 2020). However, the channel may divert more water than intended, as Piedras Creek often appears stagnant. In addition to limiting water flow, the culvert at the bypass channel also modified sediment flow and the stream bed's slope. The impacts of these modifications on the aqueduct are still not fully understood, but initial work by Carufel (2020) suggests that the implementation of consistent streamflow measurement and the installation of scour control structures can aid in understanding and protecting the historic Espada Aqueduct.

Slumping and erosion along the Espada Acequia have carried sediment directly into the aqueduct, slowly clogging it and adding weight to the structure. Recent repair work on the aqueduct and the acequia in 2023 deepened the acequia's channel and removed over 30 cubic yards of sediment from the aqueduct (Figure 15; National Park Service 2023). Slumping along the acequia is evident from both the visible erosion and the downward slump of trees along the channel. As the acequia becomes silted up, maintenance is required to dig it up. This can lead to further erosion from water and landslides, leading to more sedimentation. This feedback cycle can be difficult to escape; as such, heavy caution is recommended before digging. A focus on minimizing erosion may be the best strategy for preserving the acequia and limiting sedimentation (Denny Capps, GRD, Geomorphologist, personal communication, 30 November 2023).

Figure 15. Views of the Espada Aqueduct. A) A view across the recently cleaned Espada Aqueduct from its top. Typically, water flows through the aqueduct channel over Piedras Creek. This channel requires occasional cleaning due to sediment accumulation. B) View of the acequia that leads into the Espada Aqueduct. This acequia was recently excavated to deepen the channel and allow for an easier flow of water into the aqueduct. Slumping does occur along the banks of this acequia. Both photos taken by Matthew Harrington (Colorado State University).

Slumping is also occurring near the lime kilns at Mission Espada (KellerLynn 2008). These kilns are historic features at the mission, and nearby slumping has the potential to damage or destabilize the kilns. In addition, the nature trail at Mission San Juan runs along the cut banks of the former San Antonio River channel and is also in danger of slumping (KellerLynn 2008). The cut banks in certain areas of the trail are quite high (over 8 feet [2 meters] tall) and are composed primarily of sediments. Future investigations may be necessary to identify the best plan of action for stabilizing the cut bank or mitigating the slumping (see “Guidance for Resource Management” section for more information).

Climate Change

Although climate change planning is beyond the scope of this GRI report, a discussion of climate change is included because of the potential disruption it may cause to the historical park’s resources, including geologic resources. Climate change was listed as a concern within the scoping summary and was also mentioned during conversations with park staff in 2023 (KellerLynn 2008). Park managers are directed to the NPS Climate Change Response Program (see “Additional References, Resources, and Websites”) to address climate change planning, which helps park managers develop plausible science-based scenarios that inform strategies and adaptive management activities that allow mitigation or adjustment to climate realities.

To best identify and predict hazards for informed adaptive management strategies, the ability to understand the effects of climate change on natural hazards is essential (Holmes et al. 2013). An NPS investigation into recent climate change exposures within the park highlighted the fact that recent climatic conditions within the park have already begun shifting beyond the historical range of variability (Monahan and Fisichelli 2014). Extreme heat has become more common, along with an increase in the mean annual temperature (Monahan and Fisichelli 2014). Climate change has the potential to impact not only the climate of the park, but also its wildlife, visitation, and geoheritage (Fisichelli and Ziesler 2015; Schuurman and Wu 2018).

Currently, the biggest climate change concern for park staff is the impact it will have on the acequias and the historical buildings and their foundations (Allison Young, San Antonio Missions National Historical Park, Division Lead, Resource Management (Natural and Cultural), personal communication, 24 February 2023). Acequias are critical to the park's history and story and have remained in continual use since their creation in the 1700s. There is a growing need for updated management plans with respect to increased storm intensity. In a meeting with the park, it was noted that wet/dry cycles should occur twice a year, but in recent years, the local climate has been either far too wet or far too dry, rarely with "normal" years in between (David Vekasy, San Antonio Missions National Historical Park, Chief, Facility Management, personal communication, 24 February 2023). This increased level of irregularity and storm intensity has the potential to harm foundational geoheritage sites within the park.

Karst Features and Processes

Map Units: **Kau**

Karst is a landscape characterized by internal drainage, caves, sinkholes, and springs that form through the dissolution of soluble rock (Toomey 2009). The Edwards Aquifer, the primary source of fresh water for this region of Texas, exists in karstic limestone that is prone to dissolution (KellerLynn 2008). Although most of the park exists on non-karstic Quaternary sediments, gravels, or conglomerates (**Qal**, **Qt**, and **QTu**), karstic features exist in spring deposits (tufa) near Mission Concepción (the tufa deposits are likely part of **Qle**). No springs are active in the vicinity of Mission Concepción today, but the tufa that underlies most of the mission was likely deposited by a now plugged-up spring (Ewing 1997).

In 2008, a sinkhole appeared at the corner of Mission Concepción, where it was subsequently filled and turned into an interpretive display (KellerLynn 2008). Dissolution in the tufa underlying the mission led to the formation of the sinkhole. Unlike Mission Concepción, the other three missions are not built on tufa but on clay and clay-heavy sediment (KellerLynn 2008). None of the other three missions have experienced any subsidence or sinkholes. Park staff indicated that since the sinkhole incident at Mission Concepción, no other natural sinkholes have appeared across the park (David Vekasy, San Antonio Missions National Historical Park, Chief, Facility Management, personal communication, 24 February 2023).

A more in-depth analysis of Mission Concepción's foundations was conducted in 2022 using high-resolution GPS equipment and ground penetrating radar (GPR). The study looked to better understand the topography changes within the foundation of Mission Concepción (Quintero 2022). Although the foundational bedrock of Mission Concepción is composed of tufa, the gravelly soil that overlays and wraps around the tufa is prone to washing away or filtering through the highly porous limestone (Quintero 2022). The dissolution of tufa (from reactions with acid rain), both in bedrock and building stone, remains a concern, and monitoring will need to be an ongoing process (Quintero 2022).

Caves are common across Bexar County, but they are primarily restricted to the northern part of the county, closer to the Balcones Escarpment (Veni 1988). Most of the caves in the northern part of the county form in the Edwards Group, with a handful forming in the Austin Chalk (**Kau**), Buda Formation, and Glen Rose Formation (Smith 1971). Within park boundaries, all these units are deeply buried and do not pose management concerns with respect to caves.

Disturbed Lands

Disturbed lands (lands impacted by human activities, both current and historic) disrupt natural processes and features across the entire National Park System. Although many of these disturbed lands do not fall within the mandates of the NPS, some of the disturbed lands include features that are cultural or historical in nature and require preservation and active management. Within the park area, sites of former labores (Spanish colonial-era fields) are being purchased, restored, and actively managed as functioning farm fields (KellerLynn 2008). The acequias are cultural features that, despite disrupting natural processes, are critical historical features of the park and are treated as such. Remnants of historic quarries, such as the potential quarry near the parking lot at Mission Concepción, are preserved as historic landscape features instead of disturbances.

Most landscape disturbances that require restoration and active management occur at the Rancho de las Cabras unit (KellerLynn 2008). When flash floods wipe out or damage fences constructed to keep out trespassers, cattle wander into the unit and promote erosion along riverbanks (KellerLynn 2008). Historic overgrazing at the site before its acquisition has led to an invasion of exotic mesquite (KellerLynn 2008). Feral pigs remain a concern at the Rancho unit and cause soil erosion, damage to native vegetation, and disruption to native fauna.

The many channelization projects along the San Antonio River during the mid-1900s led to the placement of sediments and soils removed from new channels onto park lands (KellerLynn 2008). For more information on the channelization and alteration of the San Antonio River, see the “Fluvial Features and Processes” section. Disturbances outside of park boundaries that can impact park resources include the jet-fuel refinery in San Antonio, nearby invasions of exotic plants, increased urban development, and storm water erosion (KellerLynn 2008). Further assistance or information on management needs in relation to disturbed lands can be found in the “Guidance for Resource Management Needs” section.

Geothermal Features and Processes

Hot springs, geysers, fumaroles, and mudpots are all considered geothermal features by the NPS (National Park Service 2020). No geothermal features exist within the boundary of the park, but a commercial hot spring near Mission San José named “Hot Wells” used to be a popular recreational site (KellerLynn 2008).

During its peak, the resort consisted of a beautiful hotel-bathhouse complex that was also the headquarters of a silent movie studio (Aguirre 2023). After several fires in the early- to mid-1900s, the building fell into ruin and stayed unused for decades (Aguirre 2023). As of 2023, a new operation exists at the site, named “Camp Hot Wells.” Although the hot springs are close to the park’s border, there is no indication that hot springs currently or historically existed within the park.

Paleontological Resources

Paleontological resources (fossils) are any evidence of life preserved in a geologic context (Santucci et al. 2009). They may be body fossils (any remains of the actual organism such as bones, teeth, shells, or leaves) or trace fossils (evidence of an organism's activity such as nests, burrows, tracks, or coprolites [fossil feces]). All fossils are nonrenewable. Fossils in NPS areas occur in situ in rocks or unconsolidated deposits, in museum collections, and in cultural contexts such as building stones or archeological resources.

Currently, there are no paleontological specimens within the park's museum collection, nor are there any fossils exposed in outcrops within the park's boundaries (Kenworthy et al. 2007). However, formations that are mapped within the park contain fossils outside the park boundaries, creating the potential for future finds within the park (Kenworthy et al. 2007). Fossils do occur in the park within various building stones at Mission San José and Mission Concepción.

The Midway Group (**Emi**), occurring near the eastern outskirts of the San Juan Dam and Espada Dam, and just outside park boundaries east of Mission San Juan and west of the Labores de Espada, contains marine fossils in other localities away from the park, but in low abundance (Sellards 1919). The most common marine fossils include shark's teeth, molds of bivalves (aquatic mollusks with hinged shells such as oysters, clams, or mussels), and the bivalves *Venericardia* and *Exogyra* (Sellards 1919; Ewing 1996). Plant fossils have also been recovered from the Midway Group near the town of Earle, located roughly 4 miles southwest of the park. These fossils include 10 species of *Pourouma* (tree-grape), *Ficus*, *Platanus* (sycamore), *Cinnamomum* (cinnamon), *Laurus* (laurel), *Asimina* (pawpaw), *Dolichites* (members of the pea or bean family Fabaceae/Papilionaceae), and *Terminalia* (almond) (Berry 1916; Kenworthy et al. 2007). None of these fossils have been recovered from the Midway Group within park boundaries.

The Wilcox Group (**Ewi**), primarily exposed beneath and around the Espada Aqueduct, also yields marine invertebrates and plants. Sellards (1919) does not reference specific fossils but does note the clam *Venericardia* as one species. Plants within the Wilcox Group are poorly preserved but are referenced in various exposures across Bexar County (Sellards 1919; Ewing 1996). No fossils have been reported from Wilcox exposures within park boundaries (Kenworthy et al. 2007).

The three levels of terrace gravels in San Antonio consist of the Uvalde Gravel (**QTu**), Leona Formation (**Qle**), and young terrace deposits (**Qt**), with each possessing varying abundances of fossils within Bexar County. The Uvalde Gravel, which is not exposed within park boundaries, is the least fossiliferous of the three terraces, with few if any known fossils recovered from the unit (Kenworthy et al. 2007).

The Leona Formation (**Qle**), which is near Mission San Juan and beneath Mission Concepción, is made up in part of fluvial oolites (small, accretionary spherical grains that form when a nucleus of sand or another particle is coated with concentric layers of calcium carbonate), which are known to contain fossil shells (Kenworthy et al. 2007). Some of these fossil shells include both whole and fragmented shells of *Goniobasis* and *Polygyra* (snails), *charophytes* (green algae), and blue-green algae (Kenworthy et al. 2007). These fossils have yet to be uncovered within park boundaries.

The lower terrace deposits (**Qt**) are the dominant unit across the park, accounting for over 90% of its surface area. These deposits are late Pleistocene in age, and fossils are abundant across the unit (Kenworthy et al. 2007). Fossils of the land snail *Bulimulus dealbatus mooreanus* have been reported as abundant in some San Antonio localities, and they can still be found in the area today (Sellards 1919; Kenworthy et al. 2007). Proboscidean remains, including fragments of Columbian mammoth (*Mammuthus columbi*) molars, tusks, and bones and American mastodon (*Mammut americanum*) molars, have been recovered all along the San Antonio and Medina Rivers (Hay 1924; Thoms et al. 2001; Carpenter et al. 2013). Because the park is located along significant stretches of the San Antonio River, it is conceivable that some of these teeth may have originated from within park boundaries. But without better information, it is challenging to source the origin of many of these finds (Justin Tweet, GRD, personal communication, 2 November 2023). Evidence of human modification of mammoth bone material has been suggested at both sites (Carpenter et al. 2013). Although mammoth remains or other late Pleistocene megafaunal fossils have yet to be recovered within the park, the possibility remains that new material could be exposed during erosional events along riverbanks and terraces. However, due to the intense reworking of the San Antonio River channel, banks, and terraces, new and unaltered exposures are unlikely.

While no fossils have been uncovered within bedrock units in the park, fossils do occur in building stones and, in one case, within a dump site at Mission Concepción. During an archeological investigation into Mission Concepción in 1982, a fossil horse tooth (*Equus* sp.) was discovered (Ivey and Fox 1999). The fossil was interpreted as having been picked up by a curious inhabitant and brought from elsewhere, highlighting that the fascination with curious objects (including fossils) has been an enduring trait of people for centuries (Ivey and Fox 1999).

The only fossils that are found within the park occur within building stones quarried outside of the current park boundaries. These building stone fossils occur only at Mission San José and Mission Concepción within carved blocks of Austin Chalk (**Kau**). No fossils are known within the building stones at Mission San Juan or Mission Espada. At Mission San José, the Austin Chalk used in the construction of the Rose Window and door frame contains abundant marine invertebrates such as the oyster species *Phrygia (Gryphaea) aucella* and *Exogyra laeviscula* (Sellards 1919; Kenworthy et al. 2007). The Rose Window was constructed of two different types of chalk, one more fossiliferous than the other (McDowell 1997). In the upper right side of the window, a finer, grained stone with only microfossils was used; in the flatter areas near the base, the chalk contained abundant fossil shells (McDowell 1997). This variation in chalk and fossils has led to different weathering rates for different parts of the structure (McDowell 1997). At Mission Concepción, similar marine invertebrates can be found within the Austin Chalk used in the portico (Figure 16). Some of the tubular structures found within the tufa at Mission Concepción may represent trace fossils of root casts (Ewing 1997).

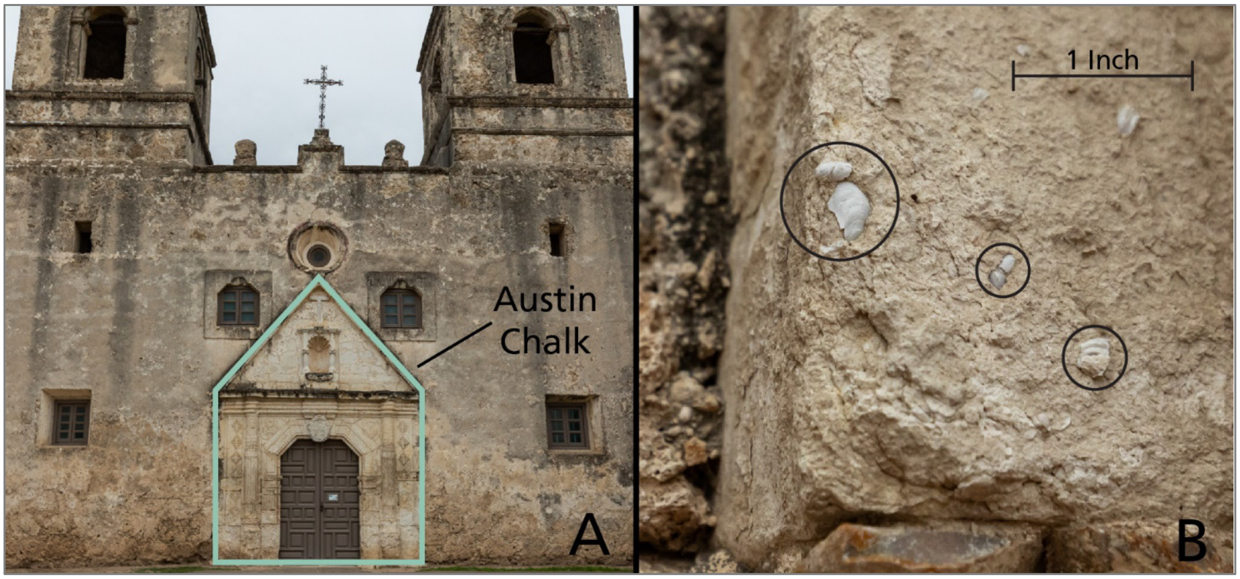

Figure 16. Paleontology within Mission Concepción. The portico on the front of Mission Concepción is composed of Austin Chalk, which allowed the stone masons to complete more intricate carvings that the locally abundant tufa did not. B) A close-up photo of fossil marine invertebrates within the Austin Chalk used in Mission Concepción's portico. These fossil shells represent a marine depositional environment for the Austin Chalk. Photos taken by Matthew Harrington (Colorado State University).

Oil and Gas Exploration and Development

Bexar County contains over 100 million barrels of crude oil, and since 1886, the first recorded instance of oil production, the county has produced over 38 million barrels of oil (Ewing 2008). Most of the oil reservoirs within the county occur in Upper Cretaceous units at depths of 275 to 3200 feet (84 to 980 meters) (Ewing 2008). The Taylor and Navarro Groups (**Knm**) contain high-quality oil in thin sandstone layers, and the Pecan Gap Chalk (**Kpg**) and Austin Chalk (**Kau)** contain oil within fractured limestone (Ewing 2008).

Relative to other counties in Texas, Bexar County currently produces low volumes of oil, producing only 44,519 barrels of oil in 2022 (compared to Midland County, which produced 215,205,730 barrels of oil in 2022) (Railroad Commission of Texas 2023). Wilson County, which contains the Rancho de las Cabras unit, produced 2,686,011 barrels of oil in 2022 (Railroad Commission of Texas, 2023). Both Bexar County and Wilson County produced negligible amounts of gas production during 2022 (Railroad Commission of Texas 2023).

Two pipelines cut through the Missions unit of the park boundary, either bordering a unit boundary or undercutting a roadway. The first, an 8-inch line carrying refined hydrocarbon liquids, lies adjacent to I-410 (Forrest Smith, National Park Service, Lead Petroleum and Environmental Engineer, personal communication, 27 July 2023). The second, a 20-inch natural gas pipeline, lies south of the first line and only bisects the Espada Acequia (Forrest Smith, National Park Service, Lead Petroleum and Environmental Engineer, personal communication, 27 July 2023).

Within the boundaries of Rancho de las Cabras, a 16-inch pipeline that primarily carries refined liquid hydrocarbons (diesel, gasoline, kerosene, etc.) runs beneath the roadway into the heart of the unit (Forrest Smith, National Park Service, Lead Petroleum and Environmental Engineer, personal communication, 27 July 2023). There are no oil or gas wells drilled within the unit, but several operations exist nearby (Forrest Smith, National Park Service, Lead Petroleum and Environmental Engineer, personal communication, 27 July 2023). Because no wells exist within park boundaries or in any proximity to the Missions unit of the park, oil and gas development remains a low management concern for the park.

Seismic Features and Processes

Seismic activity is considered low risk in the area of the park. The 2008 scoping summary noted that a 4.0 magnitude (on the Richter scale) earthquake was felt in 2008 (KellerLynn 2008). No damage was reported within the park. The United States Geological Survey (USGS) shows San Antonio in the region of lowest hazard for seismic activity (Figure 17). The Balcones Fault, located north and west of San Antonio, is no longer active and does not pose any significant seismic activity risk.

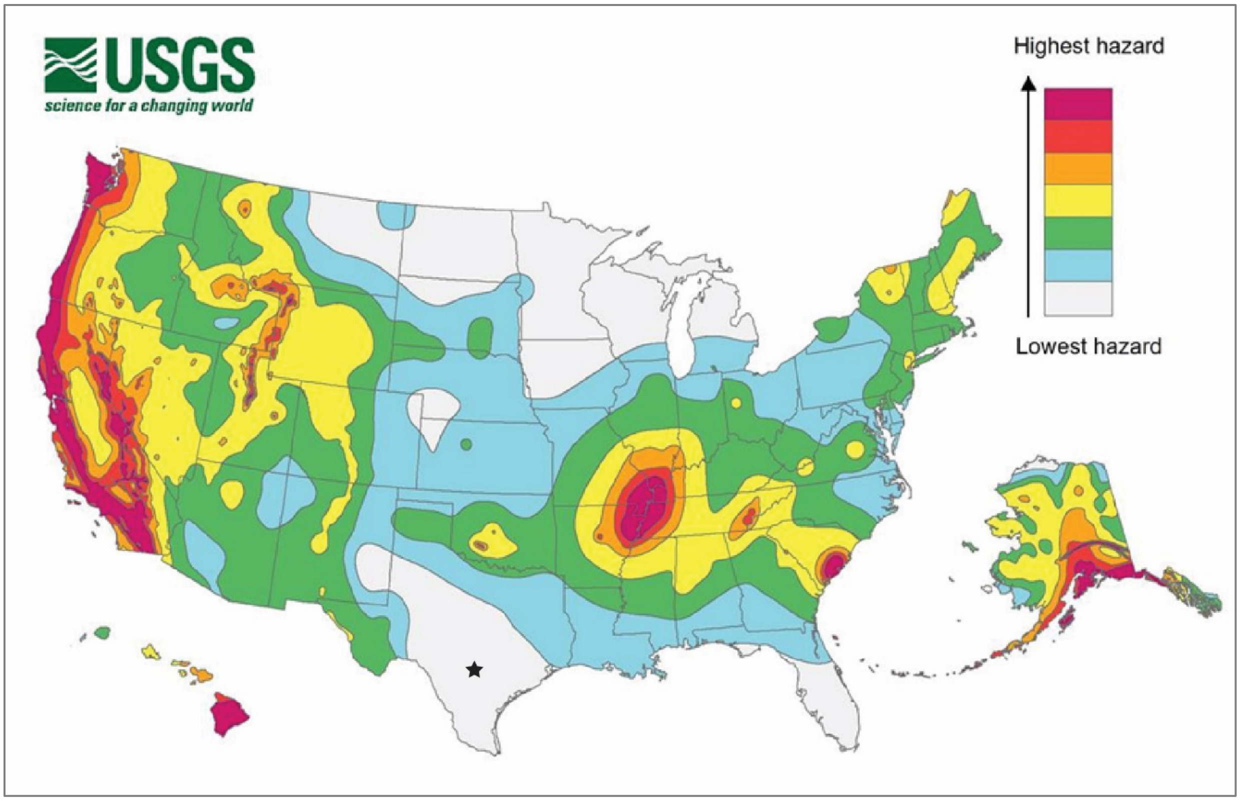

Figure 17. National seismic hazard map. Maps of earthquake shaking hazards provide information essential to creating and updating the seismic design provisions of building codes and insurance rates used in the United States. The map shows predicted earthquake hazards across the United States for the next 50 years based on the 2018 update of the National Seismic Hazard Models (https://www.usgs.gov/programs/earthquake-hazards/science/introduction-national-seismic-hazard-maps). The models are based on seismicity and fault-slip rates and consider the frequency of earthquakes of various magnitudes. Locally, the hazard may be greater than shown because site geology (particularly unconsolidated sediment) may amplify ground motions. Graphic by the US Geological Survey, available at https://www.usgs.gov/media/images/2018-long-term-national-seismic-hazard-map (accessed 24 February 2023).

The TexNet Seismic Observatory and the Center for Injection and Seismicity Research (CISR) at the University of Texas, managed by the Bureau of Economic Geology, collect high-quality seismic data across the state of Texas and engage in applied research to better understand both naturally occurring and potentially induced earthquakes (Figure 18; TexNet n.d.). This research often includes the associated risks and hazards to citizens and infrastructure within Texas. Park managers may find these resources and information useful for managing potential seismic activity within the park.

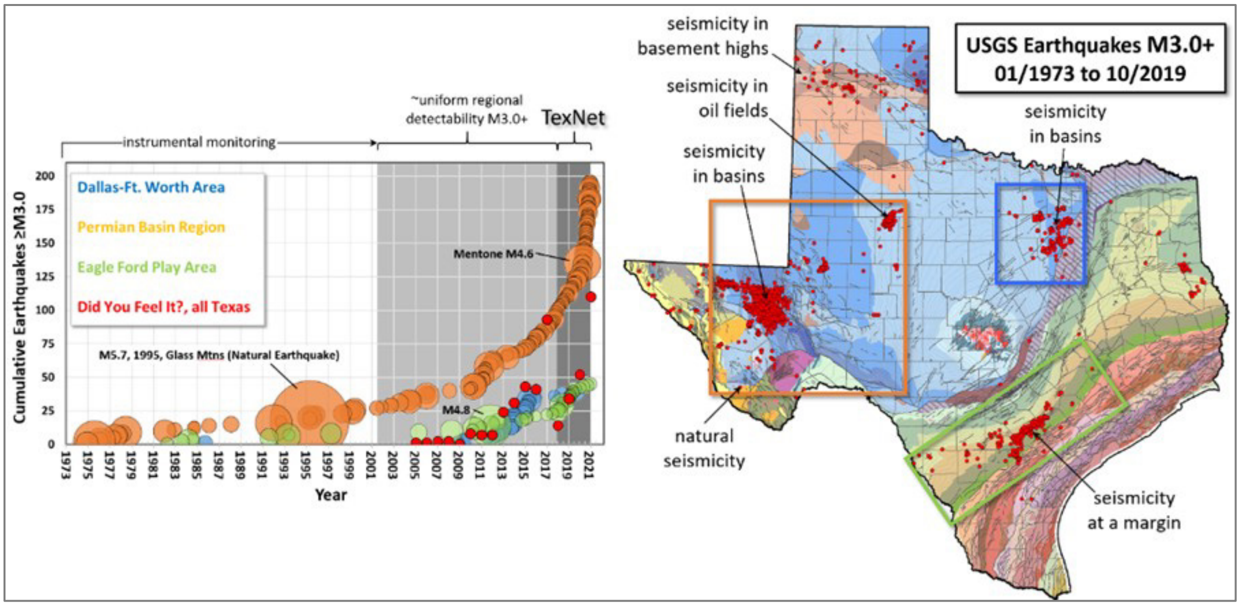

Figure 18. TexNet earthquake monitoring from 1973 to 2019. Since 1973, TexNet has monitored earthquakes across Texas. From 2001 to present, monitoring has become uniform across the state for all M3.0+ quakes. Although earthquakes are common south of San Antonio in the Eagle Ford Play Area (green box in figure), there are no recorded M3.0+ earthquakes with an epicenter near San Antonio. The use of this monitoring data can be helpful for park management. Graphic available at https://www.beg.utexas.edu/texnet-cisr (Accessed 26 April 2023).

Geologic Hazards

Park resources are not only visitor attractions but may also be potentially hazardous. The dynamic geologic landscapes preserved at many National Park System units present a variety of natural hazards that threaten NPS facilities, staff, and visitors. Geologic hazards are naturally occurring, dynamic geologic processes that have the potential to cause damage, loss of property, injury, and loss of life. Schaller et al. (2014) summarized and categorized the geologic hazards of the National Park System (Appendix A is a table of hazards at each of the 83 parks in the study). Geologic hazard categories include avalanches, cave and karst incidents, coastal and shoreline hazards, flooding, geothermal risks, glacial activity, mass wasting events, rockfalls, seismic activity, and volcanic hazards. The primary geologic hazards identified during the GRI process are slope movements, karst, riverine floods, and flash floods. Additional potential geologic hazards include earthquakes and shrink/swell soils (the extent certain clay minerals will expand when wet and retract when dry).

According to NPS Management Policies (2006), although the magnitude and timing of future geologic hazards are difficult to forecast, the NPS strives to understand hazards and, subsequently, minimize their potential impact on visitors, staff, and developed areas. NPS Policy Memorandum 15-01 (Jarvis 2015) directs NPS managers and their teams to proactively identify and document facility vulnerabilities to climate change and other natural hazards. The saving of human life will take precedence over all other management actions. The 1916 Organic Act, which, among other things, states that discretionary operations cannot harm park resources or values and must be in line with management standards, places restrictions on geologic hazard risk reduction initiatives. The NPS cannot totally control these risks; therefore, park visitors must assume a substantial degree of risk and responsibility for their own safety when visiting areas that are managed and maintained as natural, cultural, or recreational environments (National Park Service 2006). When discussing hazards and their associated risks, it is important to distinguish the difference between the two, as described in the following:

In the context of naturally occurring hazards, it is important to understand the distinction between ‘hazard’ and ‘risk.’ The level of ‘hazard’ (low, medium, high) refers to the likelihood that an event will occur. ‘Risk’ refers to the consequences of the hazard event (Holmes et al. 2013). Identifying geologic hazards, assessing the likelihood of occurrence, and defining potential risks to infrastructure or people can assist the National Park Service with the management of these hazards (quoted in Schaller et al. 2014, p. 1).

Management policies (National Park Service 2006) do not impose specific visitor safety prescriptions. This report presents recommendations for reducing risks related to geologic hazards, however, it is up to the discretion of decision-makers at the park level on whether, how, and when to implement these recommendations, which will be subject to the availability of funding and staffing as well as legal and policy considerations.

Recommendations may include the minimization of known hazards and the application of other appropriate measures, including closures of roads or trails, the installation of guard rails or fences, paving walkways, installing warning signs, and distributing weather advisories and other forms of education. Preferred actions are those that have the least impact on park resources and values. For example, safeguards such as fences and paved surfaces may negatively impact park resources and values (e.g., wilderness) and would therefore not be appropriate. Depending on the location within the park (i.e., ease of accessibility), these safeguards may not be practical. The placement of new facilities in geologically hazardous areas such as floodplains or flash flood zones could warrant careful planning. When it has been determined that building facilities in such areas is necessary, their design and siting would be based on a thorough understanding of physical processes and avoiding or minimizing risks to human life and property, as well as the effect a facility might have on the surrounding environment.

Guidance for Resource Management

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

Access to GRI Products

- GRI Products (scoping summaries, GIS data, posters, and reports): http://go.nps.gov/gripubs
- GRI products are also available through the NPS DataStore: https://irma.nps.gov/DataStore/Search/Quick. Enter "GRI" as the search text and select a park from the unit list.
- GRI GIS data model: http://go.nps.gov/gridatamodel

Three Ways to Receive Geologic Resource Management Assistance

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

Geological Monitoring

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

Park-Specific Documents

The park's Foundation Document (National Park Service 2016) is a primary source of information for resource management within the park. This document guided the writing of this GRI report.

NPS Natural Resource Management Guidance and Documents

- NPS Management Policies 2006 (Chapter 4: Natural Resource Management): https://www.nps.gov/policy/index.cfm
- National Parks Omnibus Management Act of 1998: https://www.congress.gov/bill/105th-congress/senate-bill/1693
- Natural Resources Inventory and Monitoring Guideline (NPS-75): https://irma.nps.gov/DataStore/Reference/Profile/622933
- Natural Resource Management Reference Manual #77 (NPS-77): https://irma.nps.gov/DataStore/Reference/Profile/572379
- Resist-Accept-Direct (RAD)—A Framework for the 21st-Century Natural Resource Manager: https://doi.org/10.36967/nrr-2283597
- San Antonio Missions National Historical Park Natural Resource Condition Assessment: https://irma.nps.gov/DataStore/Reference/Profile/2229095

Geologic Resource Laws, Regulations, and Policies

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

Geoheritage Resource Laws, Regulations, and Policies

Caves and Karst Systems

Resource-specific laws:

- **Federal Cave Resources Protection Act of 1988, 16 USC §§ 4301 – 4309** requires Interior/Agriculture to identify "significant caves" on Federal lands, regulate/restrict use of those caves as appropriate, and include significant caves in land management planning efforts. Imposes civil and criminal penalties for harming a cave or cave resources. Authorizes Secretaries to withhold information about specific location of a significant cave from a Freedom of Information Act (FOIA) requester.

- **National Parks Omnibus Management Act of 1998, 54 USC § 100701** protects the confidentiality of the nature and specific location of cave and karst resources.
- **Lechuguilla Cave Protection Act of 1993, Public Law 103-169** created a cave protection zone (CPZ) around Lechuguilla Cave in Carlsbad Caverns National Park. Within the CPZ, access and the removal of cave resources may be limited or prohibited; existing leases may be cancelled with appropriate compensation; and lands are withdrawn from mineral entry.

Resource-specific regulations:

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

NPS Management Policies 2006:

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

Geothermal
Resource-specific laws:

- **Geothermal Steam Act of 1970, 30 USC. § 1001** et seq. as amended in 1988, states:
    - No geothermal leasing is allowed in parks.
    - "Significant" thermal features exist in 16 park units (the features listed by the NPS at 52 Fed. Reg. 28793-28800 (August 3, 1987), plus the thermal features in Crater Lake, Big Bend, and Lake Mead).
    - NPS is required to monitor those features.
    - Based on scientific evidence, Secretary of Interior must protect significant NPS thermal features from leasing effects.
- **Geothermal Steam Act Amendments of 1988, Public Law 100-443** prohibits geothermal leasing in the Island Park known geothermal resource area near Yellowstone and outside 16 designated NPS units if subsequent geothermal development would significantly adversely affect identified thermal features.

Resource-specific regulations:

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

NPS Management Policies 2006:

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

Paleontological Resources
Resource-specific laws:

- **Archaeological Resources Protection Act of 1979, 16 USC §§ 470aa – mm Section 3 (1)** Archaeological Resource—nonfossilized and fossilized paleontological specimens, or any portion or piece thereof, shall not be considered archaeological resources, under the regulations of this paragraph, unless found in an archaeological context. Therefore, fossils in an archaeological context are covered under this law.
- **Federal Cave Resources Protection Act of 1988, 16 USC §§ 4301 – 4309 Section 3 (5) Cave Resource**—the term “cave resource” includes any material or substance occurring naturally in caves on Federal lands, such as animal life, plant life, paleontological deposits, sediments, minerals, speleogens, and speleothems. Therefore, every reference to cave resource in the law applies to paleontological resources.
- **National Parks Omnibus Management Act of 1998, 54 USC § 100701** protects the confidentiality of the nature and specific location of paleontological resources and objects.
- **Paleontological Resources Preservation Act of 2009, 16 USC § 470aaa** et seq. provides for the management and protection of paleontological resources on federal lands.

Resource-specific regulations:

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

NPS Management Policies 2006:

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

Energy and Minerals Laws, Regulations, and Policies

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

Resource-specific regulations: none applicable.

NPS Management Policies 2006: none applicable.

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

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

NPS Management Policies 2006: none applicable.

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

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

Resource-specific regulations: none applicable.

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

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

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

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

- **The Mineral Leasing Act, 30 USC § 181** et seq., and the Mineral Leasing Act for Acquired Lands, 30 USC § 351 et seq. do not authorize the BLM to lease federally owned minerals in NPS units.
- **Combined Hydrocarbon Leasing Act, 30 USC §181**, allowed owners of oil and gas leases or placer oil claims in Special Tar Sand Areas (STSA) to convert those leases or claims to combined hydrocarbon leases, and allowed for competitive tar sands leasing. This act did not modify the general prohibition on leasing in park units but did allow for lease conversion in GLCA, which is the only park unit that contains a STSA.
- **Exceptions:** Glen Canyon NRA (16 USC § 460dd et seq.), Lake Mead NRA (16 USC § 460n et seq.), and Whiskeytown-Shasta-Trinity NRA (16 USC § 460q et seq.) authorizes the BLM to issue federal mineral leases in these units provided that the BLM obtains NPS consent. Such consent must be predicated on an NPS finding of no significant adverse effect on park resources and/or administration.
- **American Indian Lands** Within NPS Boundaries Under the Indian Allottee Leasing Act of 1909, 25 USC §396, and the Indian Leasing Act of 1938, 25 USC §396a, §398 and §399, and Indian Mineral Development Act of 1982, 25 USCS §§2101-2108, all minerals on American Indian trust lands within NPS units are subject to leasing.
- **Federal Coal Leasing Amendments Act of 1975, 30 USC § 201** prohibits coal leasing in National Park System units.

Resource-specific regulations:

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

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

<u>Mining Claims (Locatable Minerals)</u>
Resource-specific laws:

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

Resource-specific regulations:

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

NPS Management Policies 2006:

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

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

Resource-specific regulations: **NPS regulations at 36 CFR Parts 1, 5, and 6** require the owners/operators of other types of mineral rights to obtain a special use permit from the NPS as a § 5.3 business operation, and § 5.7 – Construction of buildings or other facilities, and to comply with the solid waste regulations at Part 6.

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

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

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

  - 16 USC § 460m (Ozark NSR)
  - 16 USC§698c (Big Thicket N Pres.)
  - 16 USC §698f (Big Cypress N Pres.)

Resource-specific regulations:

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

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

Recreational Collection of Rocks and Minerals
Resource-specific laws:

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

Resource-specific regulations:

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

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

Transpark Petroleum Product Pipelines
Resource-specific laws:

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

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

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

Uranium

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

Resource-specific regulations: none applicable.

NPS Management Policies 2006: none applicable.

Active Processes and Geohazards Laws, Regulations, and Policies

Coastal Features and Processes

Resource-specific laws:

- **NPS Organic Act, 54 USC § 100751** et. seq. authorizes the NPS to promulgate regulations to protect park resources and values (from, for example, the exercise of mining and mineral rights).
- **Coastal Zone Management Act, 16 USC § 1451** et. seq. requires Federal agencies to prepare a consistency determination for every Federal agency activity in or outside of the coastal zone that affects land or water use of the coastal zone.

- **Clean Water Act, 33 USC § 1342/Rivers and Harbors Act, 33 USC 403** require that dredge and fill actions comply with a Corps of Engineers Section 404 permit.
- **Executive Order 13089** (coral reefs) (1998) calls for reduction of impacts to coral reefs.
- **Executive Order 13158** (marine protected areas) (2000) requires every federal agency, to the extent permitted by law and the maximum extent practicable, to avoid harming marine protected areas.

Resource-specific regulations:

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

NPS Management Policies 2006:

- **Section 4.1.5** directs the NPS to re-establish natural functions and processes in human-disturbed components of natural systems in parks unless directed otherwise by Congress.
- **Section 4.4.2.4** directs the NPS to allow natural recovery of landscapes disturbed by natural phenomena, unless manipulation of the landscape is necessary to protect park development or human safety.
- **Section 4.8.1** requires NPS to allow natural geologic processes to proceed unimpeded. NPS can intervene in these processes only when required by Congress, when necessary for saving human lives, or when there is no other feasible way to protect other natural resources/ park facilities/historic properties.
- **Section 4.8.1.1** requires NPS to:
  - Allow natural processes to continue without interference,
  - Investigate alternatives for mitigating the effects of human alterations of natural processes and restoring natural conditions,
  - Study impacts of cultural resource protection proposals on natural resources,
  - Use the most effective and natural-looking erosion control methods available, and
  - Avoid putting new developments in areas subject to natural shoreline processes unless certain factors are present.

Geologic Hazards

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

Resource-specific regulations: none applicable.

NPS Management Policies 2006:

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

Soils

Resource-specific laws:

- **Soil and Water Resources Conservation Act, 16 USC §§ 2011–2009** provides for the collection and analysis of soil and related resource data and the appraisal of the status, condition, and trends for these resources.
- **Farmland Protection Policy Act, 7 USC § 4201** et. seq. requires NPS to identify and take into account the adverse effects of Federal programs on the preservation of farmland; consider alternative actions, and assure that such Federal programs are compatible with State, unit of local government, and private programs and policies to protect farmland. NPS actions are subject to the FPPA if they may irreversibly convert farmland (directly or indirectly) to nonagricultural use and are completed by a Federal agency or with assistance from a Federal agency. Applicable projects require coordination with the Department of Agriculture's Natural Resources Conservation Service (NRCS).

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

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

Upland and Fluvial Processes

Resource-specific laws:

- **Rivers and Harbors Appropriation Act of 1899, 33 USC § 403** prohibits the construction of any obstruction on the waters of the United States not authorized by congress or approved by the USACE.
- **Clean Water Act 33 USC § 1342** requires a permit from the USACE prior to any discharge of dredged or fill material into navigable waters (waters of the US [including streams]).

- **Executive Order 11988** requires federal agencies to avoid adverse impacts to floodplains. (see also **D.O. 77-2**).
- **Executive Order 11990** requires plans for potentially affected wetlands (including riparian wetlands). (see also **D.O. 77-1**).

Resource-specific regulations: none applicable.

NPS Management Policies 2006:

- **Section 4.1** requires NPS to manage natural resources to preserve fundamental physical and biological processes, as well as individual species, features, and plant and animal communities; maintain all components and processes of naturally evolving park ecosystems.
- **Section 4.1.5** directs the NPS to re-establish natural functions and processes in human-disturbed components of natural systems in parks, unless directed otherwise by Congress.
- **Section 4.4.2.4** directs the NPS to allow natural recovery of landscapes disturbed by natural phenomena, unless manipulation of the landscape is necessary to protect park development or human safety.
- **Section 4.6.4** directs the NPS to (1) manage for the preservation of floodplain values; [and] (2) minimize potentially hazardous conditions associated with flooding.
- **Section 4.6.6** directs the NPS to manage watersheds as complete hydrologic systems and minimize human-caused disturbance to the natural upland processes that deliver water, sediment, and woody debris to streams.
- **Section 4.8.1** directs the NPS to allow natural geologic processes to proceed unimpeded. Geologic processes…include…erosion and sedimentation…processes.
- **Section 4.8.2** directs the NPS to protect geologic features from the unacceptable impacts of human activity while allowing natural processes to continue.

Additional References, Resources, and Websites

Caves and Karst

- Caves and Karst Laws, Regulations, and Policies (NPS webpage): https://www.nps.gov/subjects/caves/cave-karst-protection.htm
- National Cave and Karst Research Institute: https://www.nckri.org/
- NPS Caves and Karst website: https://www.nps.gov/subjects/caves/index.htm
- Climate Change Resources
- Intergovernmental Panel on Climate Change: http://www.ipcc.ch/
- NOAA Sea Level Rise Map Viewer: https://maps.coast.noaa.gov/digitalcoast/tools/slr.html
- NPS Climate Change Response Program Resources: http://www.nps.gov/subjects/climatechange/resources.htm
- NPS Climate Change, Sea Level Change website: https://www.nps.gov/subjects/climatechange/sealevelchange.htm/index.htm
- NPS Policy Memorandum 12-02—Applying NPS Management Policies in the Context of Climate Change: https://npspolicy.nps.gov/PolMemos/policymemoranda.htm
- NPS Policy Memorandum 15-01—Addressing Climate Change and Natural Hazards for Facilities: https://npspolicy.nps.gov/PolMemos/policymemoranda.htm
- US Global Change Research Program: http://www.globalchange.gov/home

Days to Celebrate Geology

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

Disturbed Lands Restoration

Geoconservation—Disturbed Lands Restoration: https://www.nps.gov/articles/geoconservation-disturbed-land-restoration.htm

Earthquakes

- ShakeAlert: An Earthquake Early Warning System for the West Coast of the United States (USGS sponsored): https://www.shakealert.org/

- TexNet Research and the Center for Injection and Seismicity Research (CISR): https://www.beg.utexas.edu/texnet-cisr
- USGS Earthquake Hazards Program unified hazard tool: https://earthquake.usgs.gov/hazards/interactive/

Geologic Heritage

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

Geologic Maps

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

Geological Surveys and Societies

- American Geophysical Union: http://sites.agu.org/
- American Geosciences Institute: http://www.americangeosciences.org/
- Association of American State Geologists: http://www.stategeologists.org/
- Bureau of Economic Geology: https://www.beg.utexas.edu/outreach/state-geological-survey
- Geological Society of America: http://www.geosociety.org/
- South Texas Geological Society: https://www.stgs.org/
- US Geological Survey: http://www.usgs.gov/

Landslides and Slope Movements

- Unstable Slope Management Program for transportation corridor risk reduction: https://usmp.info/client/credits.php
- *Geological Monitoring* chapter about slope movements (Wieczorek and Snyder 2009): http://go.nps.gov/geomonitoring
- *The Landslide Handbook—A Guide to Understanding Landslides* (Highland and Bobrowsky 2008): http://pubs.usgs.gov/circ/1325/

NPS Geology

- NPS America's Geologic Legacy: http://go.nps.gov/geology. This primary site for information about NPS geology includes a geologic tour, news and other inform https://www.nps.gov/subjects/geology/index.htm
- NPS America's Geologic Heritage: https://www.nps.gov/subjects/geology/americas-geoheritage.htm
- NPS Geodiversity Atlas: https://www.nps.gov/articles/geodiversity-atlas-map.htm. The NPS Geodiversity Atlas is a collection of park-specific webpages containing information about the park's geology and links to additional resources.
- NPS Geologic Resources Inventory: http://go.nps.gov/gri
- Caves and Karst: https://www.nps.gov/subjects/caves/index.htm
- Coastal Geology: https://www.nps.gov/subjects/geology/coastal-geology.htm
- Energy and Minerals Management: https://www.nps.gov/subjects/energyminerals/index.htm
- Fossils and Paleontology: https://www.nps.gov/subjects/fossils/index.htm
- Geohazards: https://www.nps.gov/subjects/geohazards/index.htm
- Geothermal Features/Hot Springs: https://www.nps.gov/subjects/geology/hot-springs.htm
- Glaciers: https://www.nps.gov/subjects/glaciers/index.htm
- Mountains—Geology and Physical Processes: https://www.nps.gov/subjects/mountains/geology.htm
- Volcanoes, Craters, and Lava Flows: https://www.nps.gov/subjects/volcanoes/index.htm

NPS Reference Tools

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

Relevancy, Diversity, and Inclusion

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

Soils

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

Texas Geology

- Bureau of Economic Geology: https://www.beg.utexas.edu/outreach/state-geological-survey
- South Texas Geological Society: https://www.stgs.org/

US Geological Survey Reference Tools

- Geologic Names Lexicon (Geolex; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex
- Geographic Names Information System (GNIS; official listing of place names and geographic features): http://gnis.usgs.gov/
- USGS Store (find maps by location or by purpose): http://store.usgs.gov
- National Geologic Map Database (NGMDB): http://ngmdb.usgs.gov/ngmdb/ngmdb_home.html
- Tapestry of Time and Terrain (descriptions of physiographic regions; Vigil et al. 2000): http://pubs.usgs.gov/imap/i2720/
- USGS Publications Warehouse: http://pubs.er.usgs.gov
- The Bureau Store (Maps, reports, guidebooks, and free resources for the public) https://store.beg.utexas.edu/

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