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Fort Davis National Historic Site

Geologic Resources Inventory Report

Columnar jointing of the Sleeping Lion Formation on North Ridge.
COLORADO STATE UNIVERSITY / MATTHEW HARRINGTON

Fort Davis National Historic Site: Geologic resources inventory report

Science Report NPS/SR—2024/200

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Acknowledgments

The GRI team thanks the participants of the 2008 scoping meeting and the 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, we are particularly thankful to the Texas Bureau of Economic Geology for its 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 "Hillslope Features and Processes," "Seismic Features and Processes & Oil and Gas Exploration and Development," and "Geologic Hazards" sections of this report, Patricia Seiser (NPS GRD) for her review of the "Talus Caves" section, and Tony Gallegos and Forrest Smith (NPS GRD) for their review of the "Seismic Features and Processes & Oil and Gas Exploration and Development" 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 the GRI report may also be useful for interpretation.

Fort Davis National Historic Site, hereafter referred to as the "park," is located in western Texas and preserves one of the best remaining examples of a frontier military post. Fort Davis existed in two separate iterations: first from 1854 to 1861, then from 1867 to 1891. The park, established in 1961, contains both ruins and restored fort buildings within Hospital Canyon, a box canyon on the eastern edge of the Davis Mountains. Over 250 buildings, ruins, and foundations associated with the two forts exist within the park. The period from 1867 to 1885 when all-Black regiments, referred to as Buffalo Soldiers, occupied the fort offers a distinctive perspective on the existence and role of African Americans in the late 1800s western frontier.

Long before Fort Davis was established, widespread volcanic activity dominated the Trans-Pecos region of Texas and formed the Davis Mountains. From 38 million to 32 million years ago, magmatic activity peaked, erupting intermixed layers of silicic lavas, ignimbrites, and trachyte porphyry lavas. The Sleeping Lion Formation (geologic map unit **Tsl**), which forms the iconic cliffs of Hospital Canyon, and the underlying Frazier Canyon Formation (geologic map unit **Tfc**), were deposited in this eruptive phase. 32 million years ago, the Davis Mountains slowly began to erode, forming the canyons and basins that define the region today. The canyon floor, on which Fort Davis is located, contains colluvium and fan deposits (geologic map unit **Qf**) eroded from volcanic formations in the area.

The geologic heritage of the historic site is tied to both the physical construction of the fort and the ways in which soldiers and passing travelers interacted with and viewed the landscape. In order to construct the more permanent stone buildings, the military quarried ignimbrite from the Fort Davis Tuff, part of the Barrel Springs Formation (geologic map unit **Tbs**). The relatively hospitable and mild climate of the Davis Mountains, in contrast to the sweltering heat of most of Trans-Pecos Texas, made the fort an ideal destination for both military personnel and travelers. Historical journal accounts of the rugged terrain, serene beauty, and enjoyable viewscapes at the fort connect the geology of the area to the history and experiences of those who lived at or experienced Fort Davis.

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. A geologic map in a geographic information system (GIS) format (referred to as the "GRI GIS data") is the principal deliverable of the GRI. The GRI GIS data was compiled in 2008 and updated in 2022. The source map used to compile the GRI GIS data was originally produced by the Texas Bureau of Economic Geology. The GRI GIS data and the geologic information and interpretations associated with it were used in preparing this report.

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 historic fort 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. This chapter provides specific information about the use of the GRI GIS data and 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 resources and stories, such as the use of locally quarried ignimbrite for building stone and the impact the vertical canyon walls had on soldiers at the fort.

Geologic History—This chapter describes the chronology of geologic events that formed the present landscape. The geologic events are discussed in chronological order, focusing on the major successional volcanic events that formed the Davis Mountains in the Eocene (56.0 million–33.9 million years ago) and Oligocene (33.9 million–23.0 million years ago). This chapter also contains a geologic time scale and a table of the GRI GIS units with unit descriptions and ages.

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, hillslope features and processes, talus caves, seismic features and processes, oil and gas exploration and development, eolian features and processes, disturbed lands, climate change, 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. A summary of laws, regulations, and policies that apply to geologic resources is also provided.

In addition to these chapters, the "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 purpose of this report is to familiarize readers with the geologic features, processes, history, and best practices for managing geologic resources for Fort Davis National Historic Site (also referred to as the "park" throughout this report). 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

The park preserves one of the best remaining examples of a frontier military post. Named after Secretary of War, Jefferson Davis, the fort was active in two separate iterations: first from 1854 to 1861, and then from 1867 to 1891. From 1867 to 1885, the 24th and 25th US Infantry and the 9th and 10th US Cavalry, all-Black regiments known as Buffalo Soldiers, served at the fort, providing an opportunity to understand the presence and role African Americans held in the American West and frontier military (National Park Service 2016). The site contains more than 250 historic buildings, ruins, and foundations associated with the two forts that existed across the mid- to late-1800s (Fort Davis National Historic Park n.d.).

The enabling legislation to form the park was signed into law on 8 September 1961, to "commemorate the historic role played by such fort in the opening of the West" (National Park Service 2016, p. 40). On 8 September 1998, the park boundaries were expanded by an additional 0.06 km^2 (16 ac) after senatorial approval of the Conservation Fund purchase and donation of the property to the NPS (Congress.gov 1998). The acquired 16 acres included one-third of Sleeping Lion Mountain and the former location of a large complex of stores and establishments operated by civilian Daniel Murphy (Congress.gov 1998). An additional expansion of the park's borders occurred in 2008, when 0.22 km^2 (55 ac) were acquired that enhanced the rural setting of the officers' quarters and the view from Skyline Drive in Davis Mountains State Park (Congress.gov 2008). The park currently consists of 2.12 km^2 (523 ac). Fort Davis has been a designated place within the National Historic Landmarks Program since 1960.

The park is located in the town of Fort Davis, Texas, which is situated within the Trans-Pecos region (Figure 1) at the eastern edge of the Davis Mountains. The Trans-Pecos region, originally defined by Texas geologist Robert T. Hill in 1887, encompasses the area between the Pecos River and the Rio Grande. The region is both the most arid and mountainous in Texas, containing all of Texas' peaks over 1524 m (5000 ft; Schmidt 1952). The park lies in the north-eastern section of the Chihuahuan Desert (Figure 1), where annual rainfall is limited. Fort Davis and the Davis Mountains lie at the very eastern edge of the Basin and Range province.

Figure 1. Map of the Trans-Pecos region of Texas and the Chihuahuan Desert. This map shows the location of Fort Davis National Historic Site in relation to the Trans-Pecos region and the expanse of the Chihuahuan Desert. The Trans-Pecos region is shown with diagonal lines. The region is bounded by the Pecos River on the east and the Rio Grande on the west. Due to the high elevation of the Davis Mountains, the Chihuahuan Desert surrounds the mountains but does not continue up the slopes. Fort Davis lies at the edge of the desert. Data for the Chihuahuan Desert range was provided by Olson et al. 2001.

The fort was built just south of Limpia Creek, which at the time was a critical source of water for the fort and the growing civilian community of Fort Davis. The fort was built within Hospital Canyon, a box canyon composed of enigmatic cliffs that display columnar jointing (see report cover and inside cover photographs). Rocks with columnar jointing display parallel, prismatic columns that are polygonal in cross section. They often form in basaltic flows but sometimes form in other extrusive and intrusive rocks because of contraction during cooling.

The climate at Fort Davis is more hospitable compared to most other historic fort locations in western Texas. Major General Zenas R. Bliss, who spent considerable time at the fort when it was active, commented, “At Fort Davis, the climate is very different from any of these other posts [referring to Fort Brown, Fort Ringgold, Fort Duncan, and Fort Bliss]. It is delightfully cool in summer for a southern post” (Bliss 2007, pp. 73–74). The appeal of the climate and landscape encouraged many officers to request Fort Davis for assignment.

Fort Davis National Historic Site’s foundation document 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 (National Park Service 2016):

Fort Davis is one of the best remaining and continuously preserved examples in the Southwest of a typical post-Civil War frontier fort because of the setting and extent of the surviving structures, ruins, objects, and artifacts.

Black regulars, known as Buffalo Soldiers, served at Fort Davis from 1867 to 1885, providing an excellent opportunity for understanding and appreciating the important role played by African Americans in the West and specifically in the frontier army.

Fort Davis was strategically located to defend the Trans-Pecos portions of the San Antonio-El Paso Road and the Chihuahua Trail. This encompassed protecting and controlling activities on the southern portions of the Great Comanche War Trail and the Mescalero Apache War Trails.

During the Indian Wars, Fort Davis provided essential troops and supplies to approximately 100 skirmishes in West Texas, and finally to the Victorio Campaign, which ended the meaningful resistance of Apache bands in the Military District of the Trans-Pecos.

The historic integrity and character of the post-Civil War fort have not been significantly altered since its establishment. Much of the landscape immediately adjacent to the post has undergone little modern development, which helps promote an authentic visitor experience.

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 site: (1) conduct a scoping meeting and provide a scoping summary, (2) provide geologic map data in a geographic information system (GIS) format, (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 DataStore (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; 1:250,000) and *Map Accuracy Standards* (US Geological Survey 1999), geologic features represented in the GRI are horizontally within 127 m (417 ft) of their true locations.

Scoping Meeting

On 15 April 2008, the NPS held a conference call for the park. The call 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 historic site. The GRI GIS data was updated in 2022 and may be updated if new, more accurate geologic maps become available or if software advances require an update to the digital format. These data are the principal deliverables of the GRI. 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. 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.

More information about the GRI GIS data can be found in the files accompanying the data on IRMA. 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.

The GRI GIS data for the site was compiled from the following source map:

- Geologic Atlas of Texas: Fort Stockton Sheet (Barnes 1982)

GRI Poster

A poster of the GRI GIS data draped over a shaded relief image of the site and surrounding area is the primary figure referenced throughout this GRI report. The poster is not a substitute for the GIS data but is supplied as a helpful tool for office and field use and for users without access to ArcGIS. Not all GIS feature classes are included on the poster 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 2024, 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 and follow-up meetings. Notably, the writing reflects the geologic interpretation provided by Barnes (1982), the author of the source map (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. Information from the site's Historic Resource Study (Greene 1986) was also invaluable in putting together this report.

The GRI report links the GRI GIS data to the geologic features and processes in the park and is discussed in this report using map unit symbols; for example, the Sleeping Lion Formation has the map symbol **Tsl**. Capital letters indicate age, and the following lowercase letters symbolize the unit name. "**T**" represents the Tertiary (~66.0 million to 2.6 million years ago), and "**sl**" represents the Sleeping Lion Formation. A geologic time scale and a list of all the map units in the park are provided as tables in the "Geologic History" section of this report.

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. In 2015, the GRD staff, in cooperation with the American Geosciences Institute, published a booklet introducing the American experience of geoheritage, geodiversity, and geoconservation: *America's Geologic Heritage: An Invitation to Leadership*. Key principles and concepts of America's geoheritage are introduced in this publication, which serves as a focal point for continuous cooperation and collaboration in the United States on geologic conservation. Geoheritage sites are conserved so that their lessons and beauty will remain as a legacy for future generations. Such areas generally have great potential for scientific studies, use as outdoor classrooms, and enhancing public understanding and enjoyment. Geoheritage sites are fundamental to understanding dynamic Earth systems, the succession and diversity of life, climatic changes over time, the evolution of landforms, and the origin of mineral deposits.

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, or management documents can be considered a part of America's geoheritage. 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.

Pre-Fort Years

Humans have lived across the Trans-Pecos region of Texas for thousands of years, but evidence of occupation pre-1600 within the Davis Mountains is limited. However, one site within the border of the park preserves evidence of extensive occupation by way of a widespread lithic scatter, burned rock, and stone tools (Myers 2000). While it is unknown where the stone tools were sourced from, the reliance of early inhabitants in the region on geological resources highlights the important role of geology in their culture. The artifacts indicate a time range spanning the Late Archaic Period (5,000 to 3,000 BCE), possibly even the Early Archaic Period (8,000 to 6,000 BCE), and into the Late Prehistoric Period (700 to 1700 CE) (Myers 2000).

Pictographs (pictures painted onto rocks or other surfaces by ancient people) remain one of the best markers of historic habitation in rock shelters within the Davis Mountains. Rock faces provided a canvas for ancient people, who often used paints colored by oxides from other geological resources. These prehistoric pictographs often depict anthropomorphic forms or animals (Greene 1986). Pictographs can also be used as historical markers, with one site in the Davis Mountains portraying a Spanish mission, which denote the arrival of Spanish exploration and settlement in the region (Greene 1986). Within the park itself, pictographs have been found along the walls of Hospital Canyon, but the erosion of the rhyolitic cliff faces has destroyed evidence of most of them (David Larson, Fort Davis National Historic Site, Superintendent, personal communication, 27 February 2023). The pictographs found in the region are interpreted to have been made after 650 BCE (Greene 1986).

Due to the aridity of the Trans-Pecos region of Texas, most Indigenous groups that utilized the region were likely transient in nature (Greene 1986). However, the Davis Mountains provided water, wildlife, and shelter, making the area an ideal destination for hunting parties and weary travelers. The Jumanos migrated south from New Mexico and entered the region in the 1100s, but their occupation ended in the late 1600s to early 1700s with the arrival of the Apaches (Knudten 2010). Journal accounts from military expeditions into the Davis Mountains in the mid-1800s indicated that the Apaches took advantage of the gentler climate of the mountains; a military party stumbled upon what they believed to be an Apache rancheria (a small Indigenous settlement) along Limpia Creek, near the current site of the fort (Greene 1986). After the establishment of the fort, officers at Fort Davis reported that Apaches had once grown melons, corn, and pumpkins at the site (Bliss 2007).

Active Fort Years

From the time of the first Spanish exploration of the region in 1583 until the mid-1850s, most of western Texas remained uninhabited by Europeans, Mexicans, or Americans (Greene 1986). The harsh, barren landscape of the region deterred settlement, with few permanent towns west of San Antonio and Austin, Texas. Following the end of the Mexican–American War in 1848, increased interest in newly acquired territories (including modern-day New Mexico, Arizona, Utah, Nevada, and California) and the failure of local attempts to build a road connecting East Texas to West Texas inspired the federal government to seek a direct route west (Greene 1986).

In February 1849, a military party led by Lieutenants H. C. Whiting and William F. Smith trekked west from San Antonio toward El Paso to scout out such a route (Greene 1986). The party reached the Davis Mountains by March, traveling into a canyon along a stream until they reached a grove of cottonwoods. They named the pass Wild Rose Pass and the stream Limpia Creek. The trunks of the cottonwoods were adorned with pictographs, prompting Whiting to name the area "Painted Comanche Camp"; this site was near the future site of Fort Davis (Greene 1986). The high elevation and the availability of water within the canyons and meadows of the Davis Mountains promoted the region as an ideal site for a military fort and a road stop.

The California Gold Rush brought over 3,000 Americans over trails through West Texas and Chihuahua in 1849 alone, with the Painted Comanche Camp offering refuge from the arid journey and replenishment for water supplies (Greene 1986). As gold rushers and cattle drovers pushed west from East Texas, attacks by Comanches and Kiowas on the route approaching Trans-Pecos Texas and raids by Lipan and Mescalero Apaches prompted the government to increase military protection in the region (Greene 1986). Geological interest in Californian gold played a major role in the formation of Fort Davis.

In 1854, Persifor F. Smith was sent west to select the optimal site for the fort after raids and attacks continued to increase (Greene 1986). After visiting another site along the Rio Grande River, the site of Fort Davis was selected in October of 1854, approximately one mile southwest (other reports say ¼ mile) of the Painted Comanche Camp at the mouth of a box canyon (Hospital Canyon) just south of Limpia Creek (Greene 1986; Myers 2000). The availability of water, resources, and game, paired with the site’s proximity to the Lower Road, convinced General Smith that the site was ideal for a military fort (Greene 1986).

The beauty of the fort’s location, situated between two near vertical cliffs, Sleeping Lion Mountain and the North Ridge, was not lost on Captain Arthur T. Lee, who painted scenes of the fort, highlighting the geological wonders of the area (Figure 2). Each of Lee’s paintings showcases the grand, columnar-jointed Sleeping Lion Formation (**Tsl**), the talus-covered slopes overlaying the Frazier Canyon Formation (**Tfc**), and the wide, flat fan deposits of the canyon floor (**Qf**). In addition to his painting, Lee described the area in detail, writing:

> *A wide deep [canyon], carpeted with the richest verdure, overshadowed by live oak, its lofty and precipitous sides festooned with perennial vines, and mantled with moss and flowers, looking out over smiling prairies and table lands, to miniature lakes, and lofty mountain peaks, that lost their summits in the clouds. Who, with good company, mirth and music, would not have compromised for Fort Davis . . . as a life long resting place? (Lee 1871, pp. 365–367).*

Figure 2. Two paintings and one sketch by Captain Arthur T. Lee of Fort Davis in the 1800s. The top painting, titled Canyon, Fort Davis, depicts the view of Hospital Canyon when standing at the mouth of the canyon, looking west. The middle painting, titled Fort Davis Scene, showcases either Sleeping Lion Mountain or the North Ridge at the mouth of the canyon. The bottom sketch, titled Fort Davis, shows the construction of military buildings across the canyon floor. This sketch was completed before local stone was mined and utilized in construction. Artwork scans provided by the University of Rochester River Campus Libraries.

The primary travel route through the region, commonly known as the Lower Road (also known as the San Antonio-El Paso Road, Lower Emigrant Road, Military Road, or Whiting Road), paralleled Limpia Creek into Wild Rose Pass, where accessible water and vegetation gave refuge to cattle herds and traveling parties (Figure 3). The road followed Limpia Creek for 20 miles through Limpia Canyon, exposing travelers to the rugged topography of the Davis Mountains. John Reid, a westward traveler who journaled his entire journey, took the route in 1857 and described the road's topography and views:

> *This is a rapid little stream [Limpia Creek], reached by the road at the mouth of a canon [canyon], bearing the same name [Limpia Canyon], through which both it and the road run, a distance of twenty miles. The stream is crossed by the road an average of one time in each mile. The road diverges from the stream, only, to run through Wild Rose Pass, a romantic looking section, embracing great hills, the steepest indeed traversed by the road between the Gulf and the Pacific, and narrow valleys, where flourish innumerable flowers; hence the name. At the further end of the canon [canyon] the road leads to the table land, and four miles further on you behold Fort Davis. (Reid 1858, p. 119)*

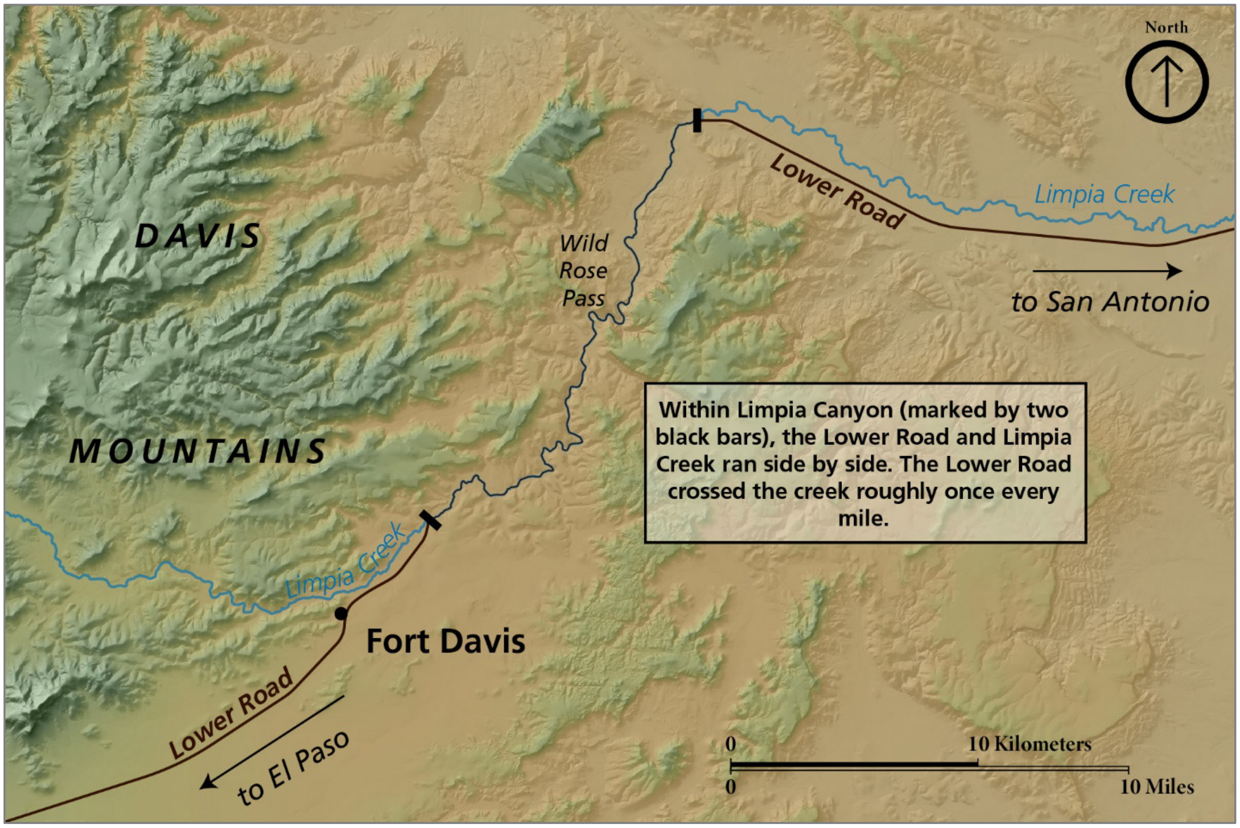

Figure 3. Map of the Lower Road's route into Fort Davis. The Lower Road (also known as the San Antonio-El Paso Road, Lower Emigrant Road, Military Road, or Whiting Road) followed Limpia Creek into Wild Rose Pass, meandering through Limpia Canyon. After exiting the canyon, the road again followed Limpia Creek towards Fort Davis, where it cut through the fort in between the corrals and the barracks. The fort (and accompanying town) provided a safe stop for refueling and rest for travelers heading west.

The site of the fort, described by Second Lieutenant Zenas R. Bliss as “the most beautifully situated of any that I have ever seen,” came at the expense of strategic positioning (Bliss 2007, p. 80). Although the box canyon shielded the fort from winds, winters, and summers that would otherwise be harsher at a more exposed site, the military drawbacks of being situated beneath two bluffs were ignored. Bliss wrote of the strategic weakness of the site: “There was hardly a chimney at the post that an Indian could not have thrown a stone in from the bluffs. A comparatively small party could have made the post untenable by occupying them, but they never attacked” (Bliss 2007, p. 81). The vertical volcanic cliffs provided clear sightlines across the entirety of the fort while providing sufficient cover to any individuals who wished to spy on or attack the fort.

During the first winter of the fort’s existence, only rudimentary structures composed of canvas and pine slabs were constructed for the stationed soldiers and officers (Greene 1986). By 1855, a lime kiln was established at a pond 30 miles (48.28 km) north of the fort for burning limestone, and more permanent construction was underway (Greene 1986). In 1856, Captain Arthur T. Lee initiated construction on six new barracks utilizing local (**Tbs**) vitric tuff (consolidated or cemented volcanic ash that is characteristically glassy) within the abundant ignimbrite (a pyroclastic flow deposit) (Reid 1858; Greene 1986). The source of the ignimbrite was likely from the northeast end of Dolores Mountain, a ridge on the southeastern end of the town of Fort Davis that contains two abandoned, historic quarries (Everett 1967).

The quarters for the men were built at the mouth of the canyon, while the officers’ quarters were scattered along the base of the canyon walls (Bliss 2007). The original hospital and laundresses’ quarters were placed further into the canyon, likely to shield the buildings from attacks and harsh north winds (Myers 2000). In addition to the military personnel living at the fort, second lieutenant Bliss noted that small groups of Mexican settlers lived around the fort in talus caves among the cliffs (Bliss 2007, p. 81; for more information on these talus caves, see “Geologic Features, Processes, and Management Issues”).

During the late 1850s, a series of experiments utilizing camels in place of horses or mules occurred at Fort Davis. Jefferson Davis, who served as Secretary of War at the time, held the belief that camels could alleviate potential supply problems caused by the arid landscape of West Texas (Greene 1986). As a desert-evolved species, camels are much better adapted to desert travel than horses or mules. Despite relative success, the onset of the Civil War pushed the project to the back burner, and it was never revisited again.

In 1861, after the secession of Texas from the Union into the Confederacy, federal forts across the state faced orders to evacuate. Fort Davis was the second to last to evacuate, and upon departing the fort, the captain at the time, Captain Edward W. Blake, ordered the flagstaff cut down so no flag of the Confederacy could ever fly above the fort (Greene 1986). The Confederates occupied the fort from 1861 through 1862 with minimal troops until the fort was retaken by the Union in August 1862 (Greene 1986). Soon after, Union forces abandoned the fort, and the Mescalero Apache ransacked and burned it, where it was left scorched until 1867 (Greene 1986).

In the summer of 1867, the all-Black 9th Cavalry was sent out to begin rebuilding the fort, now in ruins (Greene 1986). The landscape of the fort once again inspired those who were stationed there, and it became one of the few western posts actively sought after by enlisted officers (Greene 1986). The assistant quartermaster of the US Army described the fort in the Report of the Secretary of War:

It is situated at the mouth of a canon [canyon] that shelters the post from all winds except those prevailing from an easterly direction. The surrounding mountains, composed of perpendicular layers of volcanic rock, curiously piled, are grand and picturesque, and add much to the beauty of the situation, while the atmosphere is so clear and transparent that a mountain known as ‘Bishop’s Mitre,’ 25 miles distant, appears but five. Limpia spring and creek are near the post and afford an abundant supply of water. (Strang 1868, p. 865)

Unlike the first iteration of the fort, efforts were undertaken right away to build more permanent structures by utilizing the same locally available ignimbrite. Colonel Strang reported, “Quarries of an excellent quality of red sandstone [vitric tuff within the ignimbrite] were opened within a half mile of the post. Limestone could not be found nearer than 35 miles, at which distance a kiln was built and lime burned and hauled to the post” (Strang 1868, p. 865). The stone was sourced from at least three local quarries: one at Dolores Mountain (utilized the most heavily), one up Hospital Canyon, and one near Musquiz Canyon (Myers 2000). Initial buildings constructed from 1867 to 1869 were composed of just the building stone, whereas later buildings utilized the stone as foundations for adobe bricks (Figure 4; Everett 1967).

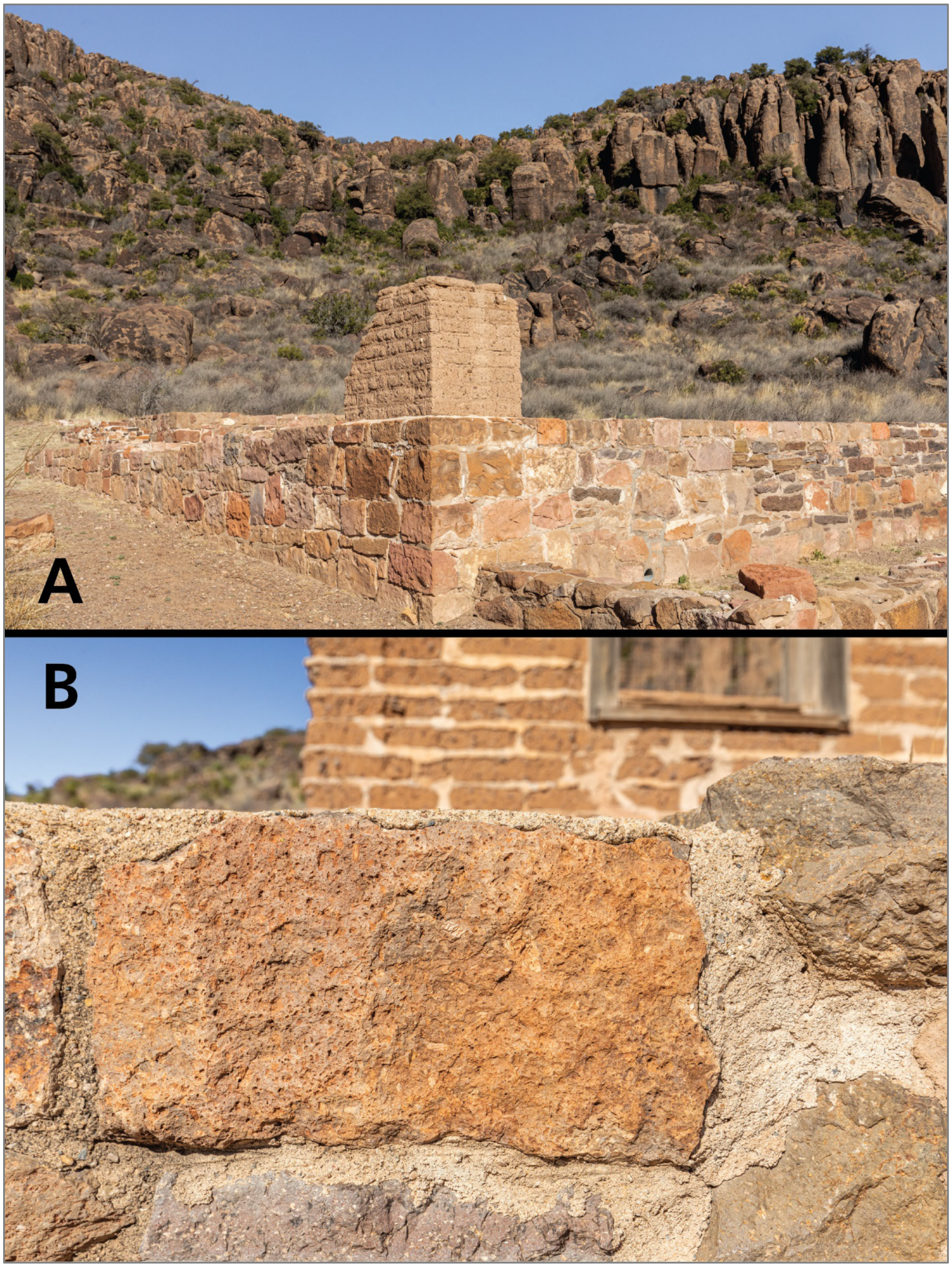

Figure 4. Photographs of vitric tuff used in building construction. Vitric tuff (a tuff composed mostly of volcanic glass fragments), locally quarried from the Barrel Springs Formation ignimbrite, was utilized for the construction of fort buildings. Early buildings were constructed entirely of stone, but later construction utilized it only for foundations, choosing to build the walls out of adobe bricks. A) A photograph shows the ruins of such a building, where the foundation of tuff supports a corner of adobe bricks still standing. B) A close-up photograph of the texture of the vitric tuff. Photos by Matthew Harrington (Colorado State University).

The revitalized fort was constructed quickly, with most buildings constructed of stone, adobe, and wooden roofs (Greene 1986). In addition to sturdier structures, accessible water became an important consideration for the inhabitants of the fort. For most of the fort's history, water was hauled in barrels by mule-drawn wagons each day from Limpia Creek (Greene 1986). In 1867, two cisterns were constructed to collect rainwater and to avert potentially contaminated water (Myers 2000). That same year, officers pushed for the development of a spring near the fort, citing the inconvenience of hauling water from the creek daily (Greene 1986). The spring was used for a few years, but fears of contamination led to a temporary return to sourcing water from Limpia Creek (Greene 1986).

By 1872, several wells had been dug along the barracks and behind officers' row (see GRI poster) to supplement the water from the creek, and by 1875, they had fully replaced the need for water from Limpia Creek (Myers 2000). Despite the clean supply of water, the inconveniences of transporting water from the spring to the surrounding buildings encouraged the development of a pipe system. In 1883, under a new plan, water was pumped from a well alongside Limpia Creek 130 yards uphill via a pipe to a 32,000-gallon holding tank on the slope of North Ridge (Greene 1986). From there, the water system utilized gravity to flow to various buildings throughout the fort. The system was fully operational by 1884, but it did not come without problems.

In addition to mechanical and contamination problems, water levels in the creek dropped significantly in 1886, and a dam was constructed (Myers 2000). Two more tanks were created to accommodate the water demands of the garrison, but continually dwindling water resources threatened the existence of the fort itself (Greene 1986). To make matters worse, water contamination became an even greater issue, and all water pulled from the creek had to be boiled for safety (Greene 1986). These water supply and sanitation issues continued to plague the fort until its official deactivation.

The all-Black regiments departed Fort Davis for Arizona in 1885, ending their nearly two-decade-long occupation (Greene 1986). By 1886, the fort had shifted from functioning as a frontier military post providing protection to becoming primarily an instructional fort, as the Native American presence in the region had diminished (Greene 1986). As the need for military action ceased, the soldiers stationed at the fort became restless. As a result, during the late 1880s, cases of crimes, off-post amusements, and accidental deaths became more than just incidental, and the need for Fort Davis vanished. With railroad lines too far north and south to effectively supply the fort, Fort Davis was officially abandoned on 21 July 1891 (Greene 1986).

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). A geologic time scale shows the chronology of geologic events (bottom to top) that led to the park's present-day landscape; this story covers more than 38 million years.

Geologic Time Scale

A Note About the Tertiary Period

"Tertiary" is a widely used but no longer formally recognized term for the geologic period from 66.0 million to 2.6 million years ago. Following Barnes (1982), the GRI GIS data use the term "Tertiary" and the symbol (T). In current geologic nomenclature, however, the Paleogene Period (66.0 million to 23.0 million years ago) and Neogene Period (23.0 million to 2.6 million years ago) replace the Tertiary. These two periods are further divided into five epochs from oldest to youngest: Paleocene, Eocene, Oligocene, Miocene, and Pliocene (Table 1).

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. Colors correspond to USGS suggested colors for geologic maps. Letters in parentheses are abbreviations for geologic time units. Where no geologic time subdivision exists, "n/a" indicates not applicable.

Eon	Era(s)	Period(s)	Epoch(s)	MYA [A]
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	201.4–145.0
	Mesozoic	Triassic (TR)	Upper, Middle, Lower	251.9–201.4
	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

[A] Boundary ages are millions of years ago (MYA) and follow the International Commission on Stratigraphy (2023).

Table 1 (continued). 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. Colors correspond to USGS suggested colors for geologic maps. Letters in parentheses are abbreviations for geologic time units. Where no geologic time subdivision exists, “n/a” indicates not applicable.

Eon	Era(s)	Period(s)	Epoch(s)	MYA [A]
Phanerozoic (continued)	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

[A] Boundary ages are millions of years ago (MYA) and follow the International Commission on Stratigraphy (2023).

Geologic History

The geologic history of Fort Davis traces back to volcanic activity triggered by plate tectonics. When a dense, oceanic plate collides with a more buoyant, continental plate, the oceanic plate subducts beneath the continental plate, often triggering volcanic activity. Roughly 100 million years ago, the Farallon slab began subducting beneath the North American plate near the modern Pacific coast, triggering volcanic activity. Over the next 53 million years, the volcanic activity migrated eastward, arriving in the Trans-Pecos region 47 million years ago (Henry and McDowell 1986). The proposed mechanism for the eastward sweeping volcanism has been attributed to progressive shallowing (when the angle at which a tectonic plate is diving below another plate becomes smaller) over time in the subducting Farallon slab (Coney and Reynolds, 1977; Keith 1978; Damon et al., 1981; Price et al., 1987; Parker et al. 2017).

As the convergence rate of the North American and Farallon plates slowed, the hot asthenospheric mantle (Earth’s relatively weak layer below the rigid lithosphere) ascended, heating the overlying continental lithosphere (Earth’s relatively rigid outer shell that consists of the entire crust plus the uppermost mantle) and triggering melting (Figure 5; Parker et al. 2012).

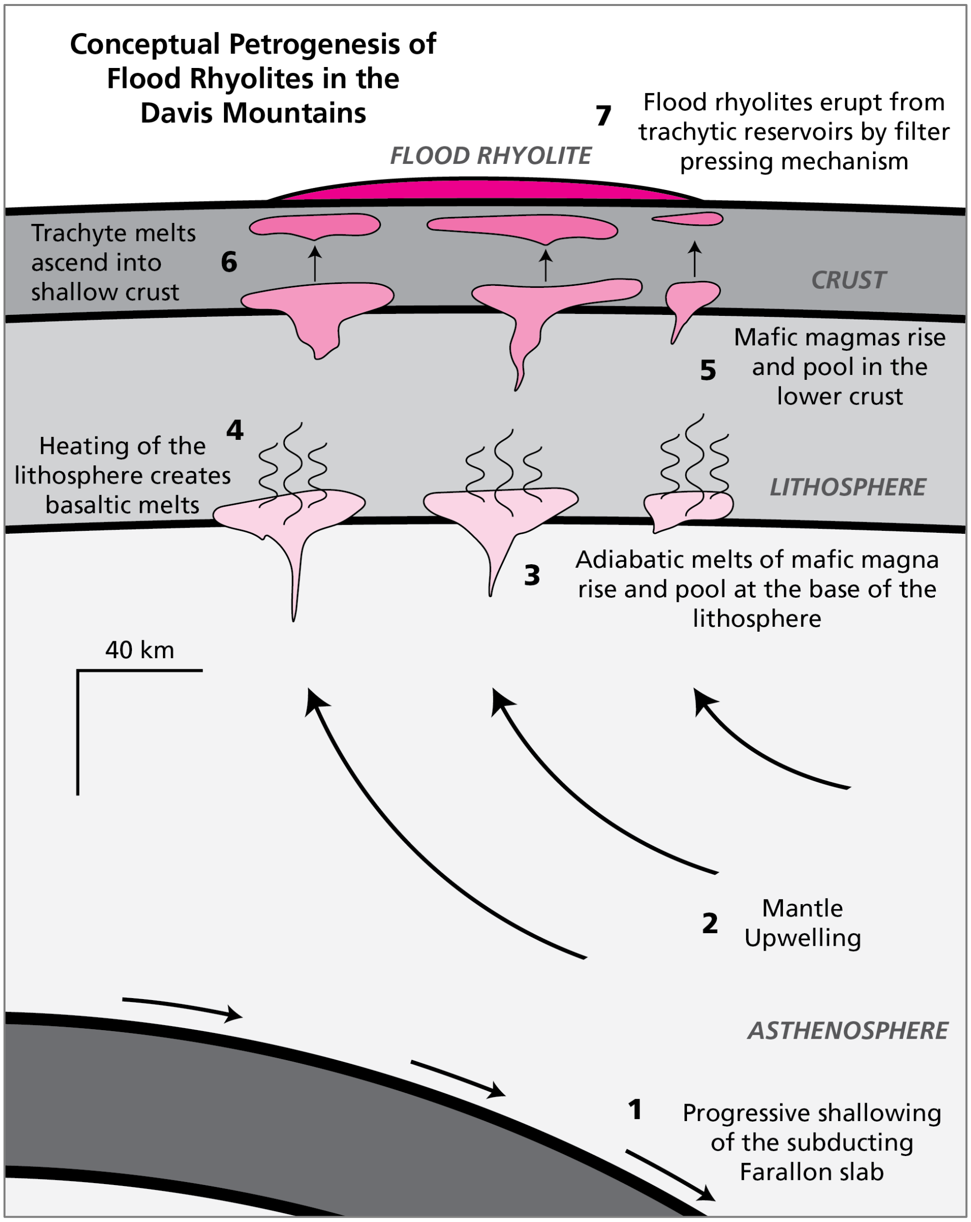

Figure 5. A conceptual diagram of the petrogenesis (rock origin) of flood rhyolites within the Davis Mountains. Flood rhyolites are silicic lavas that cover a geographically wide area (see “Volcanic Features and Processes” for more information on flood rhyolites). 1 & 2) The subducting Farallon slab undergoes progressive shallowing (gradual decrease in the angle of subduction of a tectonic plate as it moves beneath another plate) and triggers mantle upwelling (the process of upward movement of hot mantle material from the mantle’s lower regions towards the surface). 3) Adiabatic (a type of melting that occurs when hot mantle materials rise to shallower depths in the Earth’s mantle) melts of mafic magmas rise and pool at the base of the lithosphere. 4 & 5) Heating within the lithosphere creates basaltic melts that rise and pool in the lower crust as mafic magmas. 6) Trachyte (an igneous rock consisting of abundant coarse-grained crystals in a fine-grained groundmass) melts ascend from the mafic magmas into the shallow crust. 7) Flood rhyolites erupt from the trachytic reservoirs by filter pressing mechanisms (the process that occurs during the crystallization of intrusive igneous bodies in which the interstitial liquid is separated from the crystals by pressure). Graphic adapted from Parker et al. 2017.

Magmatism (the development and movement of magma and its solidification as igneous rock) within the Trans-Pecos region occurred between 47 million and 17 million years ago and peaked in the interval of 38 million to 32 million years ago (Parker and Henderson 2021). This magmatism is split into two distinct episodes: a likely continental volcanic arc from 47 million to 28 million years ago and crustal extension until 17 million years ago (Henry et al. 1989). The volcanic field that formed the Davis Mountains was most voluminously active from the late Eocene through the early Oligocene (38 million to 32 million years ago), during the continental volcanic arc episode (Parker and White 2007).

The continental volcanic arc episode is further divided into two additional phases, both of which are tied to subduction-related volcanism (Henry et al. 1989). The first phase primarily occurred in the Southern Trans-Pecos, near present-day Big Bend National Park. This phase, from 48 million to 39 million years ago, consisted of abundant but small intrusions, basaltic lava, and one small caldera complex in the Christmas Mountains, located south of Fort Davis (Henry et al. 1989).

The second phase of volcanism, the phase that formed the landscape around Fort Davis, occurred from 38 million to 32 million years ago. Within the Davis Mountains, volcanism was most active at the beginning of this phase, from 38 million to 35 million years ago (Parker and McDowell, 1979). This phase consisted of massive volumes of magmas, widespread volcanism, and the dominance of caldera-related volcanism (Henry et al. 1989). This phase emplaced large calderas (large, more-or-less circular, basin-shaped volcanic depressions formed by collapse during an eruption), small calderas, and trachyte (a group of fine-grained, generally porphyritic, volcanic rocks containing alkali feldspar and minor mafic minerals) shield volcanoes associated with small calderas across the Davis Mountains (Henry et al. 1989; Parker 1983, 1986). Abundant intrusions and lava flows unrelated to calderas also occurred across the region.

The phase began with an intrusion of basaltic magma into the upper crust (Henry et al. 1989). Next, differentiation (various processes by which magmas undergo bulk chemical change during the partial melting process, cooling, emplacement, or eruption) formed a batholith-sized magma body several kilometers beneath the surface, followed by widespread eruptions of quartz trachytes (Henry et al. 1989). Differentiation of evolved rhyolites then occurred in cupolas (small outlying igneous bodies, which may connect at depth with larger igneous masses) above the initial batholith, again followed by the eruption of evolved rhyolites (**Tsl** and **Tbs**) and the remaining less differentiated quartz trachyte (Henry et al. 1989). Table 2 lists the major volcanic units emplaced during the eruptive phase.

Table 2. Geologic units in the GRI poster and report. Volcanic units in the Eocene are listed by age, with the Frazier Canyon Formation being the oldest unit, and the Barrel Springs Formation being the youngest.

Geologic Map Unit (symbol)	Age	Description
Alluvium (Qal)	Holocene	Floodplain and alluvial plain deposits; floodplain deposits include low terrace deposits near floodplain level, bedrock locally in stream channels; alluvial plain deposits include fan deposits and colluvium locally near margins, coarser material toward margins, mostly sandy silt elsewhere, subject to modification by sheetwash action.
Fan Deposits (Qf)	Holocene	Colluvium and fan deposits; includes older Quaternary deposits in some areas.
Barrel Spring Formation (Tbs)	Eocene	From top down: indurated to friable, fine-grained vitric tuff; nonfoliated porphyritic rhyolite; pinkish gray to purplish brown, foliated porphyritic rhyolite; black foliated vitrophyre; thickness about 105 feet at type locality, thickens eastward to 290 feet in Barrilla Mountains.
Sleeping Lion Formation (Tsl)	Eocene	Porphyritic, rhyolitic ash-flow tuff, reddish brown to gray; has well-developed columnar jointing; thickness 329 feet at type locality, 610 feet 9 miles east of Fort Davis.
Frazier Canyon Formation (Tfc)	Eocene	Vitric-lithic-crystal tuff, locally contains conglomerate and sandstone, poorly bedded; white to light brown, gray, yellow, or green; three units separated by numerous mafic flows; thickness of formation at type locality 351 feet, somewhat thicker in Fort Davis area and Barrilla Mountains.

By 35 million years ago, volcanism had shifted back into the Big Bend region and away from the Davis Mountains. By the time of crustal extension-related faulting, high-volume flows ceased, and only volumetrically insignificant magmatism occurred throughout the Trans-Pecos region during the rest of the phase (Henry et al. 1989). The Davis Mountains exist on the eastern edge of the Basin and Range Province, where very little faulting occurred, preserving the original stratigraphic relationships relatively clearly (Figure 6; Henry et al. 1994). Across the rest of the Cenozoic to the present, erosion of the volcanic fields carved out canyons and cliffs within the Davis Mountains, washing away sediments into large basins (**Qf**) and forming the landscape seen today.

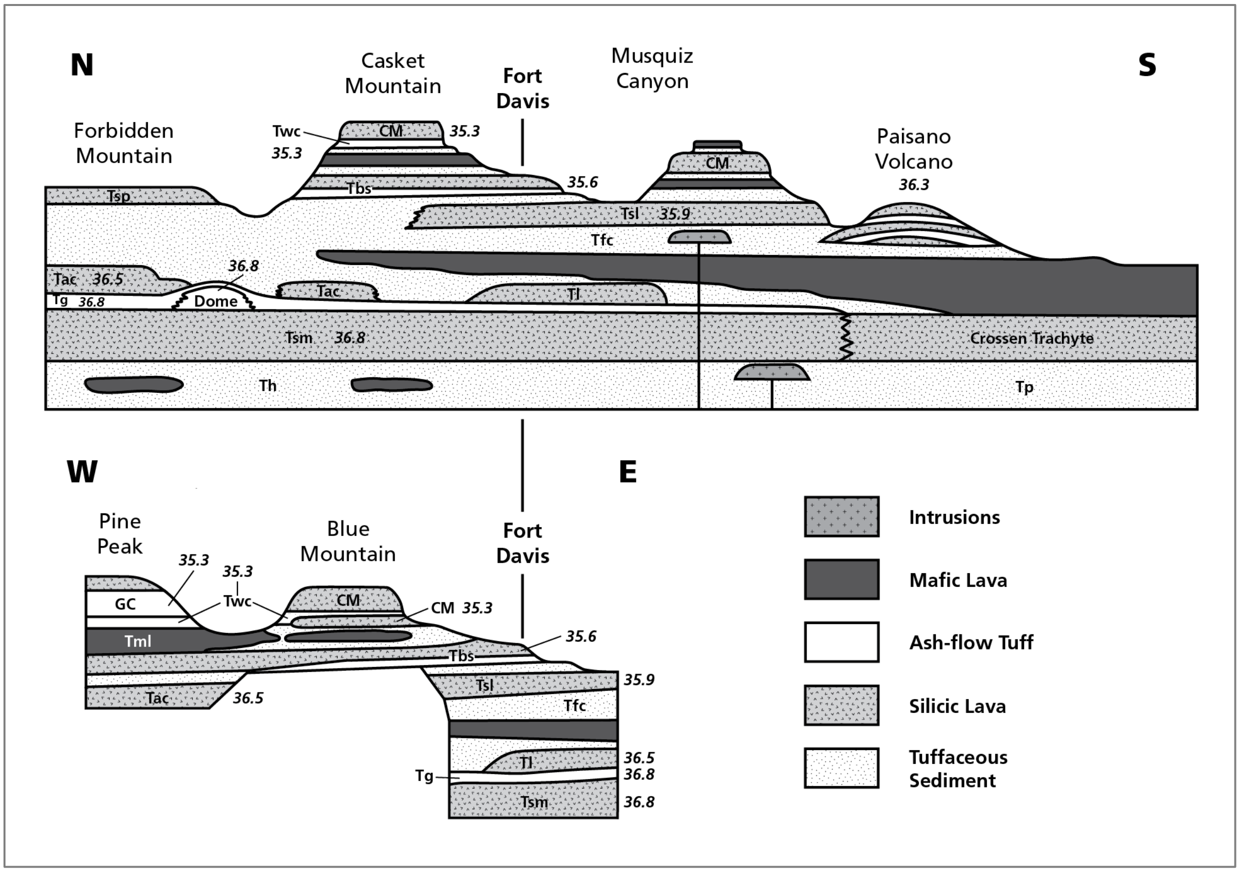

Figure 6. North-south and east-west cross sections of the Davis Mountains, centered on Fort Davis. Because the Davis Mountains avoided major faulting, the stratigraphic relationships between volcanic units still reflect the origin of their emplacement. Using stratigraphy paired with radiometric dating, temporal relationships between units are possible. In these cross sections of the Davis Mountains, average ^{40}Ar/^{39}Ar ages (provided in millions of years ago) are based on work by Henry et al. (1994). Some geologic units listed are not included in the GRI GIS data, poster, or report but are present across the Davis Mountains. GC: tuff of Goat Canyon; CM: lavas of Casket Mountain; Twc: Wild Cherry Formation; Tml: Mount Locke Formation; Tsp: Sheep Pasture Formation; Tbs: Barrel Springs Formation (silicic lava and ash-flow tuff); Tsl: Sleeping Lion Formation; Tfc: Frazier Canyon Formation (tuffaceous sediment and mafic lava); Tl: Limpia Formation; Tac: Adobe Canyon Formation; Tg: Gomez Tuff; Tsm: Star Mountain Formation; Th: Huelster Formation; Tp: Pruett Formation. Graphic adapted from Henry et al. 1994.

Geologic Features, Processes, and Management Issues

This chapter highlights geologic features and processes significant to the site's landscape and history. Selection of these features and processes was based on input from scoping and follow-up meeting 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 GRD provides technical and policy assistance for these issues (see "Guidance for Resource Management").

At the beginning of each of the following sections, map units corresponding to the GRI GIS data and 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.

Volcanic Features and Processes

The Davis Mountains are the largest individual feature within the Trans-Pecos volcanic field and the largest alkalic (rocks that are enriched in sodium and potassium) province in North America, containing abundant and widespread silicic lavas, ignimbrites, and trachyte porphyry (an igneous rock consisting of abundant coarse-grained crystals in a fine-grained groundmass) lavas (Henry et al. 1994; Parker and Henderson 2021). Encompassing over 2,590 km^2 (1,000 mi^2) and a thickness of roughly 1,000 m (3281 ft mi), the present Davis Mountains represent only an erosional remnant of the original volcanic field that was likely 5 to 10 times larger (Anderson 1969; Smith 1975).

Depending on the abundance of silica (SiO_2, the compound that forms many common minerals, including quartz), alkalic magma can either be silicic (>65% SiO_2) or mafic (<65% SiO_2; Kunk et al. 1994). The Davis Mountains contain extensive, high-volume silicic lavas (also called flood rhyolites; see Figure 5), unlike most other silicic volcanic fields, which are dominated by ash-flow tuffs (consolidated or cemented volcanic ash and lapilli deposited by an ash flow; Henry and Wolff 1992; Henry et al. 1994; Cameron et al. 1996). Only two major ash-flow tuffs are documented within the Davis Mountains, and both have undergone intensive secondary flow (the movement and deformation of volcanic deposits after their initial emplacement; Henry et al. 1994). The prevalence of silicic lavas over ash-flow tuffs has been attributed to low eruptive water contents in the magmas, leading to hot and dry eruptions (Henry et al. 1994).

The silicic eruptions in the Davis Mountains seemingly had a high surface area to volume ratio, erupting from widespread fissures across the region while mafic lava flows only sporadically erupted between the dominant silicic episodes (Henry et al. 1994). The lower-density silicic magmas overlaid the higher-density mafic magmas, blocking and restricting the eruption of the mafic magmas until the silicic magmas had erupted, cooled, and solidified (Henry et al. 1994).

Frazier Canyon Formation

Map unit: Frazier Canyon Formation (**Tfc**)

The Frazier Canyon Formation is a widespread bedded tuff unit composed of reworked ash, sandstone, and conglomerate, interbedded with mafic lava flows of intermediate composition (Figure 7; Smith 1975; Vincent 1988; Don Parker, Baylor University, Professor Emeritus of Geology, personal communication, 4 June 2024). Most of the tuff beds within the formation are rhyolitic vitric-crystal tuff, with some containing enough fine-grained shards to be classified as tuffaceous sandstone (Smith 1975). The top few meters of the formation exhibit signs of baking from the sharp contact of the overlaying Sleeping Lion Formation (Smith 1975).

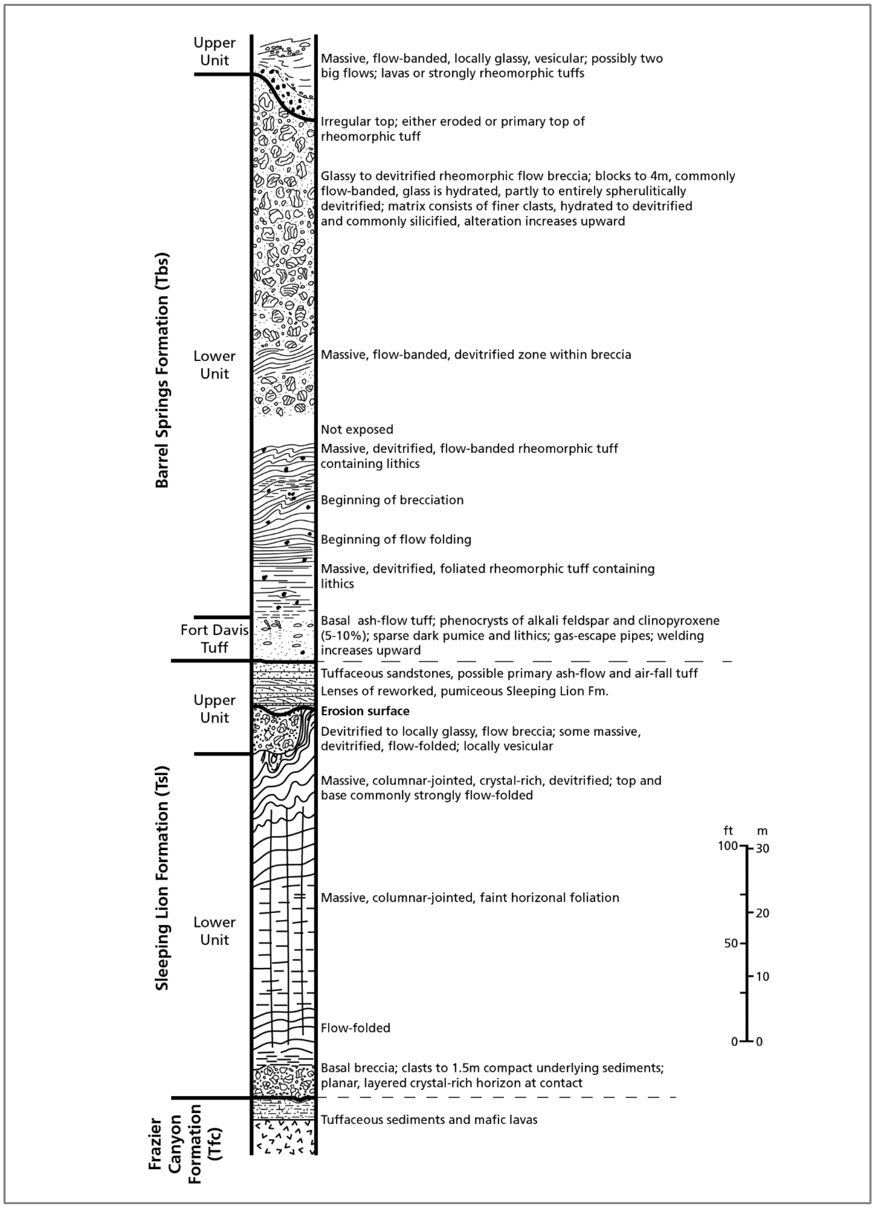

Figure 7. Stratigraphic section of the Barrel Springs, Sleeping Lion, and Frazier Canyon Formations from Davis Mountains State Park. Davis Mountains State Park is adjacent to Fort Davis National Historic Site. Each formation is broken down into units and described in detail. Erosional surfaces are noted. Many of these units can be seen within the park. Adapted from Henry et al. (1989).

The formation mostly crops out in places east of Fort Davis, with varying thicknesses. Exposures of the Frazier Canyon Formation are often overlain by talus slopes eroded from the Sleeping Lion Formation or Fort Davis Tuff (Voldseth 2001). Within the park, the Frazier Canyon Formation is mostly mafic lava exposed in gulleys around the fort and excellently in roadcuts along State Highway 118 (Don Parker, Baylor University, Professor Emeritus of Geology, personal communication, 4 June 2024).

Sleeping Lion Formation

Map unit: Sleeping Lion Formation (**Tsl**)

Directly above the Frazier Canyon Formation lies the Sleeping Lion Formation. Although not a formally designated stratotype, the formation is named after Sleeping Lion Mountain, located within the boundary of the park. The origin of the Sleeping Lion Formation puzzled researchers for decades. It is less widespread than many of the other formations in the region at only 30 km (18.6 mi) wide and has been suggested to have originated west of Fort Davis, although no clear associating caldera has been identified, likely having been covered by younger volcanics (Henry et al. 1989, 1994). However, recent correlation work by Parker (2018) has shown the Sleeping Lion Formation to be an outflow of the Moore Tuff (not on the geologic poster), located within Muerto Caldera of the northwestern Davis Mountains.

For decades, the composition of the unit, which reaches thicknesses of up to 130 m (426.5 ft), was debated between a low-silica rhyolite lava or a rhyolitic ash-flow tuff (ignimbrite; Smith 1975; Henry et al. 1994). Henry et al. (1994) date the Sleeping Lion Formation to around 35.92 million years ago (± 0.8 million years ago) using $^{40}\text{Ar}/^{39}\text{Ar}$ dating. The formation has an estimated volume of 50 km^3 (12 mi^3; Henry et al. 1994).

The formation possesses a unique flow pattern in which initial flows originated in vents northwest of Fort Davis, flowed through a paleovalley to the northeast, changed course to move southeast, and ultimately flowed southwest, thinning out for a total flow distance of roughly 40 km (24.9 mi; Hicks 1983; Henry et al. 1989). The formation primarily shows lava-flow features; however, various textures found across the formation suggest a possible pyroclastic origin. It has been suggested that the initial eruption was an ash-flow tuff that was obliterated by primary laminar viscous flow (a smooth, highly viscous [slow] flow moving in a constant direction) and extreme rheomorphism (when a pyroclastic rock's texture is obscured by ductile deformation upon emplacement; Henry et al. 1989). At present, it is believed that the unit is a strongly rheomorphic ignimbrite that flowed as lava after its initial pyroclastic flow deposit (Don Parker, Baylor University, Professor Emeritus of Geology, personal communication, 4 June 2024).

The formation is easily recognizable, with massive columnar jointing and large folding visible from the fort (Figure 8). It reflects a coarse and abundantly porphyritic flow with high-amplitude folding, indicating a possible constriction in a paleovalley during its original flow (Figure 9; Henry et al. 1989). The top of the formation consists of breccia (a coarse-grained, generally unsorted volcanic rock consisting of partially welded angular fragments of ejected material), which is generally poorly exposed within park boundaries (see Figure 7). The core of the formation consists of massive columnar jointing (see Figure 8), flow-folding, and flat to low-angle sheets. The bottom of the formation, exposed near the eastern base of Sleeping Lion Mountain within the park, consists of a 2 m (6.6 ft) thick breccia overlaying a distinct 20–30 cm (7.8–11.8 in) crystal-rich layer that represents either air-fall or surge deposits (volcanic deposits resulting from turbulent gas and rock fragments moving rapidly outward from the eruption source; Henry et al. 1989). Large boulders up to 8 m (26.2 ft) across are common along the slopes and base of the formation (Smith 1975).

Figure 8. Columnar jointing in the Sleeping Lion Formation along the North Ridge. The massive, columnar-jointed cliff faces of the Sleeping Lion Formation (Tsl) create a stunning backdrop to the fort. The Frazier Canyon Formation (Tfc) crops out at the base of the cliffs, although it is often covered by debris and boulders from the Sleeping Lion Formation. Photograph by Matthew Harrington (Colorado State University).

Figure 9. Photograph of rhyolite. A close-up view of the texture of the rhyolitic rock found within the columnar-jointed section of the Sleeping Lion Formation. The columnar-jointed section of the Sleeping Lion Formation (Tsl) is crystal-rich and course in texture. Most of the accessible exposures of the Sleeping Lion Formation within the park share this texture. Photograph by Matthew Harrington (Colorado State University).

Barrel Springs Formation

Map unit: Barrel Springs Formation (**Tbs**)

Named for the old Barrel Springs stagecoach stop, the formation erupted roughly 35.6 million years ago with large volumes of lava and tuff, primarily porphyritic, low-silica rhyolite (Henry et al. 1994). The Barrel Springs Formation overlies the Sleeping Lion Formation (see Figure 7) and has been beautifully exposed in various historic quarries around Fort Davis (Smith 1975). The formation is the most voluminous and widespread in the Davis Mountains and contains both lava flows and extremely rheomorphic ash-flow tuffs (Smith 1975; Henry et al. 1989). However, the lower section of the unit does not have a clear distinction between rheomorphic ash-flow tuff and lava in most places (Henry et al. 1989; Henry et al. 1994).

As with many of the volcanic units within the Davis Mountains, the origin of the Barrel Springs Formation is also enigmatic. It spreads roughly 90 km (56 mi) across the Davis Mountains and is composed of a series of poorly understood lava flows that possibly stemmed from a caldera in the southwestern area of the Davis Mountains (Henry et al. 1989). Younger flows have likely covered up the original source, and intensive field work across the eastern Davis Mountains indicates that neither a caldera nor feeder dikes are present (Henry et al. 1994). Parker and Henderson (2021) proposed elevating the Barrel Springs Formation to the Barrel Springs Group, containing the Mount Locke Formation, Wild Cherry Tuff, Fort Davis Tuff, Casket Mountain Formation, and undifferentiated lavas.

Near the fort, ash-flow tuffs exist at the base of the formation and blend upward into rock that underwent an extreme secondary flow that wiped away all traces of the initial pyroclastic features, indicating the unit is a rheoignimbrite (a type of ignimbrite that has undergone secondary flowage due to high temperatures; see Figure 9; Henry et al. 1989; Henry et al. 1988). The formation displays an upward transition from a typical eutaxitic ash-flow tuff to a highly rheomorphic ash-flow tuff (Henry et al. 1989). Only the lower part of the Barrel Springs Formation exists within the boundary of the park. This ash-flow-tuff section of the formation contains abundant pumice (up to 50 cm [19.7 in]), occasional lithic fragments, and elutriation pipes (elutriation pipes are vertical or slightly tilted structures within volcanic deposits that contain dense materials like lithic clasts and crystals, have better sorting, and are coarser-grained than the surrounding sediment; Henry et al. 1989). This section is often referred to as the Fort Davis Tuff (Smith 1975; Parker and Henderson 2021). The Fort Davis Tuff was the primary building stone used in fort construction. Although exposures exist at the head of Hospital Canyon and the upper part of North Ridge (see the GRI poster), most quarrying occurred at Dolores Mountain, a ridge on the southeastern end of the town of Fort Davis (Smith 1975).

Water Features and Processes

Groundwater and Springs

The town of Fort Davis lies within the Igneous Aquifer system, a series of small, discontinuous aquifers located among the porous extrusive lava flows and weathered volcanic sediments (Hart 1992; Chastain-Howley 2001; Beach et al. 2004). The recharge for these aquifers relies exclusively on the infiltration of precipitation into fractured and weathered zones within the rock; additional recharge from adjacent aquifers does not occur (Chastain-Howley 2001; Beach et al. 2004). Due to climate change, consistent precipitation has become less common, and increasingly variable conditions have prevailed. Between 2000 and 2017, nine of the seventeen years experienced drought conditions over at least 80% of the Chihuahuan watershed where springs occur, with four of the nine drought years categorized as severe to exceptional drought conditions (exceptional being the highest rating for droughts; Robertson et al. 2019). During years of drought, recharge to the Igneous Aquifer system is limited, thereby reducing the availability of water to all users.

Aquifers within the Trans-Pecos region provide water to at least 150 springs; water quality and rates of discharge vary widely among them (Heitmuller and Reece 2003). Apart from the Pecos and Rio Grande Rivers (the defining borders of the eastern and western ends of the Trans-Pecos region, respectively), the only perennial source of water within Trans-Pecos Texas stems from natural springs (Robertson et al. 2019). In a region devoid of surface water, these springs supply vital water for livestock, flora, and local civilization. During the active period of the fort, springs and Limpia Creek (until the water in the creek began to dwindle; see “Geologic Heritage”) provided water for crops, livestock, horses, and human consumption.

As groundwater consumption has grown, the availability of springs has declined. Monitoring groundwater levels in aquifers is a priority for both the park and region, as increasing drought severity and hampered aquifer recharges have the potential to threaten the accessibility of water. The current primary water users in the region are agricultural (irrigation and livestock), domestic, and industrial, with variable municipal use in towns (Robertson et al. 2019). This use, along with shifting impacts from climate change, has threatened the sustainability of groundwater in the region (Robertson et al. 2019).

Within park boundaries, concerns over the health of the cottonwood grove exist. With lowered water tables, the cottonwoods may not be able to consistently access water. As relicts of the fort's active years, the cottonwoods are an important historical aspect of the park's landscape, and park administration is concerned about preventing a mass die-off (David Larson, Fort Davis National Historic Site, Superintendent, personal communication, 27 February 2023).

Precipitation and Erosion

Most precipitation falls in the town of Fort Davis in late summer and winter, with the majority falling during monsoonal events in the summer (Poulos et al. 2009). Typical annual precipitation in the town of Fort Davis is 40 cm (15.8 in), with a range of 25 to 140 cm (9.8 to 55.1 in; Poulos et al. 2009). During heavy rain events, Hospital Canyon is the drainage basin for water running off the slopes to the north, south, and west (Greene 1986). The flows from precipitation have created arroyos (small, deep, flat-floored channels or gullies of ephemeral streams in the arid and semiarid regions of the southwestern United States) that cut into the bajada-like (a broad, continuous alluvial slope or gently inclined detrital surface formed from the coalescence of alluvial fans along a basin margin) fan deposits (**Qf**) on which the fort was built (KellerLynn 2008). Tinaja-like depressions (depressions formed by erosion in the bedrock that hold water after a rain) at the western end of the park hold water that pours off the cliffs during storms.

Heavy rainfall and runoff during the fort's active years created perpetual issues including flooding and erosional damage to structures and the parade grounds. Efforts to limit the damage caused by these water flows were largely unsuccessful. Earthworks, walls, and drainage ditches were constructed by soldiers to channel water out of the canyon, but many historical accounts of the fort's second iteration describe inundation in many of the buildings, particularly on officers' row (Myers 2000). One of the first documented ditches, created in 1880, ran from the back of the canyon, along the base of North Ridge (see GRI poster), exiting the canyon north of the officers' row, north past the church, and ending in between the guard house and a barrack (Myers 2000).

Mixed success from the initial drainage ditch (constructed into the fan deposits **Qf**) led to the planning and implementation of an upgraded ditch system in 1883: the existing ditch was widened, and two new ditches, one in the center of the fort and one to the south, were excavated (Myers 2000). By 1888, the post commander ordered yet another ditch to be built along the base of Sleeping Lion Mountain, as the other ditches were either too high to receive water, not sloped enough to properly drain, or too shallow (Myers 2000). These ditches were maintained until the fort's closure in 1891.

Water runoff from monsoonal events is still a problem in the canyon. During heavy rains, flash floods can occur in Limpia Creek and the ephemeral creek coming out of Hospital Canyon. These flash floods can scour riparian corridors and incise the banks. During heavy rain events when Limpia Creek swells above its banks, water can flow over State Highway 118 and damage the road pavement and edges (David Larson, Fort Davis National Historic Site, Superintendent, personal communication, 27 February 2023). The ephemeral creek running out of Hospital Canyon lies along the pathway that leads to the Visitor Center (Figure 10). Incision along the creek channel has the potential to destabilize the path over time.

A historical berm exists between the hospital and officers' row to aid in flood mitigation (Figure 11). During heavy rains, water can backflow between the hospital and the berm (David Larson, Fort Davis National Historic Site, superintendent, personal communication, 27 February 2023). Work to rebuild and maintain the berm is planned (David Larson, Fort Davis National Historic Site, Superintendent, personal communication, 27 February 2023). Efforts are also underway to limit bank expansion and incision along the ephemeral creek out of Hospital Canyon and to slow the water's path to limit the erosional impacts (David Larson, Fort Davis National Historic Site, Superintendent, personal communication, 27 February 2023).

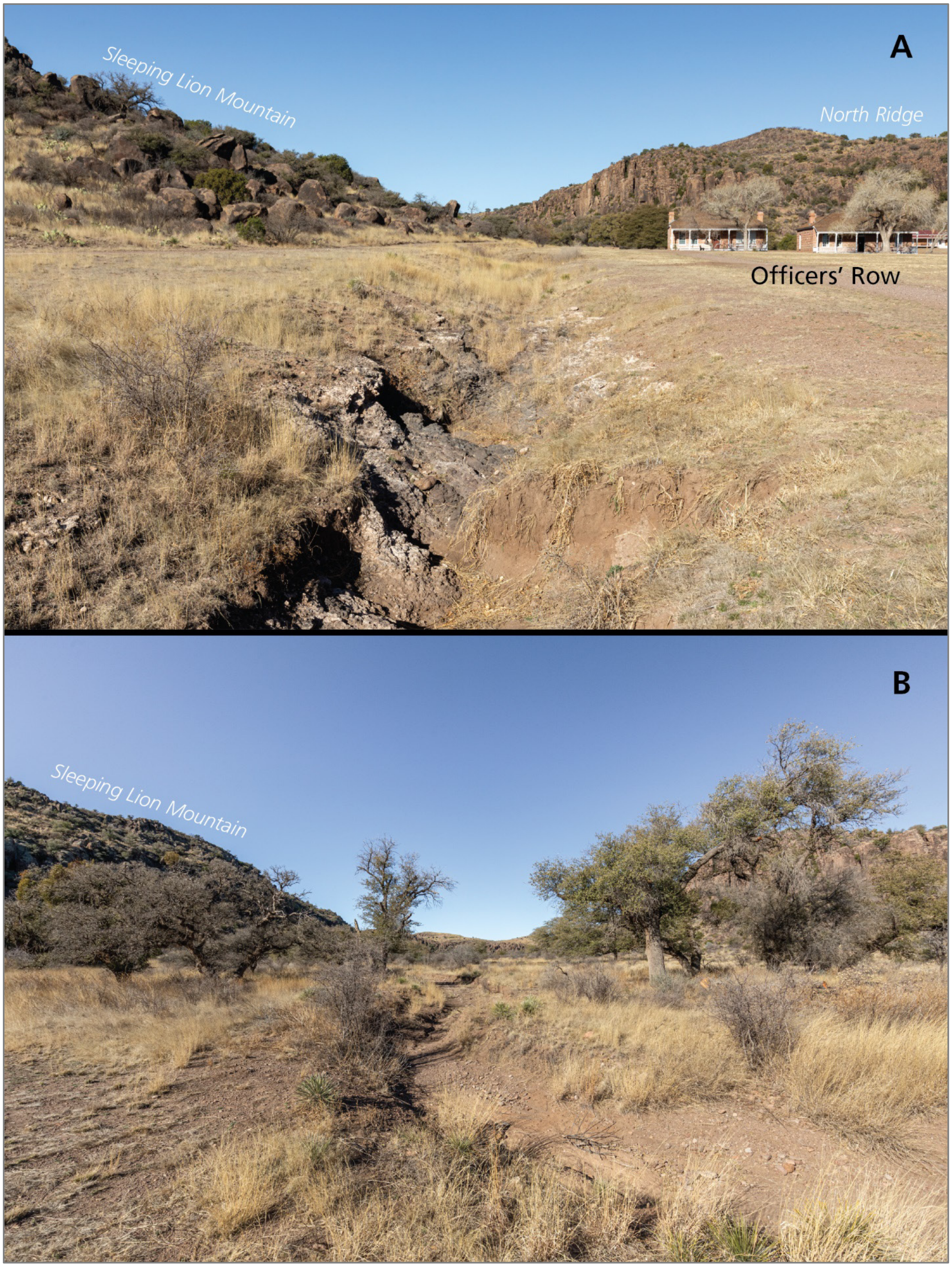

Figure 10. A view of the ephemeral creek that runs out of Hospital Canyon. A) Water has cut down into the canyon floor (Qf) to expose both rock and soil. The risk for erosion is higher on the exposed soil side. This creek is near the path that leads to the Visitor Center, Officers’ Row, and deeper into the canyon. B) A view of the same creek bed deeper into the canyon. The channel is slightly wider here than in photograph A and cuts mostly into sediment. Photos by Matthew Harrington (Colorado State University).

Figure 11. Photographs of the berm between the hospital and Officers' Row. The berm was built to limit water flow into the main section of the fort. A) Officers' Row, the line of houses, spans across the entrance to Hospital Canyon. The berm exists west of Officers' Row. Water can get trapped behind the berm, resulting in flooding toward the hospital. Sleeping Lion Mountain can be seen towering over the fort in the background. B) A close-up view of the berm as of 2023. The hospital can be seen in the background at the side of the photo. Photos by Matthew Harrington (Colorado State University).

Hillslope Features and Processes

Map unit: Sleeping Lion Formation (**Tsl**)

The Sleeping Lion Formation (**Tsl**) forms the iconic cliff faces that surround the fort within Hospital Canyon (see Figure 8). The cliff walls jut out of inclined slopes composed of formerly eroded sediments that merge into the flat canyon floor. Due to the steep incline of the cliffs, rockfall hazards are a potential concern for park staff, particularly along trails. Recording rockfall episodes to better quantify the risks to trails, facilities, and visitors is recommended (Denny Capps, GRD, Geomorphologist, personal communication, 23 May 2024). While the chance of a rock column falling is always a possibility, the formation tends to erode in fine grains, and as such, rockfalls are uncommon and not an immediate threat (Chelsea Rios, Fort Davis National Historic Site, Lead Interpretation, personal communication, 27 February 2023). As of 2024, rockfalls are considered low-risk for roads, trails, and facilities (David Larson, Fort Davis National Historic Site, Superintendent, personal communication, 18 June 2024).

During years of heavy precipitation, there can be potential for unstable soils and collapse (Davis Larson, Fort Davis National Historic Site, Superintendent, personal communication, 18 June 2024). Various trails along and on top of the canyon walls, including Photographer's Trail, Hospital Canyon Trail, Scenic Overlook Trail, Tall Grass Trail, and North Ridge Trail, get heavy foot traffic from park visitors. Paired with aoudad disturbances along trail edges (see "Disturbed Lands" section for more info on aoudads), significant erosion has been occurring along slopes, threatening the integrity of the trails (David Larson, Fort Davis National Historic Site, Superintendent, personal communication, 5 June 2024). A more detailed evaluation of these impacts along the trails is needed to assess the geology and limit future erosion.

The GRD employs three slope management strategies: (1) an Unstable Slope Management Program (USMP) for transportation corridor risk reduction; (2) quantitative risk estimation for specific landslide hazards; and (3) monitoring of potential mass wasting areas. Park managers can contact the GRD to discuss these options and determine if submitting a technical request is appropriate. Further information about slope movements is provided in "Guidance for Resource Management."

Talus Caves

Map unit: Sleeping Lion Formation (**Tsl**)

Various talus caves exist within gaps between boulders, eroded rock columns, and the columnar-jointed cliffs of Sleeping Lion Mountain (**Tsl**) itself. Water and wind-driven erosion have cut into Sleeping Lion Mountain over the last 35 million years, carving out rock from the mountain. Some of the talus caves are quite large, with enough space for multiple people to congregate (Figure 12). The caves have been utilized by people for at least two hundred years; during the period of the fort's occupation, soldiers took note of Mexican settlers utilizing the caves as shelters (see "Geoheritage"; Bliss 2007).

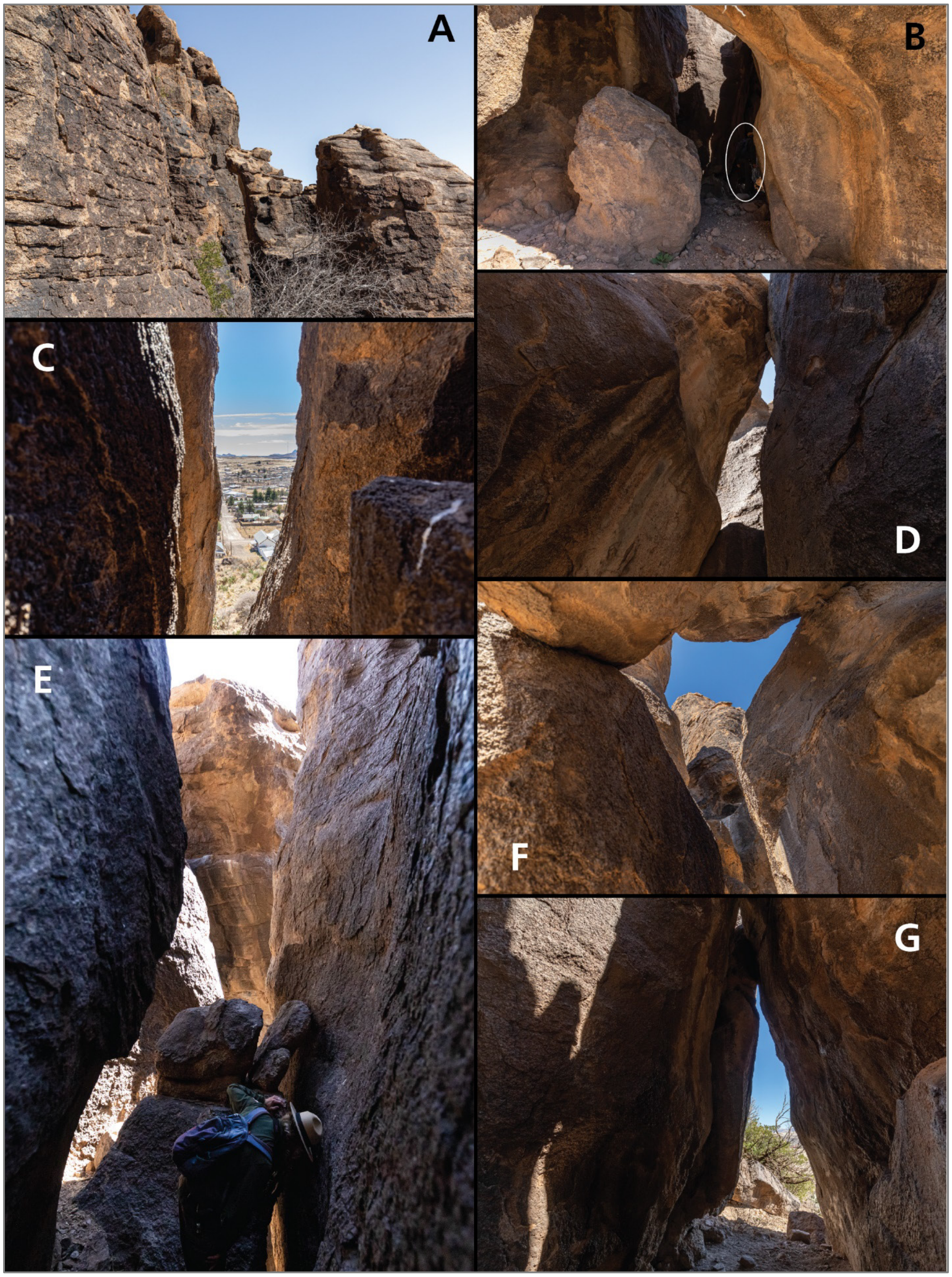

Figure 12. Photographs of talus caves along Sleeping Lion Mountain. A) A view of how the rhyolitic tuff has eroded when viewed on the mountainside. Gaps between rocks create large cavities. B) An entry point to one of the talus caves. The white oval showcases the size of a person relative to the surrounding rock. C) A hidden view of the town of Fort Davis from within a talus cave. D) An example of how the talus caves are not fully enclosed by rock; these openings are between massive boulders and cliff faces. E) Superintendent David Larson examines the route out of a talus cave. F) Skylight view from within one cave. G) A smaller entry point to a talus cave. Photos by Matthew Harrington (Colorado State University).

The caves have mostly avoided damage and graffiti from visitors. Outside one of the caves, park staff identified an area where graffiti had been illegally applied a few years prior to 2023. However, natural weathering and erosion had almost completely removed all traces of the graffiti (Chelsea Rios, Fort Davis National Historic Site, Lead Interpretation, personal communication, 27 February 2023).

The caves are isolated and hidden, and few signs of use or visitation by visitors are present. The caves preserve both physical and historical landmarks of the park; an inventory of the caves followed by occasional monitoring for litter or graffiti will be helpful in maintaining their pristine form.

Seismic Features and Processes Related to Oil and Gas Exploration and Development

Hydrocarbon production in the Permian Basin, located across western Texas and southeastern New Mexico, first began in the 1920s (Skoulmal and Trugman 2021). Since then, most earthquakes in the region have presumably been induced by hydrocarbon production activities (Skoulmal and Trugman 2021). Over the last decade, seismic activity has increased by orders of magnitude, particularly near the town of Pecos and throughout Reeves and Culberson counties, north of Fort Davis (Figure 13; Skoumal et al. 2020; Skoulmal and Trugman 2021; Douglas 2022a, 2022b). From 2008 to 2016, the rate of earthquakes with magnitudes greater than 3.0 has grown from two events per year to over 12 events per year (Frohlich et al. 2016). From 2020 to 2021 alone, the number of earthquakes with a magnitude of 3.0 or higher doubled, from 98 in 2020 to 209 in 2021 (Douglas 2022a).

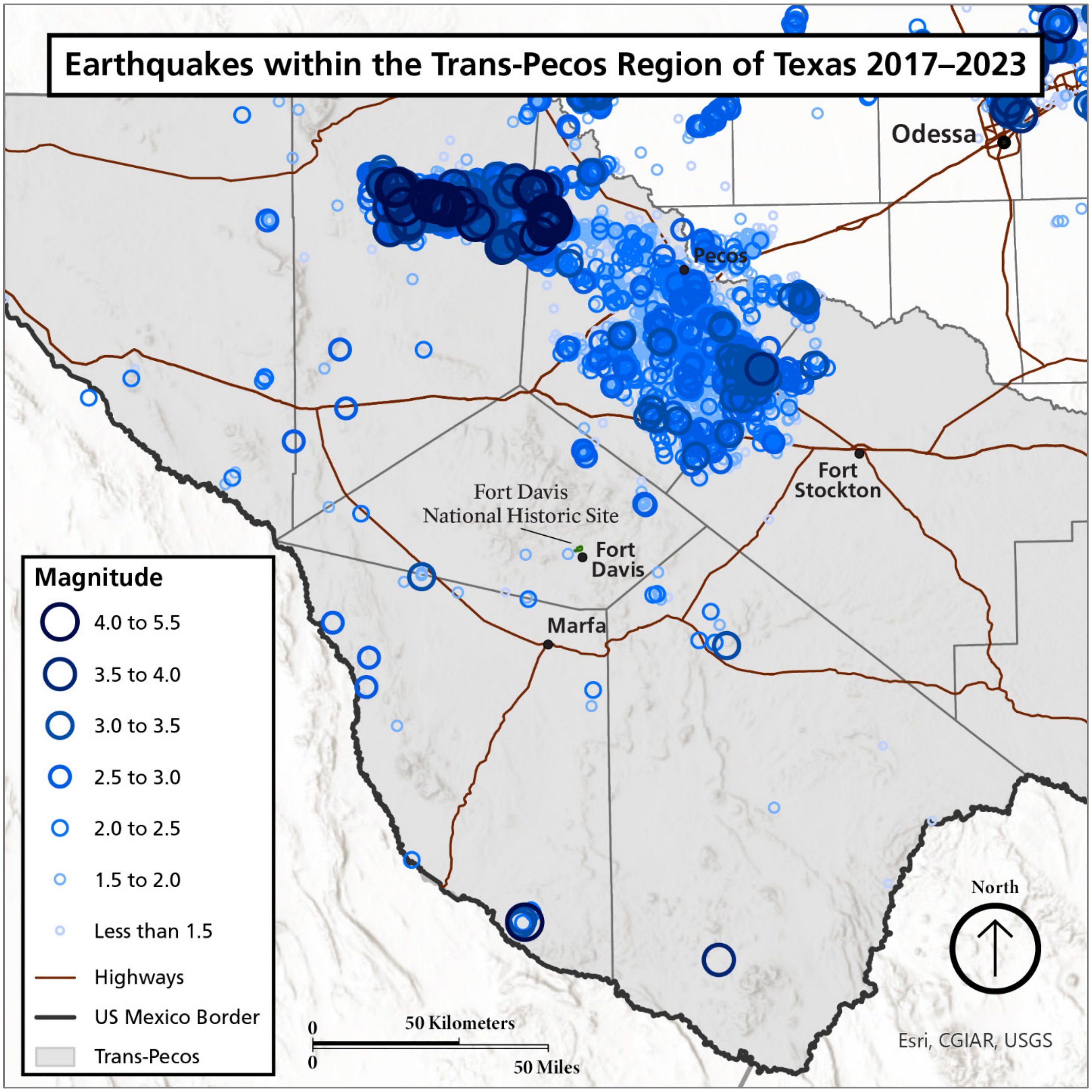

Figure 13. Map of earthquakes within Trans-Pecos Texas from 2017 to 2023. Wastewater disposal from fracking has been proposed as the primary cause of the increase in earthquakes within Trans-Pecos Texas. Most of this activity is concentrated north of Fort Davis, around the town of Pecos. Larger and darker circles represent higher magnitude earthquakes. Earthquake data is provided by the TexNet Earthquake Catalog https://www.beg.utexas.edu/texnet-cisr/texnet/earthquake-catalog. TexNet is a statewide earthquake monitoring system and research program funded by the State of Texas and managed and operated by the Bureau of Economic Geology at The University of Texas at Austin. The Bureau is the State Geological Survey of Texas. The TexNet system has a network of permanently installed seismometers across the state, as well as an inventory of portable seismometers that are deployed on a temporary basis. TexNet's role is to detect, locate, and report on earthquakes within the State of Texas. TexNet research includes analysis and reporting of earthquakes and their possible causes (whether naturally occurring or induced).

Since 2009, roughly 5% of the earthquakes in the region were induced by hydraulic fracturing (colloquially known as “fracking”), the process of injecting water, sand, and/or chemicals into underground strata to break up bedrock and free up oil or gas reserves (Skoumal et al. 2019; US Geological Survey 2019). However, most of the earthquakes were induced by wastewater disposal into wells deeper than 1.5 km (Skoumal et al. 2020; Skoumal et al. 2021). Wastewater disposal refers to the practice of disposing of contaminated water (a mixture of the initial fracking fluid, water trapped within the gas/oil bearing formation, fracking chemicals, salts, oils, grease, metals, and radioactive material) by injecting it deep underground into wells (Hammer 2012; Douglas 2022b). A number of earthquakes have also been attributed to waterflooding and the injection of supercritical CO_2 (Frohlich et al. 2016).

In 2022, a 5.4 magnitude earthquake was recorded west of Pecos, near the boundary between Reeves and Culberson counties (US Geological Survey 2022). The earthquake was the largest recorded in Texas since 1995 and the third-largest earthquake in the state’s history (Douglas 2022b). The earthquake was felt within the park, though no major damage or rockfalls occurred (David Larson, Fort Davis National Historic Site, Superintendent, personal communication, 27 February 2023).

Unless updated regulations or precautions are implemented to manage wastewater disposal more safely, the current trend of earthquakes in the region is likely to continue. Although the park does not lie directly within the earthquake hot spot, as seen in the 2022 5.4 magnitude earthquake, earthquakes can still be felt at the park. Monitoring the potential impact of earthquakes on historic buildings, park facilities, roads, trails, and cliff faces may prove useful in determining any potential risks (Figure 14).

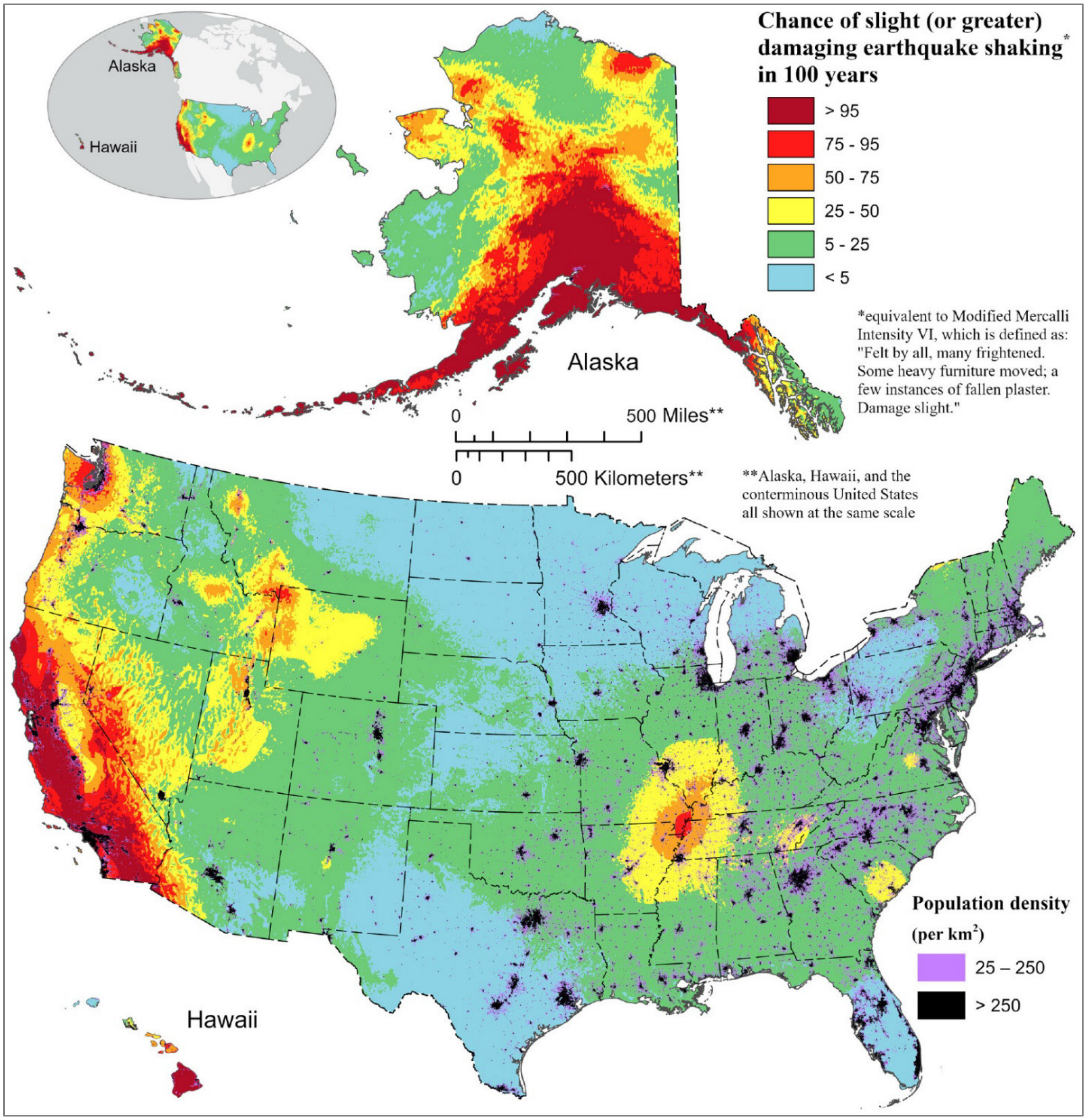

Figure 14. National seismic hazard map. The map shows the chance of any level of damaging earthquake shaking in 100 years from the 2023 50-State National Seismic Hazard Model. The shaking is equivalent to Modified Mercalli Intensity VI and higher and is based on the average peak ground acceleration and 1-s horizontal spectral response acceleration (using Worden et al. 2012 model without uncertainty). Ground motions are amplified using hybrid VS30 estimates (Heath et al. 2020). Population density (LandScan, Dobson et al. 2000 with 1 km×1 km resolution from Oak Ridge National Laboratory) is superimposed on the map. Map by Petersen et al. (2024, Figure 3) available at https://doi.org/10.1177/87552930231215428. (Accessed 24 April 2024).

Eolian Features and Processes

The term eolian refers to windblown erosion, transportation, and deposition of sediments (Lancaster 2009). Features created by eolian processes include depositional landforms and deposits such as dunes, loess (windblown silt-sized sediment), and sand sheets, as well as erosional forms such as desert pavement, yardangs (a sharp irregular ridge of compact sand lying in the direction of the prevailing wind), and ventifacts (a stone shaped by the erosive action of windblown sand). There are no significant dunes or loess deposits within the park, but dust storms are common, primarily because of disturbed agricultural fields (KellerLynn 2008). When dust storms occur during precipitation events, rain can mix with the dust within the air to cause "mud storms" (KellerLynn 2008). As dust storms are commonplace in western Texas, there are no immediate threats or concerns associated with them.

Wind erosion can also break down soil and expose geological features to further erosion. Data from the Web Soil Survey highlights each soil unit's susceptibility to wind erosion (Figure 15). Most of the canyon floor is rated as possessing a very low or moderate risk for wind erosion. The rocky cliffs, possessing little to no soils, are unrated. Only a small segment of the park at the northern boundary, along Limpia Creek, possesses a high risk for wind erosion.

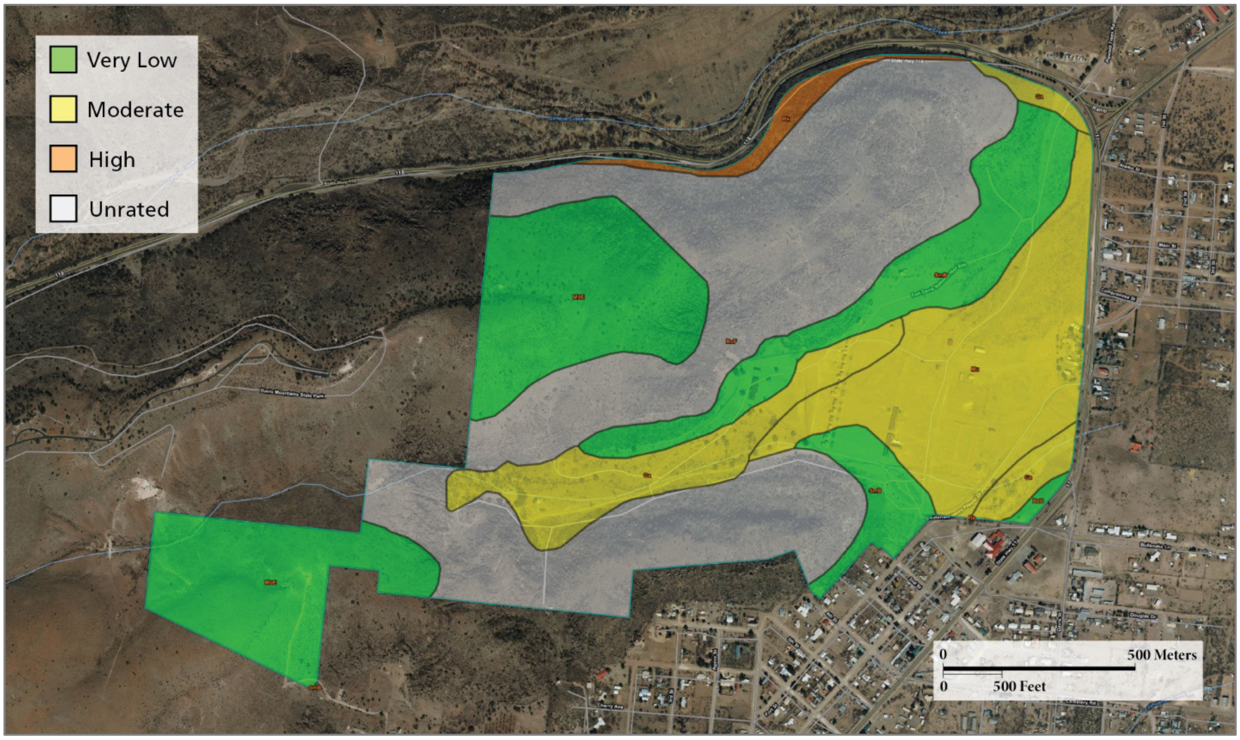

Figure 15. Map of soil susceptibility to wind erosion in the park. Most of the park falls within the very low to moderate risk range, with the far northern edge of the park showing a higher risk. Data from Web Soil Survey; map created by Matthew Harrington (Colorado State University).

Disturbed Lands

Historical Landscape

Disturbed lands (lands impacted by human activities, both current and historic) disrupt natural processes and features across the entire National Park System. Some of the disturbed lands, however, include features that are cultural or historical in nature and require preservation and active management.

The landscape of the park was altered by the military and civilians living in and around the active fort. Junipers and scrub oak were logged locally and from higher elevations in the Davis Mountains (Greene 1986). The heavy removal of vegetation from the region altered erosional patterns and local biodiversity. Wells were dug within the fort to access groundwater in a spring that no longer produces (KellerLynn 2008). The physical alteration of the canyon floor (**Qf**) by means of berms, ditches, dams, and earthworks disrupted the natural flow of water from precipitation events to protect fort structures. The quarrying of locally available ignimbrite for building stone (**Tbs**) physically removed rock from the surrounding mountains.

The existing remains of the old quarries, earthworks, and wells reflect the history of the park's impact on the landscape. Preserving and interpreting the roles and impacts of these features helps to highlight the relationship between people and the land.

Aoudad

The Barbary sheep, or aoudad (*Ammotragus lervia*), which is native to North Africa, has increasingly become problematic in Texas (Figure 16). After their introduction into North America via zoos in the early 1900s, the aoudad was introduced into private ranches in Texas by 1970 (Wright et al. 2022). As of 2022, it was estimated that over 30,000 free-ranging aoudads exist in Texas; more aoudads occur in Texas than in their native habitat, where they are listed as "vulnerable" (according to the International Union for Conservation of Nature [IUCN] Red List of Threatened Species; Wright et al. 2022).

Figure 16. Aoudad at Big Bend National Park. These photographs were taken nearby at Big Bend National Parl. Aoudad can often be mistaken at a distance for bighorn sheep by visitors. Aoudad herds can contain over 100 individuals, vastly increasing their damage to local geology and vegetation. National Park Service photos.

In addition to concerns over competition and disease transmission with native bighorn sheep (*Ovis canadensis*), aoudads damage the local environment, including at the park. These herds not only trample and consume native flora but can also damage soils and geological resources. Aoudads will often scrape their horns against rock faces, scratching and carving into the surface. In addition, they are known to create shallow pits in the ground—areas they dig up, roll around in, or simply disturb (Figure 17). These pits can be large and numerous, damaging the plants and soils essential for native species and processes.

Figure 17. Aoudad pit on Sleeping Lion Mountain. Superintendent David Larson stands next to an aoudad pit on Sleeping Lion Mountain (Tsl) in the park. The removal of plants within the area is noticeable, as are the upturned soil and scattered rocks. These types of pits also encourage future erosion that plants and soil crusts would otherwise limit. Photograph by Matthew Harrington (Colorado State University).

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 in the scoping summary (KellerLynn 2008) and was also mentioned during conversations with park staff in 2023. Park managers are directed to the NPS Climate Change Response Program (see "Additional References, Resources, and Websites") to address climate change planning, which helps parks 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). Because climate change affects geologic features and processes in different ways, the impacts of climate change on various systems are described within each applicable subsection (e.g., the impact of climate change on precipitation and storms is discussed within the subsection “Water Features and Processes”). In general, climate change manifestations that may intensify geologic hazards include the following: more intense droughts and more intense storms.

Shrink/Swell Soils

When soils contain clay, changes in moisture levels can cause soils to swell or shrink in size. In particularly clay-rich soils, shrinking and swelling can lead to major volume changes, potentially causing major damage to nearby structures. When building park infrastructure, understanding areas of high susceptibility to shrinking or swelling soils is helpful for avoiding long-term damage.

At the park, most of Sleeping Lion Mountain and North Ridge (**Tsl**) are unrated for linear extensibility (the measurement for shrink/swell soils) due to their rocky nature and lack of soil (Figure 18). The northern boundary of the park, south of Limpia Creek, only possesses a low rating (**Qal**; Figure 18). The base of Hospital Canyon (Qf) and areas in the western part of the park are split between low and moderate ratings (Figure 18). Historic buildings and ruins overlaying areas rated as moderate should be monitored for shrink/swell damage. However, no part of the park falls under a high or very high rating, limiting potential damage.

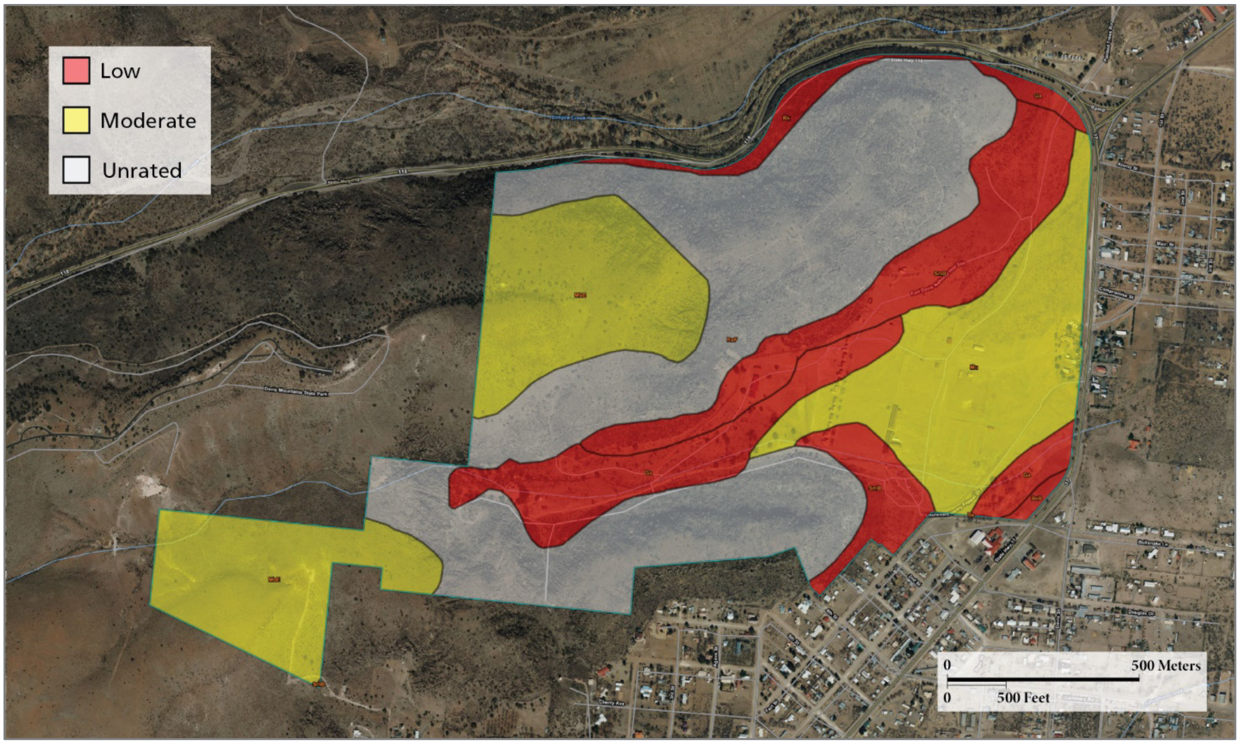

Figure 18. Map of soil susceptibility to shrink or swell in the park. Linear extensibility measures the change in length of an unconfined clod as moisture content is decreased from a moist to a dry state. A low rating indicates a small change (less than 3%), in contrast to a high or very high rating, indicating a large range in volume from moist to dry. The shrink-swell potential is low if the soil has a linear extensibility of less than 3%; moderate if 3 to 6%; high if 6 to 9%; and very high if more than 9%. If the linear extensibility is more than 3%, shrinking and swelling can cause damage to buildings, roads, and other structures and to plant roots. Special design is commonly needed. At the park, the rocky areas are unrated, and the canyon floor is split between a low rating and a moderate rating. Note that the red color indicates a "low" rating. Data from Web Soil Survey; map created by Matthew Harrington.

Geologic Hazards

Park resources are not only visitor attractions but may also be potentially hazardous. The dynamic landscapes preserved at many national park units present a variety of natural hazards that threaten NPS facilities, staff, and visitors. Many of these natural hazards are geologic. 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 in the park, identified during the GRI process, are flash floods and rockfalls. Additional potential geologic hazards include earthquakes, shrink/swell soils, and radon. For more detailed descriptions of potential hazards, refer to the "Geologic Features, Processes, and Management Issues" section. Table 3 summarizes the geologic hazards at the park.

Table 3. Geologic hazards checklist. This summary table is a synthesis of existing GRI-compiled map data and information, as well as published US Geological Survey or state geological survey information. It is appropriate for use at park-scale discussions and assessments. It is not a substitute for site-specific investigations or NEPA analysis. Ground-disturbing activities should neither be approved nor denied based upon the information here. This table is modeled after the Natural Hazard Checklist (see National Park Service 2015 and Jarvis 2015). It is meant to provide general information to identify the full range of natural hazard-based risks for the site.

Potential Hazard	**Best Professional Judgement**	**Risk or Secondary Hazard**	**Sources of Geohazard Information**
Earthquake	Known Hazard	Falling objects. Collapsing structures. Loss of strength to foundations. Trigger to other hazards e.g., rockfall.	US Geological Survey Earthquake Probability Map (see Figure 16) Texas Seismological Network and Seismology Research (TexNet) (see Figure 15)
Slope movements (landslide/avalanche)	Potential Hazard	Rockfall Human injury or casualty	Communication with Chelsea Rios (lead interpretation) and David Larson (superintendent) 2023
Permafrost	Not applicable	Not applicable	Not applicable
Cave/karst	Not applicable	Not applicable	Not applicable
Shrink/swell soils	Known Hazard	Damage to structure “heaving” of ground beneath structure.	Web Soil Surve (see Figure 17)
Coastal storm surge/ sea or lake level change/shoreline erosion	Not applicable	Not applicable	Not applicable
Tsunami	Not applicable	Not applicable	Not applicable
Riverine Flood	Known Hazard	Flooding (from heavy rain) Destruction of roadways. Stream channel migration. Stream bank erosion.	Texas Water Development Board https://www.twdb.texas.gov/flood/index.asp
Flash Flood	Known Hazard	Sudden rising water (i.e., dry wash) Destruction of infrastructure	Texas Water Development Board https://www.twdb.texas.gov/flood/index.asp
Volcanic eruption	Not applicable	Not applicable	Not applicable
Hydrothermal activity	Not applicable	Not applicable	Not applicable
Radon	Potential Hazard	Health hazard (lung cancer)	Radon in Texas https://www.depts.ttu.edu/ceweb/radon/texas-radon.php

According to National Park Service (2006) management policies, 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. Human safety takes 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:

> *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. (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 and will be subject to the availability of funding and staffing as well as legal and policy considerations.

Recommendations may include the removal of known hazards and the application of other appropriate measures, including closures of roads or trails, installation of guard rails or fences, paving of walkways, installation of warning signs, distribution of weather warnings or advisories, limitation of backcountry or climbing permits, or application of 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 also not be practical.

Park managers may need to plan the placement of new visitor and other facilities in geologically hazardous areas such as fault zones, thermal areas, floodplains, flash flood zones, fire-prone vegetation areas, and coastal high-hazard areas. In addition, some park facilities subject to hazardous processes may need to be phased out, relocated, or have alternatives provided. If facilities must be placed in more hazardous areas, their design and siting should be based on a thorough understanding of the nature of physical processes to not only avoid risks to human life and property but also be aware of the impact the facility may have on natural physical processes and the ecosystem.

Guidance for Resource Management

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

Access to GRI Products

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

Three Ways to Receive Geologic Resource Management Assistance

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

Geological Monitoring

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

Park-Specific Documents

The park's Foundation Document (National Park Service 2016) and Historic Resource Study (Greene 1986) are primary sources of information for resource management within the park. These documents guided the writing of this GRI report.

NPS Natural Resource Management Guidance and Documents

- Fort Davis National Historic Site Natural Resource Condition Assessment: https://irma.nps.gov/DataStore/Reference/Profile/2218542
- National Parks Omnibus Management Act of 1998: https://www.congress.gov/bill/105th-congress/senate-bill/1693
- NPS-75: Natural Resources Inventory and Monitoring guideline: https://irma.nps.gov/DataStore/Reference/Profile/622933
- NPS Management Policies 2006 (Chapter 4: Natural Resource Management): https://www.nps.gov/subjects/policy/management-policies.htm
- NPS Natural Resource Management Reference Manual #77: https://irma.nps.gov/DataStore/Reference/Profile/572379
- Resist-Accept-Direct (RAD)—A Framework for the 21st-century Natural Resource Manager: https://irma.nps.gov/DataStore/Reference/Profile/2283597

Geologic Resource Laws, Regulations, and Policies

The following sections, which were developed by the GRD, summarize laws, regulations, and policies that specifically apply to NPS geologic resources, geologic processes, 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 include 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 the 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 (SMCRA) 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 the 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 Glen Canyon National Recreation Area, which is the only park unit that contains a STSA.
- **Exceptions:** Glen Canyon National Recreation Area (NRA) (16 USC § 460dd et seq.), Lake Mead NRA (16 USC § 460n et seq.), and Whiskeytown-Shasta-Trinity NRA (16 USC § 460q et seq.) authorize 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 of coal from Indian Tribal and Allotted leases.

    - **43 CFR Part 3160** governs onshore oil and gas operations, which are overseen by the BLM.

NPS Management Policies 2006:

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

Mining Claims (Locatable Minerals)

Resource-specific laws:

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

Resource-specific regulations:

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

NPS Management Policies 2006:

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

Nonfederal Minerals other than Oil and Gas

Resource-specific laws:

- NPS Organic Act, 54 USC §§ 100101 and 100751

Resource-specific regulations:

- **NPS regulations at 36 CFR Parts 1, 5, and 6** require the owners/operators of other types of mineral rights to obtain a special use permit from the NPS as a business operation (§ 5.3) or for construction of buildings or other facilities (§ 5.7), 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.

Nonfederal Oil and Gas

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, and 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 National Recreation Area.
- **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 National Historical Park (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 ensure 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

Climate Change Resources

- Intergovernmental Panel on Climate Change: http://www.ipcc.ch/
- *Global and regional sea level rise scenarios for the Unites States* (Sweet et al. 2022): https://oceanservice.noaa.gov/hazards/sealevelrise/sealevelrise-tech-report.html
- NPS Climate Change Response Strategy (2023 Update): https://www.nps.gov/subjects/climatechange/response-strategy.htm
- NPS Green Parks Plan: https://www.nps.gov/subjects/sustainability/green-parks.htm
- NPS National Climate Change Interpretation and Education Strategy: https://www.nps.gov/subjects/climatechange/nccies.htm
- NPS Policy Memorandum 12-02—Applying NPS Management Policies in the Context of Climate Change: https://npspolicy.nps.gov/PolMemos/policymemoranda.htm
- NPS Policy Memorandum 15-01—Addressing Climate Change and Natural Hazards for Facilities: https://npspolicy.nps.gov/PolMemos/policymemoranda.htm
- NPS Sea Level Change website: https://www.nps.gov/subjects/climatechange/sealevelchange.htm/index.htm
- *Sea level rise and storm surge projections for the National Park Service* (Caffrey et al. 2018): https://irma.nps.gov/DataStore/Reference/Profile/2253283
- U.S. Global Change Research Program: http://www.globalchange.gov/home

Days to Celebrate Geology

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

Earthquakes

- 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

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

Geologic Maps

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

Geological Surveys and Societies

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

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

NPS Reference Tools

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

Relevancy, Diversity, and Inclusion

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

Soils

- Web Soil Survey (WSS) provides soil data and information produced by the National Cooperative Soil Survey. It is operated by the USDA Natural Resources Conservation Service (NRCS): https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm

- WSS_four_steps (PDF/guide for how to use WSS): https://irma.nps.gov/DataStore/Reference/Profile/2305342

Texas Geology

- Texas Geological Survey: https://www.beg.utexas.edu/outreach/state-geological-survey
- West Texas Geological Society: https://www.wtgs.org/

USGS Reference Tools

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

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