National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

Fort Bowie National Historic Site

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2011/443

ON THE COVER
The ruins of the second Fort Bowie near the base of Bowie Peak.

National Park Service photograph by Karen Gonzales.

THIS PAGE
The doorway of the cavalry barracks frames the American flag flying to the west. Note the local stones used in the construction of the building and the lime plaster used to cover the walls.

National Park Service photograph.

Photographs available online:
http://www.nps.gov/fobo/photosmultimedia/photogallery.htm

Fort Bowie National Historic Site

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2011/443

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

September 2011

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

The National Park Service, Natural Resource Stewardship and Science office in Fort Collins, Colorado publishes a range of reports that address natural resource topics of interest and applicability to a broad audience in the National Park Service and others in natural resource management, including scientists, conservation and environmental constituencies, and the public.

The Natural Resource Report Series is used to disseminate high-priority, current natural resource management information with managerial application. The series targets a general, diverse audience, and may contain NPS policy considerations or address sensitive issues of management applicability.

All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner. This report received informal peer review by subject-matter experts who were not directly involved in the collection, analysis, or reporting of the data.

Printed copies of this report are produced in a limited quantity and they are only available as long as the supply lasts. This report is available from the Geologic Resources Inventory website (http://www.nature.nps.gov/geology/inventory/gre_publications.cfm) and the Natural Resource Publications Management website (http://www.nature.nps.gov/publications/nrpm/).

Please cite this publication as:

Graham, J. 2011. Fort Bowie National Historic Site: geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2011/443. National Park Service, Fort Collins, Colorado.

NPS 424/109950, September 2011

Contents

List of Figures

Executive Summary

This report accompanies the digital geologic map data for Fort Bowie National Historic Site in Arizona, produced by the Geologic Resources Division in collaboration with its partners. It contains information relevant to resource management and scientific research. This document incorporates preexisting geologic information and does not include new data or additional fieldwork.

Fort Bowie National Historic Site, authorized in 1964, commemorates the nineteenth century conflict between the Chiricahua Apache and the U.S. military. The site also preserves a slice of geologic history that dates back over 1 billion years and includes the intense deformation that gave rise to Apache Spring. In this arid climate, water has always been a valuable resource, and Fort Bowie was built in 1862 to protect Apache Spring and provide safe passage for the Butterfield Overland Mail route.

Apache Spring is located in Apache Pass at the juncture of the Dos Cabezas and Chiricahua mountains. Part of the Basin and Range physiographic province of southeastern Arizona, these mountains rise abruptly from relatively flat, sediment filled basins that formed millions of years ago. Older yet is the Apache Pass fault zone. Initiated over one billion years ago and reactivated throughout geologic time, this zone of extensively fractured and faulted rock units provides a conduit for the groundwater that feeds Apache Spring.

The 1- to 2- km- (0.6- to 1.2- mi) wide Apache Pass fault zone is the dominant structural feature in Fort Bowie National Historic Site. The fault zone contains fault slices separated by normal, strike-slip, and thrust faults. Erosion of the shattered rocks formed the topographic saddle of today's Apache Pass.

Erosion in the Apache Spring watershed is the most critical geologic issue facing resource management at Fort Bowie National Historic Site. Past management practices have aggravated the issue. Vegetation has been removed from the slopes above Apache Spring, causing accelerated soil loss during periodic intense rainfalls. Erosion caused by water cascading over brush dams in drainages has cut deep gullies into the slopes.

In 2006, a debris flow swept down Siphon Canyon and into Fort Bowie National Historic Site. The turbulent flow transported granitic boulders greater than 1.8 m (6 ft) in diameter. These boulders scoured the debris flow channel down to bedrock.

Rounded domes of relatively erosion-resistant granodiorite dominate the landscape in the western part of the park and at higher elevations beyond the park's boundaries. The granodiorite solidified from magma approximately 1.4 billion years ago. The much younger limestones, sandstones, and siltstones in the Apache Pass fault zone record a variety of depositional environments that have covered southeastern Arizona in the last 500 million years. Fossils and other stratigraphic features provide evidence of shallow seas that advanced and retreated across the region for millions of years before being replaced by fluvial, estuarine, and other terrestrial environments.

Tectonic activity along the western margin of North America resulted in mountain-building episodes and catastrophic volcanic eruptions in southeastern Arizona. About 20 million years ago, the crust of the southwestern United States switched from a compressional to an extensional regime and began to be pulled apart. This extension produced the fault-bounded basins and ranges of today's southwestern United States.

The history of human activity in Apache Pass includes the ruins of two Fort Bowies, remnants of the Butterfield Overland Mail route and stage station, the Fort Bowie cementary, and sites of conflict between the Chiricahua Apache and U.S. military.

A Map Unit Properties Table, glossary, and geologic timescale are included in this report. The Map Unit Properties Table describes characteristics such as erosion resistance, suitability for infrastructure development, potential for geologic hazards, geologic significance, and associated paleontological and mineral resources for each mapped geologic unit. The glossary contains explanations of many technical terms used in this report, and the geologic timescale (fig. 9) provides a general reference to major geologic activity that has occurred over the past 4.6 billion years.

Acknowledgements

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

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

Special thanks to: Colleen Filippone (NPS Sonoran Desert Network) and Ann Youberg (Arizona Geological Survey) for providing photographs and information regarding the 2006 debris flows within Fort Bowie NHS.

Credits

Author
John Graham (Colorado State University)

Review
John Bezy (Arizona Geological Survey)
Jason Kenworthy (NPS Geologic Resources Division)

Editing
Jennifer Piehl (Write Science Right)

Digital Geologic Data Production
Stephanie O'Meara (Colorado State University)

Digital Geologic Data Overview Layout Design
Derek Witt (Colorado State University intern)
Philip Reiker (NPS Geologic Resources Division)
Georgia Hybels (NPS Geologic Resources Division)

Introduction

The following section briefly describes the National Park Service Geologic Resources Inventory and the regional geologic setting of Fort Bowie National Historic Site.

Purpose of the Geologic Resources Inventory

The Geologic Resources Inventory (GRI) is one of 12 inventories funded by the National Park Service (NPS) Inventory and Monitoring Program. The GRI, administered by the Geologic Resources Division of the Natural Resource Stewardship and Science Directorate, is designed to provide and enhance baseline information available to park managers. The GRI team relies heavily on partnerships with institutions such as the U.S. Geological Survey, Colorado State University, state geologic surveys, local museums, and universities in developing GRI products.

The goals of the GRI are to increase understanding of the geologic processes at work in parks and to provide sound geologic information for use in park decision making. Sound park stewardship requires an understanding of the natural resources and their role in the ecosystem. Park ecosystems are fundamentally shaped by geology. The compilation and use of natural resource information by park managers is called for in section 204 of the National Parks Omnibus Management Act of 1998 and in NPS-75, Natural Resources Inventory and Monitoring Guideline.

To realize these goals, the GRI team is systematically conducting a scoping meeting for each of the 270 identified natural area parks and providing a park-specific digital geologic map and geologic report. These products support the stewardship of park resources and are designed for nongeoscientists. Scoping meetings bring together park staff and geologic experts to review available geologic maps and discuss specific geologic issues, features, and processes.

The GRI mapping team converts the geologic maps identified for park use at the scoping meeting into digital geologic data in accordance with their Geographic Information Systems (GIS) Data Model. These digital data sets bring an interactive dimension to traditional paper maps. The digital data sets provide geologic data for use in park GIS and facilitate the incorporation of geologic considerations into a wide range of resource management applications. The newest maps contain interactive help files. This geologic report assists park managers in the use of the map and provides an overview of park geology and geologic resource management issues.

For additional information regarding the content of this report and current GRI contact information please refer to the Geologic Resources Inventory website (http://www.nature.nps.gov/geology/inventory/).

Regional Information

Located in southeastern Arizona, Fort Bowie National Historic Site occupies 404 ha (999 ac) of Apache Pass, a valley separating the Dos Cabezas Mountains to the north from the Chiricahua Mountains to the south. Fort Bowie was established in 1862 to guard Apache Spring and provide safe passage through Apache Pass. The fort was constructed on land that records over 1 billion years of geologic history. Millions of years of intense deformation produced the complexly fractured bedrock underlying Apache Spring as adjacent tectonic plates collided. The historic site contains the ruins of two Fort Bowies, remnants of the Butterfield Overland Mail route and stage station, the Fort Bowie cemetery, and sites of conflict between the Chiricahua Apache and U.S. military (fig. 1).

Like other mountains in southeastern Arizona, the Dos Cabezas and Chiricahua mountains rise abruptly from the surrounding sediment-filled basins to form islands of rock in an arid desert. At Fort Bowie National Historic Site, elevations range from approximately 1,390 m (4,560 ft) at the mouth of Siphon Canyon to 1,600 m (5,250 ft) on Overlook Ridge. The internally-drained Wilcox Playa lies to the west at roughly 1,250 m (4,100 ft), and the San Simon Valley borders the mountains to the east. Fort Bowie National Historic Site is located 19 km (12 mi) south of Bowie, Arizona, and 187 km (116 mi) east of Tucson, Arizona via Interstate 10 and Arizona Highway 186. Chiricahua National Monument lies in the central Chiricahua Mountains, approximately 16 km (10 mi) southeast of the historic site (Graham 2009).

Regional Geology

The impressive Apache Pass fault zone cuts diagonally across the eastern section of Fort Bowie National Historic Site (see "Overview of Digital Geologic Data" graphic). One of the more extensive fault zones in southeastern Arizona, the Apache Pass fault zone is up to 2 km (1.2 mi) wide and trends northwest–southeast for nearly 60 km (38 mi) across the Dos Cabezas and Chiricahua mountains (Drewes 1980; Bezy 2001). The fault zone enters the Dos Cabezas Mountains about 19 km (12 mi) northwest of the historic site. In the Chiricahua Mountains, south of Fort Bowie, the fault zone curves to the southeast and crosses the northeastern corner of Chiricahua National Monument before exiting the range and becoming buried in the San Simon Valley (Drewes 1980).

The Apache Pass fault zone forms a belt of fractured rock layers (strata) ranging from approximately 500 million (Cambrian period) to 65 million (Cretaceous period) years in age (fig. 2). The faulted rocks within Fort Bowie National Historic Site consist primarily of Cretaceous and Permian rock units. The 146- to- 100-million-year-old Lower Cretaceous units are dominated by conglomerate, sandstone, and siltstone (map units Kc and Kg) with minor amounts of volcanic material (map unit Ksv) and limestone (map unit Kmu). In contrast, the 299- to- 271-million-year-old Permian strata are dominated by limestone (map units Pcn, Pc, Pe, and PPNh), with lesser amounts of sandstone and shale (map units Ps and Pea).

Geologists recognize three main types of rocks: igneous, sedimentary and metamorphic, all of which are present at Fort Bowie National Historic Site. Igneous rocks are formed through the solidification of magma on the surface (extrusive, or volcanic rocks) or beneath the surface (intrusive, or plutonic rocks). The Apache Pass fault zone is bordered by Proterozoic granodiorite, an intrusive igneous rock approximately 1.4 billion years old (fig. 2; Drewes 1984; Bezy 2001). Light-colored quartz and feldspar and darker-colored biotite give the rock its characteristic salt-and-pepper appearance.

Conglomerate, sandstone, siltstone, and limestone are the primary sedimentary rocks in the historic site. The sedimentary rocks within the Apache Pass fault zone began as sediments eroded from pre-existing rock units or formed through chemical or biological activity. The sediments were then transported by wind or water, deposited, buried, and cemented together by mineral cements, commonly silica dioxide or calcium carbonate. Sedimentary rocks composed of eroded fragmental material (clasts) are classified according to clast size. For example, conglomerate in the Glance Conglomerate (map unit Kg) consists of pebble-size or larger clasts, and sandstone, such as that found in the Scherrer Formation (map unit Ps), consists of sand-sized clasts. Chemical or biological activity produced the limestones in Fort Bowie National Historic Site, some of which contain fossils.

Metamorphic rocks are produced when intense heat, pressure, or shearing stress transforms rocks of other types. Rather than melting, the original rocks deform plastically and form a gel-like substance in which new minerals form or individual mineral grains fuse together. The Cintura Formation (map unit Kc) exposed near Apache Pass contains andalusite and staurolite, minerals that form only during metamorphism. Metamorphic recrystallization of the Horquilla Limestone (map unit Phl) on Overland Ridge has rendered it more resistant to erosion than the surrounding units.

The Dos Cabezas and Chiricahua mountains lie within the expansive Basin and Range physiographic province, which covers much of the western United States and extends into Mexico (fig. 3). This province contains mountain ranges (horsts) separated by fault-bounded, sediment-filled basins (grabens). This distinctive topography was formed when tectonic forces pulled apart Earth's crust (extension) during the most recent tectonic episode (beginning about 20 million years ago) to shape southeastern Arizona. The region records a complex geologic history that includes episodes of tectonic compression, catastrophic volcanic eruptions, and crustal extension.

Over millions of years, weather and fluvial erosion carved the park's Siphon and Cutoff canyons. The rock foundation upon which Fort Bowie was constructed was formed by a combination of ancient tectonic events and relatively recent processes. By the nineteenth century, weathering and erosion of sedimentary strata in an elongate fault sliver had formed the saddle that separates Siphon Canyon and Bear Gulch. This saddle was recognized as an ideal site for Fort Bowie.

Park History

Fort Bowie has a rich and storied past. Chiricahua Apaches lived in the region since at least the sixteenth century. With the Gadsden Purchase in 1854, Apache Pass and the surrounding area became part of the United States. In 1856, a military road was built across the pass to connect Fort Thorn, New Mexico, with Fort Yuma, California. Apache Spring became a regular water stop for the San Antonio to San Diego stage line in 1857 and 1858. In 1857, the Overland Mail Company, better known as the Butterfield Overland Mail, received an annual contract of $600,000 to carry U.S. Mail to California. A Butterfield stage station was built a few hundred yards from Apache Spring, and Anglo-Americans began to settle in Apache Pass.

Chiricahua Apache/Anglo-American relations were peaceful until 1861, when Lieutenant George Bascom mistakenly accused Cochise's band of Chiricahua Apaches of stealing a boy in a raid near Fort Buchanan. During a parley with Cochise, Bascom tried to take the chief captive, but Cochise escaped and following a series of U.S. military blunders, the Apache Wars began (Gardner 1994).

The first Fort Bowie consisted of a haphazard assortment of buildings constructed in 1862. The fort was named in honor of Colonel George Washington Bowie, a friend of Brigadier General Carleton and fellow officer in the California Volunteers. By 1867, at least 29 structures were scattered over a hill south of Apache Spring and in the surrounding draws.

The second Fort Bowie was a dramatic improvement on the first fort. Constructed from 1864 to 1869, the second fort was built on a saddle of land between Overlook Ridge and Bowie Mountain, 270 m (890 ft) southeast of the first fort. Unlike the first Fort Bowie, the second fort consisted of adobe and wood buildings that were neatly arranged in a square facing the parade ground. Water was piped to all of these structures.

After Cochise agreed to end hostilities in 1872, Apache Pass became relatively quiet. A reservation designated in 1873 included the Chiricahua Mountains, treasured by the Apache. After Cochise's death in 1874, however, raiding erupted again, and all Chiricahua Apaches were ordered to the San Carlos Reservation on the Gila River.

Only about one-third of the Chiricahuas marched to San Carlos; the others remained in the mountains of Arizona and Mexico for the next 10 years.

In 1885, Geronimo, a powerful medicine man, and Naiche, a son of Cochise, led over 100 Chiricahuas from the San Carlos Reservation into Mexico. Fort Bowie served as the base of operations in the U.S. military's attempt to find and subdue these Apache. When Geronimo surrendered in September 1886, he and his followers were brought to Fort Bowie, loaded into wagons, and expatriated to Florida, where the remainder of the Chiricahuas from San Carlos had already been imprisoned. These military actions concluded the Apache wars.

Fort Bowie received telegraph service in 1877 and limited telephone service in the late 1880s. In 1880, the Southern Pacific railroad began service in southern Arizona, stopping 20 km (13 mi) north of the post at Bowie Station. In 1894, the Fort Bowie garrison moved to their new post in Colorado, and locals quickly began dismantling the fort.

Fort Bowie National Historic Site was authorized in 1964. A 2.4-km (1.5-mi) trail connects a portion of historic Apache Pass to the ruins of the old post. Today, the adobe walls, stone ruins, and trickle of water from Apache Spring are all that remains of the clash between an emerging nation pursuing its "manifest destiny" and a valiant indigenous society fighting to preserve its existence (fig. 4).

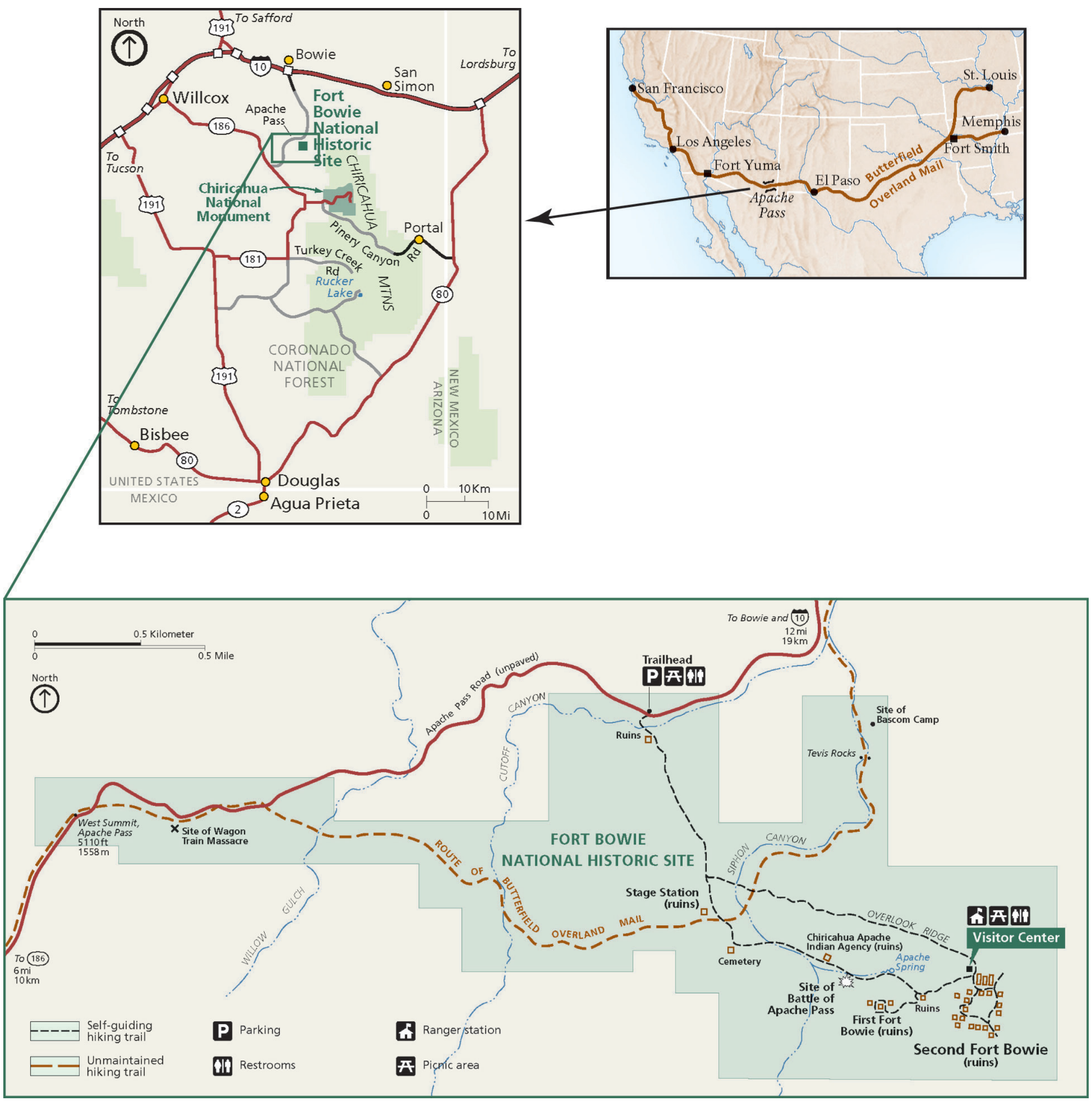

Figure 1. Maps of Fort Bowie National Historic Site, Arizona. The top right map shows the route of the Butterfield Overland trail. The top left map illustrates the area surrounding Fort Bowie National Historic Site. The bottom map shows the details of the park. National Park Service graphics available online: http://home.nps.gov/applications/hafe/hfc/carto.cfm.

Era	Period*	Epoch		Formation/Unit (map unit symbol)
CENOZOIC	Quaternary	Holocene		Unconsolidated gravel, sand, and silt (Qg)
		Pleistocene		Unconsolidated gravel, sand, and silt (Qgt)
				Unconsolidated gravel and sand (QTg)
	Neogene	Pliocene		
		Miocene		Rhyolite and latite porphyry (Tr)
	Paleogene	Oligocene		
				Sedimentary and volcanic rocks (Ksv, Ksvs, Ksvbc, Ksvr)
		Eocene		
		Paleocene		
MESOZOIC	Cretaceous	Upper		
		Lower	Bisbee Group	Upper part, undivided (Kbu, Kbup, Kbus)
				Cintura Formation (Kc, Kcs)
				Mural Limestone (Kmu, Kmup, Kmus, Kmuc)
				Morita Formation (Km, Kms, Kmc)
				Glance Conglomerate (Kg)
	Jurassic			Locally absent
	Triassic			
PALEOZOIC	Permian	Lopingian		
		Guadalupian		
		Cisuralian (Lower)	Naco Group	Concha Limestone (Pcn)
				Scherrer Formation (Ps)
				Colina Limestone (Pc)
				Epitaph Formation (Pe)
				Earp Formation (Pea)
	Pennsylvanian	Upper		Horquilla Limestone (PPNh, Phu, PNhl)
		Middle		Locally absent
		Lower		
	Mississippian	Upper		Paradise Formation (Mp)
		Middle		Escabrosa Limestone (Me)
		Lower		
	Devonian	Upper		Portal Formation of Sabins (1957) (Dp)
		Middle		
		Lower		
	Silurian			Locally absent
	Ordovician	Upper		
		Middle		
		Lower		El Paso Formation (Oe)
	Cambrian	Upper		Coronado Sandstone (Cc, Ccq)
		Middle		
		Lower		
Neoproterozoic Era				Locally absent
Mesoproterozoic Era				
				Granodiorite (Yg) and aplite (Yga)
Paleoproterozoic Era				Pinal Schist (Xp, Xpq, Xpp), amphibolite (Xa), and metavolcanic rock (Xpv)
				Locally absent
Neogene to Precambrian				Quartz (q) [wide age range]

***** See the Geologic Timescale (fig. 9) for the age of these periods and epochs.*

Figure 2. Generalized stratigraphic column for Fort Bowie National Historic Site and the immediate vicinity. The Map Unit Properties Table contains detailed descriptions of each unit. Based on a map by Drewes (1984).

Figure 3. Physiographic provinces of the western United States. Fort Bowie National Historic Site (yellow star) lies within the Mexican Highland portion of the Basin and Range province. Note the distinctive basin-and-range topography of elevated mountain ranges bordering flat basins, particularly in the Great Basin section. The ranges are uplifted "horsts" while the basins are down-dropped "grabens" separated by normal faults (see fig. 7). Compiled by Philip Reiker (NPS Geologic Resources Division) from ESRI Arc Image Service, National Geographic Society TOPO Imagery.

Figure 4. Ruins of the Cavalry Barracks at Fort Bowie National Historic Site. The area's complex geologic history contributed to the mountainous topography visible within and surrounding the park. National Park Service photograph by Karen Gonzales, available online: http://www.nps.gov/fobo/photosmultimedia/Archeological-Sites.htm, accessed July 20, 2011.

Geologic Issues

The Geologic Resources Division held a Geologic Resources Inventory scoping session for Fort Bowie National Historic Site on April 5, 2006, to discuss geologic resources, address the status of geologic mapping, and assess resource management issues and needs. This section synthesizes the scoping results, in particular those issues that may require attention from resource managers. Contact the Geologic Resources Division for technical assistance.

Fort Bowie National Historic Site has been negatively impacted by years of human activity. Grazing and water diversion have altered the hydrology around Apache Spring and roads have altered natural runoff patterns.

During the April 2006 Geologic Resources Inventory scoping session, participants (listed in the Appendix) identified two primary geologic issues facing the park: geologic mapping and erosion (Graham 2006). In August 2006, after the April 2006 scoping session, debris flows swept through the park. These debris flows are also discussed in this section. Abandoned mine lands (AMLs) are present within or near the park, but were not identified as significant issues during the scoping session (Graham 2006).

Geologic Mapping

During the scoping meeting, participants agreed that the best available maps for Fort Bowie National Historic Site were the 1:24,000 scale maps of the Bowie Mountain North and Bowie Mountain South quadrangles by Drewes (1981, 1984). However, according to Todd Shipman (geologist, Arizona Geological Survey, verbal communication, April 5, 2006), some of the contacts between mapped units may have been incorrectly identified as fault contacts. The locations of the contacts were correctly mapped, but the contacts may simply identify unit boundaries rather than movement along faults. The area of interest was limited to approximately 5 sq km (2 sq mi), some of which was outside park boundaries (Ed du Bray, geologist, U.S. Geological Survey, personal communication, April 5, 2006).

Participants at the meeting were also interested in new mapping that would include areas potentially involved with any future park expansion and greater detail of surficial deposits, east of the park. Participants felt that additional mapping would provide a more accurate geologic map for the park while including geology adjacent to the park as well as the geology within park boundaries (Graham 2006).

Deliverable products from new mapping, such as field maps and digital data, were not discussed at the meeting, but at the time, GRI staff had digitized both Drewes maps. Further review of the digitized data for the Bowie Mountain North and the Bowie Mountain South quadrangles suggested that the existing data would capture an area even beyond the extent of the proposed re-mapping. After review, GRI staff decided to use the existing maps, noting that some of the contacts may be incorrectly identified as fault contacts. As of this report, the Drewes maps remain the best available maps for Fort Bowie National Historic Site.

Erosion

Erosion is the most significant geologic issue for Fort Bowie resource management (Graham 2006). Erosional processes have impacted the upper Apache Spring watershed, and past management practices have accelerated erosion rates. Past park personnel have piled brush in drainages in an attempt to reduce erosion; however, this practice substantially accelerated erosion in the area. Water collected behind the brush dams and then cascaded over the dams, creating increased turbulence that scoured the streambed. Erosion also progressed upstream from the dams to form deep gullies.

The removal of mesquite above Apache Spring further increased erosion. Vegetation has not been re-established on slopes affected by this practice. Grasslands have been restored in the relatively flat area of the cemetery, situated on Pleistocene deposits of gravel, sand, and silt (map unit Qgt).

The areas immediately above the spring and just below the ruins are most in need of re-vegetation. Mesquite removal has accelerated soil loss during intense rainfalls on these slopes. Rapid soil loss is occurring in the immediate area of the ruins. Erosional processes are creating gullies by the flagpole, and these gullies continue to erode farther upslope.

The judicious use of straw waddles and reseeding could mitigate soil loss. If mitigation practices are not implemented, ongoing erosion and rapid runoff will continue to impact the long-term viability of the spring.

Debris Flows

On July 30–31, 2006, 18 cm (7 in) of rain initiated a debris flow (sediment-rich slurry) just east of Helen's Dome on land owned by the Bureau of Land Management (BLM). Traveling down slopes of granodiorite (map unit Yg) into Siphon Canyon and Fort Bowie National Historic Site, the debris flow transported boulders greater than 1.8 m (6 ft) in diameter and scoured its channel to bedrock (fig. 5) (Colleen Filippone, Intermountain Region-Southwest Hydrologist, NPS, personal communication, August 7, 2006). Although such flows are commonly initiated by intense rainfall on slopes with scant vegetation in the arid Southwest, meeting participants could not recall any debris flow that had a greater impact on Fort Bowie National Historic Site than this one. Likewise Ann Youberg (Arizona Geological Survey, personal communication, August 16, 2011) commented that the debris flow was probably the largest known in southern Arizona. The historical impact of debris flows in the area is unknown. Significant debris flows associated with the July 2006 storm also swept through other National Park Service units in Arizona including Saguaro National Park (Graham 2010), Coronado National Memorial (Graham 2011a), and near Tumacácori National Historical Park (Graham 2011b).

Wieczorek and Snyder (2009) described various types of slope movements and mass wasting triggers. They suggested the following five methods and "vital signs" for monitoring slope movements: landslide type, landslide triggers and causes, geologic contents of landslides, measurement of landslide movement and assessment of landslide hazards and risks. Their publication provides guidance in the use of vital signs and monitoring methodology.

Less Significant Issues

As discussed at the scoping session (Graham 2006), geologic issues involving mining, flooding, wetlands, or fossils are not of significant interest at Fort Bowie National Historic Site.

The National Park Service AML database includes 32 AML features at six sites within or near Fort Bowie. In 1998, NPS Geologic Resources Division staff responded to a technical assistance request from the park to close unsafe mine features (Cloues 1998). As detailed by Cloues (1998), polyurethane foam was used to plug an abandoned adit. Associated waste-rock piles were left undisturbed because they are considered historic features. Most AML features at Fort Bowie are gated or fenced, minimizing safety and bat-habitat issues. Contact the Geologic Resources Division for more information regarding AML features and sites.

Although iron bacteria may pose a water quality problem, this issue is not currently considered significant. Contact the Water Resources Division for more information regarding water quality or other water issues.

Issues concerning paleontological resources at Fort Bowie National Historical Site also are not significant. Paleontological resources primarily consist of marine invertebrate fossils and are summarized in the "Geologic Features and Processes" section of this report.

Figure 5. Debris flow deposits. Top images show the massive granodiorite boulders (map unit Yg) transported by the debris flow in 2006 as well as some of the finer-grained material transported down Siphon Canyon. Lower images show the large scale of the impacted area (left) and the source area (right). Note human figures for scale. National Park Service photographs courtesy of Colleen Filippone (NPS Intermountain Region-Southwest Hydrologist).

Geologic Features and Processes

This section describes the most prominent and distinctive geologic features and processes in Fort Bowie National Historic Site.

The structural complexity of the Chiricahua and Dos Cabezas mountains, the diverse character of the sedimentary rocks, and the geologic processes that formed Apache Pass have created a variety of geological features in the Fort Bowie region. Springs, faults, fossiliferous limestone, and erosional domes shape the current landscape of Fort Bowie National Historic Site.

Apache Spring

Apache Spring was a key water source for Apache and pre-Apache groups in the region, and the primary reason for the establishment of Fort Bowie in this location (fig. 6). The spring's constant supply of fresh water and its location near a common travel route made it a heavily utilized and fought-over site. Apache Spring is on the north side of the trail that leads from the parking lot on Apache Pass Road to the Fort Bowie National Historic Site Visitor Center.

Because the rock units in the Fort Bowie area are generally impermeable, groundwater is stored only in fractures created by folding and faulting. In the Basin and Range province of western North America, springs are typically located along fault zones. Apache Spring is no exception. Rainwater and snowmelt drain from higher elevations, percolate through the unconsolidated sediments of Siphon Canyon, and flow into the zone of fault-fractured rock below the alluvium. Groundwater that feeds Apache Spring flows to the surface where Siphon Canyon intersects a zone of shattered bedrock along the Apache Pass Fault (see "Overview of Digital Geologic Data" graphic; Bezy 2001).

Apache Spring has been modified for human use. A masonry box collects water from the spring, and some of the water is diverted to a stock tank on private land to satisfy previously established water rights (Bezy 2001). The spring discharges an average of 19 L (5 gal) of water per minute, but this flow fluctuates seasonally and annually and is dependent on precipitation.

Structural Features

Apache Pass Fault Zone

The Apache Pass fault zone is the most significant geologic feature in the Fort Bowie area and is characterized by steeply dipping and contorted rocks. Nearly 60 km (38 mi) of the 1- to- 2-km (0.6- to- 1.2-mi) wide fault zone is oriented northwest–southeast in the Apache Pass area (see "Overview of Digital Geologic Data" graphic; Drewes 1980; Bezy 2001). East of the parking area for the Fort Bowie trailhead, Apache Pass Road crosses the southwestern border fault of the Apache Pass fault zone and enters a thick section of sedimentary and volcanic rocks (map units Ksv and Kc). Fault slivers of Permian limestone (map units PNhl, Pc, and Pcn) and clastic sedimentary rocks (map units Ps and Pea) are exposed along the Overlook Ridge Trail. A trailside marker about 0.6 km (0.4 mi) along the Overlook Ridge Trail from the Visitor Center discusses the Apache Pass fault.

The Apache Pass fault zone contains examples of the three primary fault types (fig. 7). The Apache Pass fault was created about 1.4 billion years ago as a strike-slip fault. In such faults, rocks on one side of the fault plane move horizontally relative to those on the other side. Shattered sedimentary rocks within the Apache Pass fault zone have been moved more than 12 km (7.5 mi) southeast relative to the igneous rocks bordering the zone (fig. 8). The fault also exhibits a vertical, reverse fault component. Precambrian rocks (map unit Yg) on the southwestern side have been moved upward relative to the Paleozoic and Mesozoic strata on the northeastern side (fig. 8). Fault contact between the much younger, light-gray Horquilla Limestone (about 310 million years old; map unit Phu) and the Proterozoic granodiorite (about 1.4 billion years old) is visible from Overlook Ridge.

Although the fault initially formed about 1.4 billion years ago, slippage has occurred throughout geologic time. Repeated horizontal and vertical movement has disturbed the once-horizontal sedimentary layers, creating tilted, broken, and elongated slices of rock that dip steeply to the southwest (Drewes 1984; Bezy 2001). During the extensional episode that produced the basin-and-range topography, reverse faults that had been formed by compressive forces were reactivated as normal faults (figs. 7, 8).

The complex system of high-angle fractures provides conduits for groundwater, which emerges as springs and seeps along the fault zone. Apache Spring is one of several springs that discharge along the Apache Pass fault zone.

Overturned Syncline

Between Apache Pass Road and Fort Bowie, Paleozoic and Mesozoic strata have been tilted, upended, and overturned to form a tight "overturned" syncline, a concave (U-shaped) fold with younger rocks at its core. Both limbs of the fold tilt to the northeast. The syncline is part of a folded package of sedimentary strata forming the hanging wall of a thrust fault dipping to the southwest (Drewes 1984).

Fort Bowie Thrust Fault

In an undisturbed vertical sequence, younger rocks are found above older rocks. Thrust faults (fig. 7) transform such simple stratigraphic relationships into a complex jumble of units. In Fort Bowie National Historic Site, for example, compressive forces from the southwest generated the Fort Bowie thrust fault, carrying older Horquilla Limestone (map unit PNhl) over younger Colina Limestone (map unit Pc) (Drewes 1984; Bezy 2001). The Horquilla Limestone forms Overlook Ridge, and these thrust relationships are exposed along the Overlook Ridge Trail. The Horquilla Limestone in the Fort Bowie thrust slice was torn from the main mass of Horquilla Limestone about 65- to- 63 million years ago, during the late Cretaceous or early Paleocene. Deformation along the fault plane also folded the limestone strata.

The Fort Bowie thrust fault is one of several thrust slices within the Apache Pass fault zone. The Colina Limestone beneath the Horquilla Limestone, for example, is part of another thrust slice that has also been transported from the southwest over siltstone and shale layers of the younger Cintura Formation (map unit Kc).

Stratigraphic Features

The sedimentary rocks in the Fort Bowie area have been metamorphosed to varying degrees. Carbonate rocks have been recrystallized to create commercial-grade marble deposits south of Fort Bowie National Historic Site (Drewes 1981). Overlook Ridge exists because the metamorphism of Horquilla Limestone (map unit PNhl) made it harder and more resistant to erosion than the surrounding strata.

Metamorphism of the shale and siltstone of the Cretaceous Cintura Formation (map unit Kc) has produced large crystals (porphyroblasts) of andalusite and staurolite, as well as flakes of chloritoid, tourmaline, and graphite. A 1- m- (3.3- ft-) thick pod of graphitic shale is exposed in a fault zone in the gully immediately southeast of the Visitor Center (Drewes 1984).

Rounded domes of Proterozoic granodiorite (map unit Yg) are present in the western portion of Fort Bowie National Historic Site (Drewes 1984). This nearly 1.4 billion-year old granodiorite was formed as magma cooled slowly, allowing the growth of feldspar and quartz crystals and producing the coarse-grained texture of this intrusive igneous rock. Although fresh granodiorite samples are gray, this rock weathers to the brownish color visible on surrounding slopes (Drewes 1984; Bezy 2001).

Paleontological Resources

Marine invertebrate fossils have been noted in Paleozoic limestones in the Fort Bowie region (Map Unit Properties Table; Drewes 1984; Tweet et al. 2008). Within the park, the Horquilla Limestone has produced large fusulinids, which helped determine the age of the unit (Drewes 1984; Tweet et al. 2008). South of the park the Horquilla Limestone has yielded a variety of marine invertebrates (fusulinids, corals, bryozoans, and brachiopods) (Tweet et al. 2008). Echinoid spines and gastropods have been discovered in the Colina Limestone (map unit Pc). Although many other units mapped within the park are known to preserve fossils outside of Fort Bowie National Historic Site, none have been documented within the park (Tweet et al. 2008). For example, the Escabrosa (map unit Me), Colina (map unit Pc), and Concha (map unit Pcn) limestones and the Earp (map unit Pea), Epitaph (map unit Pe), and Scherrer (map unit Ps) formations range in age from Mississippian to Permian (about 345 to 275 million years ago) and preserve a variety of marine invertebrate fossils. The Cretaceous Glance Conglomerate (map unit Kg) may preserve fossiliferous fragments of older rocks now found as cobbles in the conglomerate, although Drewes (1984) noted no particular fossil species. The Cretaceous Mural Limestone (map unit Kmu) and Cintura Formation (map unit Kc) also preserve marine invertebrate fossils. Although the Gila Conglomerate is not mapped within the park, vertebrate fossils have been found in this formation outside of the park. Similarly, much younger Quaternary (the past 2.6 million years) fossils are present in several localities within Cochise County, although Drewes (1981, 1984) reported none in the Fort Bowie area.

Santucci and others (2009) have outlined potential threats to in situ paleontological resources and suggested that “vital signs” be monitored to qualitatively and quantitatively assess the potential impacts of these threats. Paleontological vital signs include: erosion (due to geologic and climatic factors), catastrophic geohazards, hydrology/bathymetry, and human access/public use. The authors also present detailed methodologies for monitoring each vital sign.

Figure 6. Apache Spring. As with most springs in the Basin and Range province, faults control the location of springs at the surface. National Park Service photograph courtesy of Colleen Filippone (NPS Intermountain Region-Southwest Hydrologist).

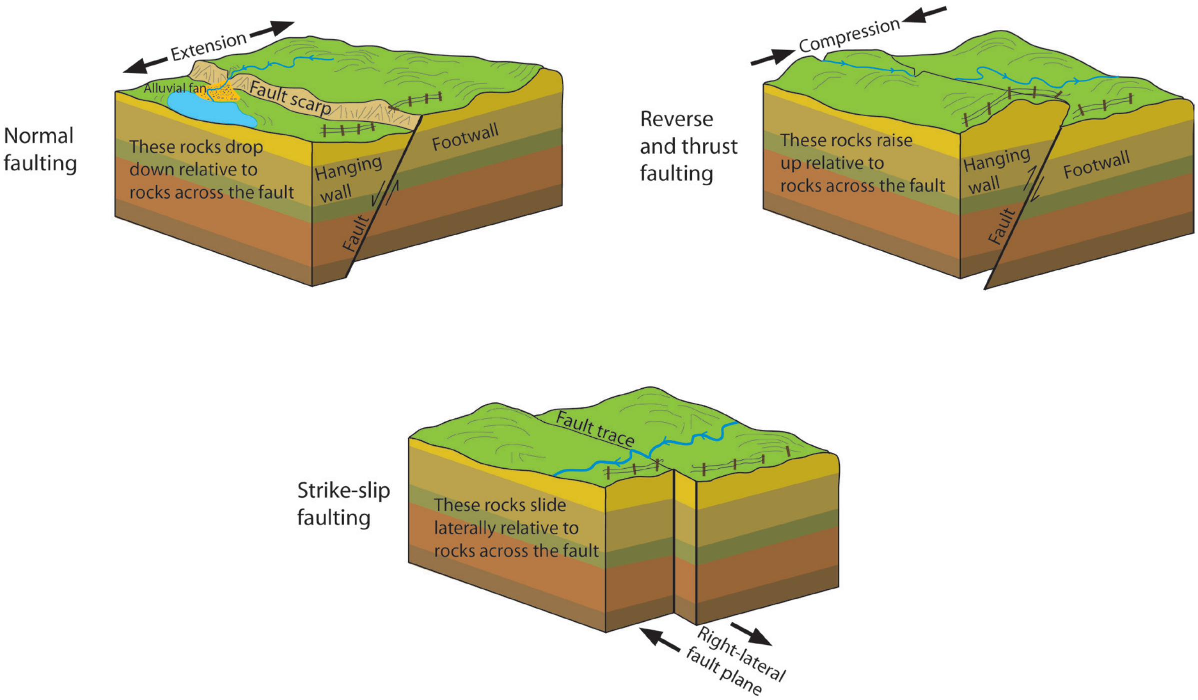

Figure 7. Schematic graphics illustrating different fault types present in southern Arizona. As a way of orientation, if you walked down a fault plane, your feet would be on the "footwall," and the rocks over your head would form the "hanging wall." In a normal fault the hanging wall moves down relative to the footwall. Normal faults result from extension (pulling apart) of the crust. In a reverse fault the hanging wall moves up relative to the foot wall. A thrust fault is similar to a reverse fault only the dip angle of a thrust fault is less than 45°. Reverse faults occur when the crust is compressed. In a strike-slip fault, the relative direction of movement of the opposing plate is lateral. If the movement across the fault is to the right, it is a right-lateral (dextral) fault, as illustrated above. If movement is to the left, it is a left-lateral (sinistral) fault. A strike-slip fault between two plate boundaries is called a transform fault. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

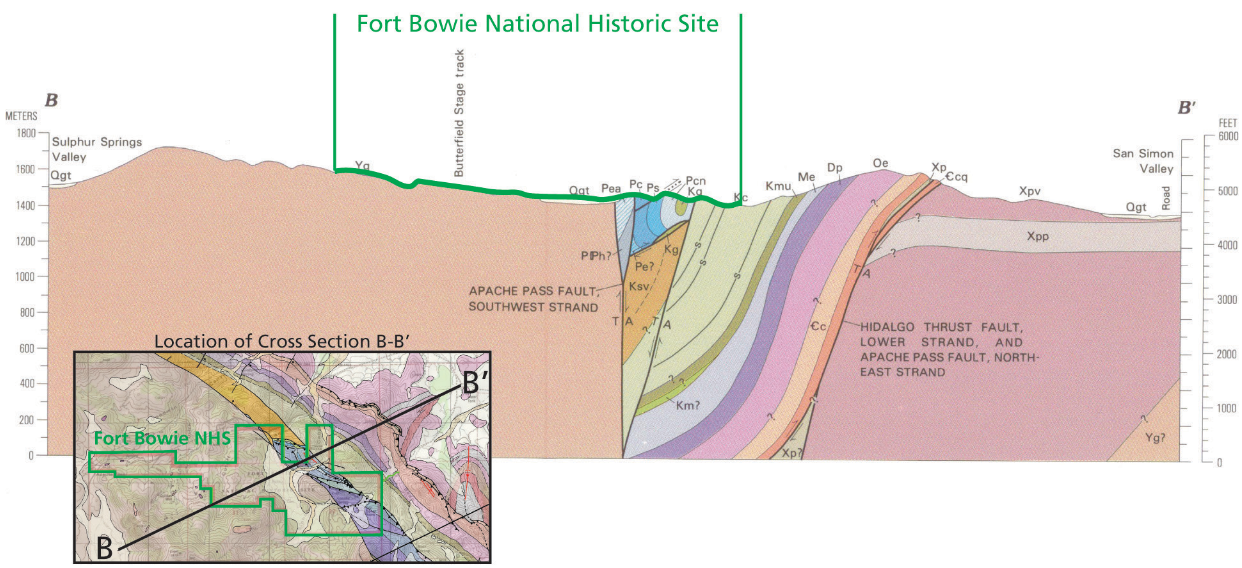

Figure 8. Southwest (B) to northeast (B') geologic cross section through Fort Bowie National Historic Site showing the lithologic units and structural interpretation of Drewes (1984). The green bar indicates the approximate span of the park. Arrows next to fault surfaces indicate the direction of fault movement. Note that the Apache Pass fault zone contains all three primary fault types. Strike-slip movement is noted along the faults as toward (T; coming out of the page) or away (A; going into page) from the reader. Note the location of Butterfield Trail in the granodiorite unit (Yg). Refer to the Map Unit Properties Table for more information regarding the geologic units present on the cross-section. Graphic extracted from Drewes (1984), park extent and location map by Jason Kenworthy (NPS Geologic Resources Division).

Geologic History

This section describes the rocks and unconsolidated deposits that appear on the digital geologic map of Fort Bowie National Historic Site, the environment in which those units were deposited, and the timing of geologic events that formed the present landscape.

The mountains surrounding Fort Bowie National Historic Site record fragments of a complex structural and stratigraphic history that dates back over a billion years. Precambrian tectonic accretion of oceanic terranes onto the fledgling core of North America initiated zones of faulting that have been reactivated throughout geologic time. Convergence of tectonic plates during the Late Cretaceous to Middle-Paleogene caused regional folding and thrust faulting in the Chiricahua and Dos Cabezas mountains. Crustal extension during the Cenozoic produced normal faults (fig. 7), which border the structural basins (grabens) and mountain ranges (horsts) in today's Basin and Range province.

The igneous and sedimentary rocks in Fort Bowie National Historic Site represent a variety of marine and terrestrial environments and record episodes of tectonic deformation and volcanic eruptions that occurred throughout southeastern Arizona (fig. 9). This tectonic and depositional history led to the development of Apache Spring, central to the history of Fort Bowie National Historic Site.

Precambrian History (prior to 542 million years ago)

About 1.65 billion years ago, crust in the southwestern United Sates was added to the growing North American craton during the Yavapai and Mazatzal mountain-building episodes (orogenies) (Hoffman 1989). The 1.65-billion-year-old Pinal Schist (map unit Xp), found in the Dos Cabezas and Chiricahua mountains beyond the boundaries of the historic site, is the oldest rock exposed in southeastern Arizona. The presence of phyllite (metamorphosed shale and siltstone), metamorphosed volcanic rock units, and thin interbedded units of quartzite, sandstone, and metamorphosed arkose suggests that the sediments were deposited in a marine environment adjacent to accreted terranes to the north (fig. 10) (Drewes 1984; Hoffman 1989; Bezy 2005).

About 1.38 billion years ago, the Pinal Schist was intruded by the younger Rattlesnake Point granodiorite (map unit Yg) (Drewes 1981). Metamorphosed sediments and younger Precambrian granites in the mountains of southeastern Arizona resulted from the collision of the proto-North American tectonic plate with an oceanic plate to the southwest (Hoffman 1989).

The Apache Pass fault zone was initiated during the Precambrian as a sinistral (left-lateral) strike-slip fault (fig. 7). Rocks were displaced about 10 km (6 mi), and strike-slip movement affected rocks deep within the crust (Drewes 1981, 1984). The Apache Pass fault zone was subsequently reactivated and often intruded by magma.

Many large granodiorite plutons intruded the ancient metamorphosed sedimentary rocks, which were folded and, in places, deformed to mylonite, a fine-grained rock with distinct lineation produced by extensive ductile deformation. The Precambrian rocks were then uplifted, planed off to near sea level by erosion, and covered by a sequence of Paleozoic marine deposits.

Paleozoic History (542 to 251 million years ago)

Although the Paleozoic era represents about 290 million years of Earth's history, few geologic remnants from this era are exposed in Fort Bowie National Historic Site. Cambrian through Devonian rocks are absent in the park, and other Paleozoic units are exposed only in fault slices within the Apache Pass fault zone. The margin of western proto-North America was tectonically passive from the Late Proterozoic through the Early Ordovician (fig. 9). From the Cambrian through the Middle Devonian, a sea lay to the west and south of southeastern Arizona. However, tectonic compression along the western margin of proto-North America began to affect southeastern Arizona during the Late Devonian (Johnson et al. 1991). Subduction of the oceanic tectonic plate beneath proto-North America gave rise to the Antler Orogeny, which sutured the land that is now Nevada to the western margin of proto-North America.

Sea level rose along the active tectonic margin. The flooding (transgression) of the sea onto the proto-North American continent during the Early and Middle Mississippian is represented by the bioclastic, carbonate-platform rocks of the Escabrosa Limestone (map unit Me) (fig. 11; Armstrong et al. 1980; Poole and Sandberg 1991). In southern Arizona, lower Escabrosa strata record a major transgressive event during which the epicontinental sea flooded much of southern and central Arizona. By the end of the Early Mississippian, sea level had fallen (regression) and marine regression, regional uplift, and erosion had removed some of the Escabrosa Limestone. A subsequent transgressive episode is recorded in Upper Escabrosa strata of Middle Mississippian age. Late Mississippian rocks are absent in southern Arizona, as this was a time of regional regression and subsequent subaerial erosion along the western margin of proto-North America.

The Pennsylvanian and Permian periods were characterized by great tectonic instability in the western interior United States. On the western margin of the continent, in the vicinity of central Nevada, continental shelf and slope rocks were "telescoped" against the continental margin as the Sonoma Orogeny advanced eastward (fig. 9). Southeast of Arizona, the South American tectonic plate collided with the North American plate and the proto-Gulf of Mexico closed, causing the uplift of the northwest–southeast trending Ancestral Rocky Mountains in Colorado, the northeast–southwest trending Sedona Arch in central Arizona, and the Mogollon Rim, an uplifted feature in east-central Arizona. A carbonate shelf developed south of the Mogollon Rim in southeastern Arizona (fig. 12; Blakey 1980; Peterson 1980).

The arid and dry Permian climate of the west–central United States produced marine evaporitic conditions. The sediments forming the Pennsylvanian and Permian strata in Fort Bowie National Historic Site were deposited in transitional environments between the open marine carbonate shelf and the subaerial uplands of the Mogollon Rim (fig. 12). Fossils in the limestones provide a record of life in these ancient seas.

Mesozoic History (251 to 65.5 million years ago)

By the end of the Paleozoic, all of the continents had come together to form a single landmass (supercontinent) called Pangaea around the equator (Dubiel 1994). Southeastern Arizona was again uplifted at the end of the Paleozoic, and a long period of emergence eroded any Triassic and Jurassic sediments deposited in the Fort Bowie region. Following this period of emergence, the area was covered by fluvial and estuarine deposits of Early Cretaceous age (Drewes 1981).

In Fort Bowie National Historic Site, the Glance Conglomerate (map unit Kg) rests on Permian strata, forming an unconformity (gap in stratigraphic succession). Throughout southeastern Arizona, the Glance Conglomerate, the basal formation of the Lower Cretaceous Bisbee Group, rests unconformably on rocks of Jurassic through Precambrian age (Bilodeau and Lindberg 1983). The clasts of limestone, sandstone, dolomite, and quartzite in the Glance Conglomerate were eroded from Paleozoic units and deposited in alluvial-fan systems that rimmed local fault-block mountain ranges and basins. The normal faults that bordered the basins were oriented to the northwest or west-northwest, approximately parallel to the western margin of the continent (fig. 13).

Sandstone, siltstone, and mudstone dominate the Morita Formation (map unit Km), which is exposed east of the park in the Apache Pass fault zone. These deposits represent fluvial and tidal flat environments that were laterally equivalent to the Glance Conglomerate alluvial fans (Bilodeau and Lindberg 1983).

The carbonate banks and patch reefs of the shallow marine Mural Limestone (map unit Kmu) represent the transgression of marine waters northwestward from the Chihuahua trough, a marine basin extending northwest from the Gulf of Mexico (fig. 13; Bilodeau and Lindberg 1983). When sea level subsided and the sea regressed toward the Gulf of Mexico, the deltaic and fluvial sandstones and siltstones of the Cintura Formation (map unit Kc) buried the marine environments.

Unnamed Upper Cretaceous sedimentary and volcanic rocks (map unit Ksv) record the northeastward extension of magma generation and volcanism. A new tectonic setting of northeast–southwest–oriented compression gave rise to the Laramide Orogeny (about 75 to 35 million years ago) and subsequent uplift and deformation (fig. 9; Drewes 1981; Bilodeau and Lindberg 1983). As the orogeny developed, stratovolcanoes, such as that associated with the Tucson Mountain Unit at Saguaro National Park, erupted in southeastern Arizona (Elder and Kirkland 1994; Kring 2002; Bezy 2005). The compressive phase of Laramide deformation produced several major thrust and tear faults, and plutons intruded into the faulted rocks. The Apache Pass fault zone was reactivated during a later phase of this orogeny (Drewes 1981; Pallister et al. 1997).

Cenozoic History (the past 65.5 million years)

Granodiorite was intruded along faults in the Apache Pass fault zone during the Oligocene epoch (34 to 23 million years ago) to form small stocks, igneous bodies less than 100 km^2 (40 mi^2) in area (Drewes 1981). Some magma reached the surface and formed dikes (narrow igneous intrusions that cut across strata), lava flows, and ash-flow tuff deposits. However, Fort Bowie lacks any record of Paleogene or Neogene geologic history.

Numerous catastrophic volcanic eruptions during the Paleogene produced volcanic calderas in southern Arizona and New Mexico (fig. 14). Calderas are bowl-shaped depressions that form following an especially explosive eruption and summit collapse of a cone-shaped stratovolcano. The Turkey Creek caldera, which is the source of most volcanic rocks in Chiricahua National Monument, is perhaps the best known Paleogene caldera in this region (Graham 2009). Formed about 25 to 30 million years ago, the Turkey Creek caldera is about 20 km (12 mi) in diameter (Drewes 1982; Kring 2002).

About 20 million years ago, during the Miocene epoch, subduction off the southwestern coast of North America ceased (Pallister et al. 1997) and volcanism waned in southeastern Arizona. Plate motion shifted to strike-slip faulting, initiating the San Andreas Fault system of California. Strike-slip faulting and high heat flow beneath the southwestern United States combined to cause crustal extension. Large crustal blocks were downdropped along high-angle normal faults to create grabens, while other blocks were uplifted into mountain ranges, known as horsts. This type of regional faulting produced today's basin-and-range topography.

Nearly vertical normal faults separate the Chiricahua and Dos Cabezas mountains from the San Simon Valley to the east and the Sulphur Springs Valley and Wilcox Playa to the west (Pallister et al. 1997; Bezy 2001). The normal fault-bounded ranges in southeastern Arizona are generally oriented north-northwest–north and contain grabens that are longer than the individual bordering mountain ranges (Morrison 1991). During this extension process, small amounts of basalt magma leaked from the underlying mantle to form the San Bernadino volcanic field along the southeastern flank of the Chiricahua Mountains.

Erosion during the Quaternary filled the basins with thick sequences of gravel and sand eroded from the adjacent mountain ranges. Mass wasting and erosion by water of the shattered fault blocks in Apache Pass exposed the rocks in the Fort Bowie area.

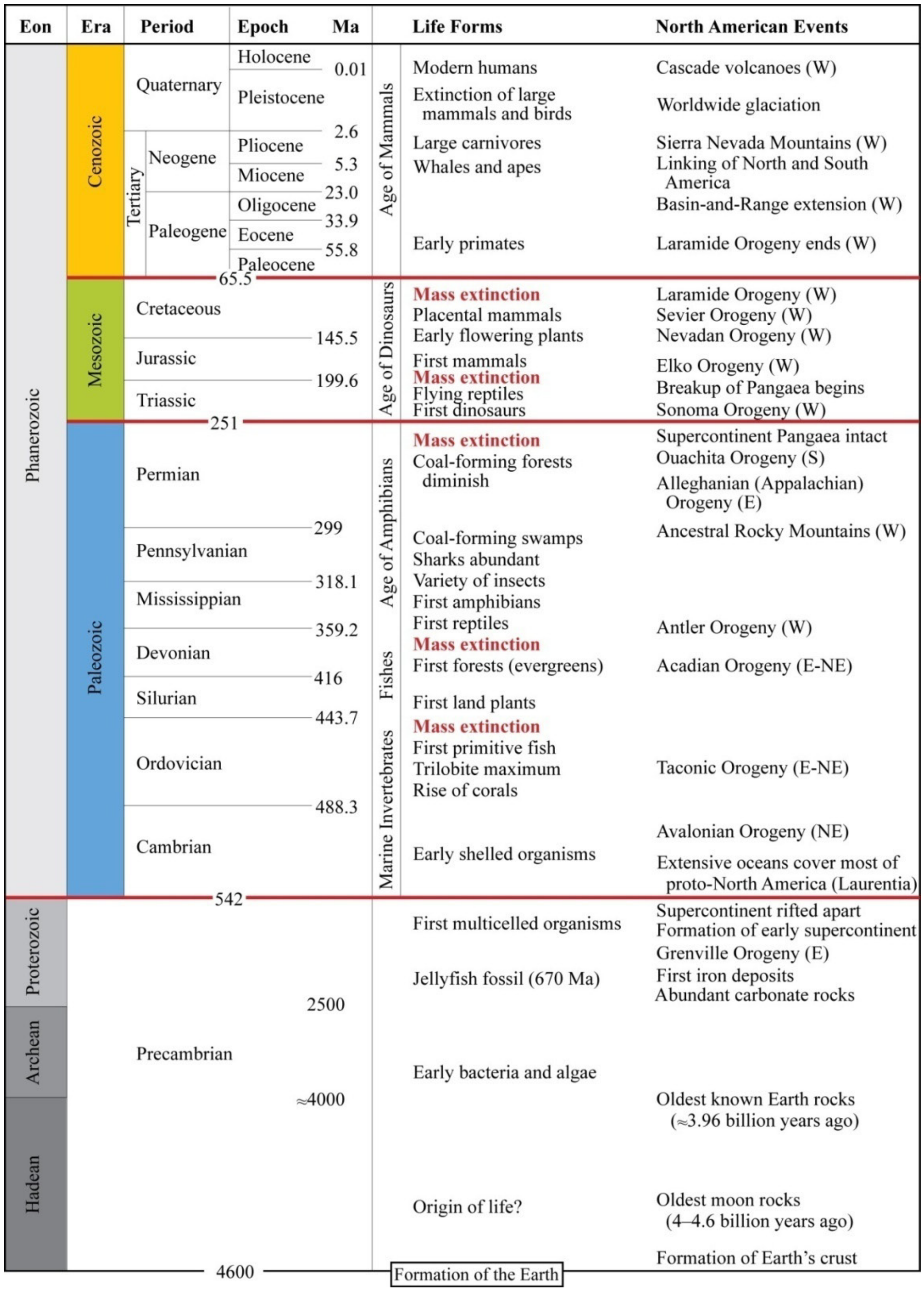

Figure 9. Geologic timescale. Included are major life history and tectonic events occurring on the North American continent. Red lines indicate major unconformities between eras. Radiometric ages shown are in millions of years (Ma). Compass directions in parentheses indicate the regional location of individual geologic events. Graphic by Trista Thornberry-Ehrlich (Colorado State University) with information from the U.S. Geological Survey, (http://pubs.usgs.gov/fs/2007/3015/) and the International Commission on Stratigraphy. (http://www.stratigraphy.org/view.php?id=25).

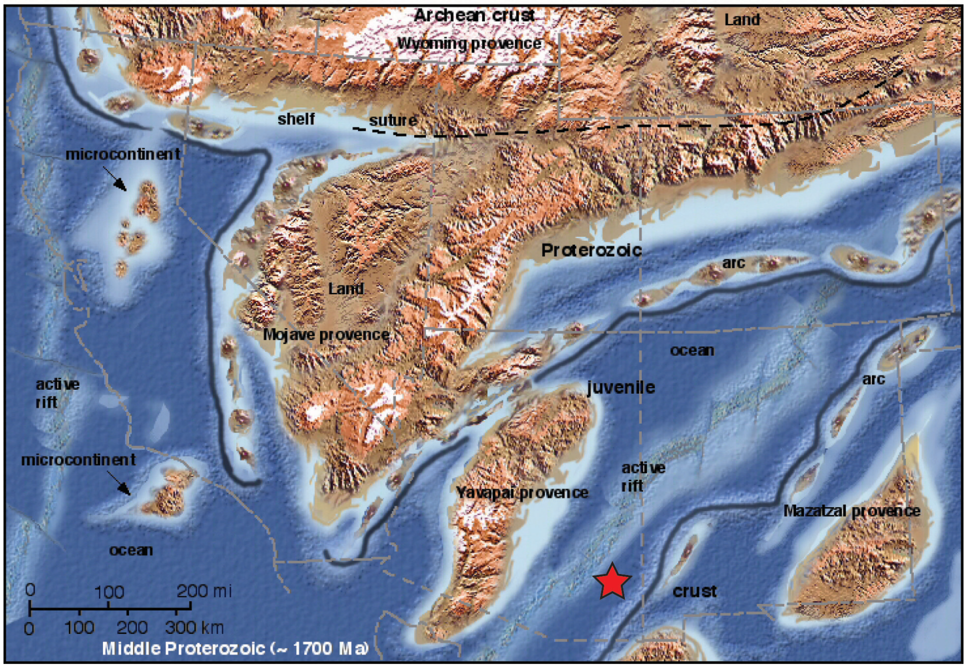

Figure 10. Proterozoic paleogeographic map of the southwestern United States. Approximately 1,700 million years ago (Ma), the Mojave, Yavapai, and Mazatzal provinces collided with the Archean crust. The dark-gray lines mark potential divisions between provinces. The dashed gray line marks the speculative suture zone between the Wyoming province and the Mojave province. Red star indicates the approximate location of Fort Bowie National Historic Site. Brown color is land surface. White indicates ice or snow on mountain peaks. Relative depths of marine water are divided into shallow (light blue) and deep (dark blue). Base paleogeographic map by Ron Blakey, Colorado Plateau Geosystems, Inc., available online: http://www2.nau.edu/rcb7/pcpaleo.html, accessed March 5, 2011.

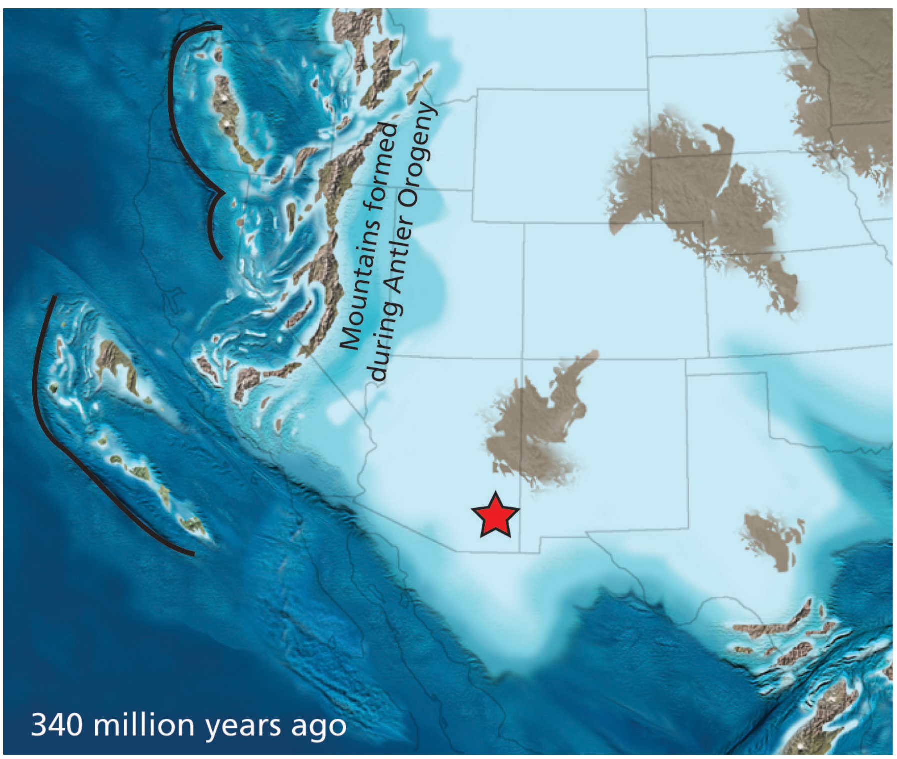

Figure 11. Early Mississippian paleogeographic map of the southwestern United States. Approximately 340 million years ago, shallow marine environments covered southeastern Arizona. Mountains formed in Nevada during the Antler Orogeny as proto-North America collided with the oceanic plate to the west. Black solid and dashed lines represent possible subduction zones between the proto-North American plate and the oceanic plate. The red star indicates the approximate location of Fort Bowie National Historic Site. Brown color is land surface. Relative depths of marine water are divided into shallow (light blue) and deep (dark blue). Base paleogeographic map by Ron Blakey, Colorado Plateau Geosystems, Inc., available online: http://cpgeosystems.com/garm340.jpg, accessed July 20, 2011. Annotation by the author.

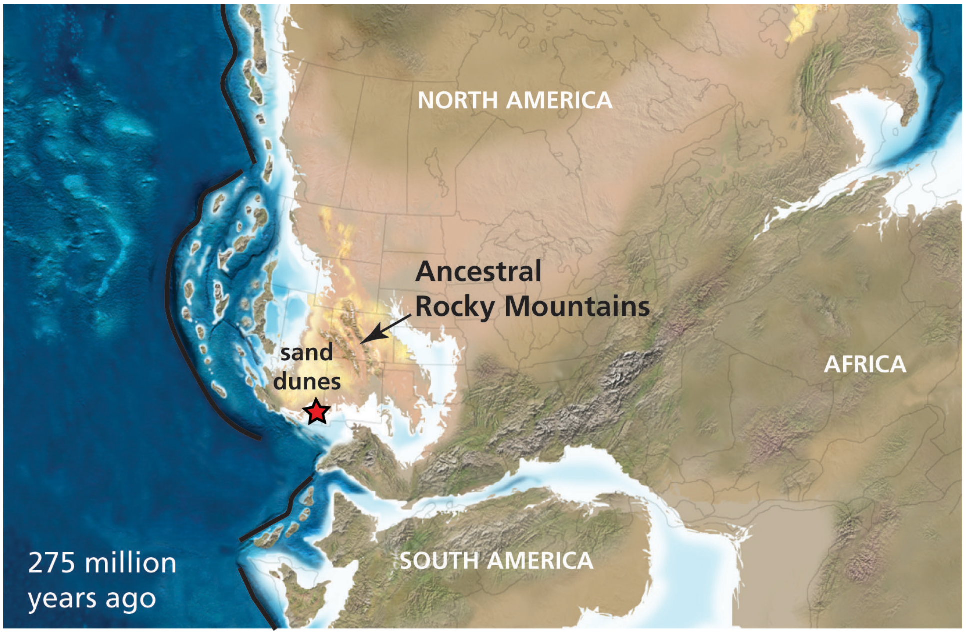

Figure 12. Middle Permian (275 million years ago) paleogeographic map of North America. Remnants of the northwest-southeast trending Ancestral Rocky Mountains (dark brown) can still be seen in Colorado. The yellowish-brown color in northeastern and central Arizona represents sand deposited in an arid dune environment. Proto-South America and proto-Africa collided with proto-North America, closing basins in southeastern Arizona and southwestern New Mexico. The dark line bordering the western shoreline marks the location of the subduction zone off the western margin of the land mass that will soon become the supercontinent, Pangaea. The red star represents the approximate location of today's Fort Bowie National Historic Site. Brown color is land surface. Relative depths of marine water are divided into shallow (light blue) and deep (dark blue). Base paleogeographic map by Ron Blakey, Colorado Plateau Geosystems, Inc., available online: http://cpgeosystems.com/namP275.jpg, accessed July 20, 2011. Annotation by the author.

Figure 13. Early Cretaceous paleogeographic map of the southwestern United States. About 130 million years ago, a shallow marine environment (Chihuahua trough) encroached into southeastern Arizona and an epicontinental seaway encroached into the Western Interior from the north. A belt of thrust-faulted mountain ranges formed in Nevada and western Utah as the North American plate collided with the Farallon plate. Thick marine and continental deposition occurred in strike-slip, pull-apart basins in southern Arizona and California. Volcanoes erupted along the western margin in a setting similar to today's Andes Mountains along the western coast of South America. The Sierra Nevada batholith formed beneath these active volcanoes. Red star approximates the location of Fort Bowie National Historic Site. Brown color is land surface. Relative depths of marine water are divided into shallow (light blue) and deep (dark blue). Base paleogeographic map by Ron Blakey, Colorado Plateau Geosystems, Inc., available online: http://jan.ucc.nau.edu/~rcb7/crepaleo.html, accessed July 21, 2011.

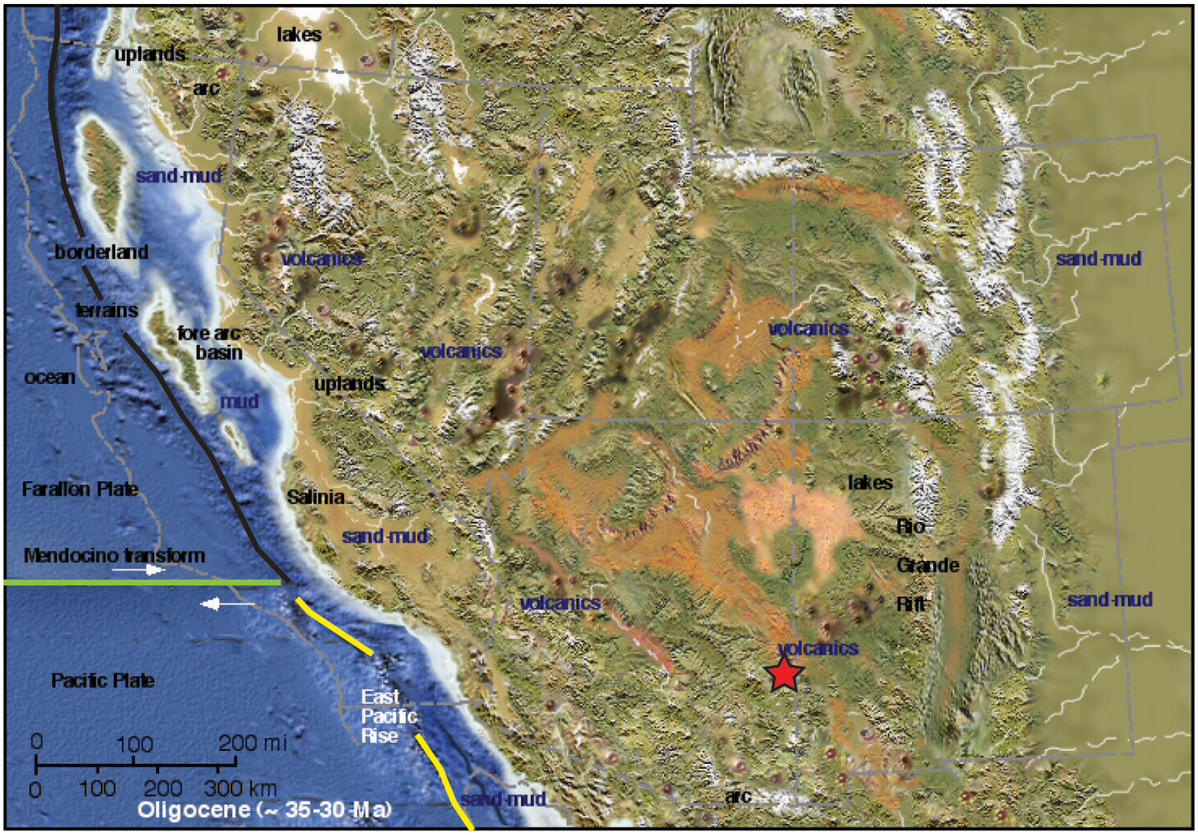

Figure 14. Oligocene paleogeographic map of the southwestern United States. About 30- to 35 million years ago, volcanism was widespread across much of the Western Interior of North America. The first stages of the Rio Grande Rift in New Mexico and southern Colorado developed as parts of western North America shifted from compressional to extensional tectonics. The East Pacific Rise (orange line), a Pacific spreading center, neared the coast of southwestern North America. Its impending collision would cause subduction to cease, initiating strike-slip faulting and creating the San Andreas Fault system. The arrows in the lower left corner show the direction of movement along the Mendocino transform fault (green line), which separated the Pacific Plate (south of the fault) from the Farallon Plate (north of the fault). The thick, black line represents the boundary between the North American and Farallon plates. The red star is the approximate location of today's Fort Bowie National Historic Site. Base paleogeographic map by Ron Blakey, Colorado Plateau Geosystems, Inc., available online: http://jan.ucc.nau.edu/~rcb7/terpaleo.html, accessed July 21, 2011. Tectonic boundary annotations by the author.

Geologic Map Data

This section summarizes the geologic map data available for Fort Bowie National Historic Site. It includes a fold-out geologic map overview and a summary table that lists each map unit displayed on the digital geologic map for the park. Complete GIS data are included on the accompanying CD and are also available at the Geologic Resources Inventory (GRI) publications website: http://www.nature.nps.gov/geology/inventory/gre_publications.cfm.

Geologic Maps

Geologic maps facilitate an understanding of an area's geologic framework and the evolution of its present landscape. Using designated colors and symbols, geologic maps portray the spatial distribution and relationships of rocks and unconsolidated deposits. Geologic maps also may show geomorphic features, structural interpretations, and locations of past geologic hazards that may be prone to future activity. Additionally, anthropogenic features such as mines and quarries may be indicated on geologic maps.

Source Maps

The Geologic Resources Inventory (GRI) team converts digital and/or paper source maps into the GIS formats that conform to the GRI GIS data model. The GRI digital geologic map product also includes essential elements of the source maps including unit descriptions, map legend, map notes, references, and figures. The GRI team used the following source maps to create the digital geologic data for Fort Bowie National Historic Site:

Drewes, H. 1981. Geologic Map and Sections of Bowie Mountain South Quadrangle, Cochise County, Arizona. Miscellaneous Investigations Series Map I-1363. U.S. Geological Survey Miscellaneous Investigations Series Map I-1363 (scale 1:24,000).

Drewes, H. 1984. Geologic Map and Sections of Bowie Mountain North Quadrangle, Cochise County, Arizona. U.S. Geological Survey Miscellaneous Investigations Series Map I-1492 (scale 1:24,000).

These source maps provided information for the "Geologic Issues," "Geologic Features and Processes," and "Geologic History" sections of this report.

Geologic GIS Data

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

GRI digital geologic data for Fort Bowie National Historic Site are included on the attached CD and are available through the NPS Integrated Resource Management Applications (IRMA) (https://irma.nps.gov/App/Reference/Search?SearchType=Q). Enter "GRI" as the search text and select the park from the unit list. Note that as of September 2011, IRMA is only compatible with the Internet Explorer browser. Enter "GRI" as the search text and select Buck Island Reef National Monument from the unit list. The following components and geology data layers are part of the data set:

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

Table 2. Geology data layers in the Fort Bowie National Historic Site GIS data.

Data Layer	Code	On Geologic Map Overview?
Geologic Cross Section Lines	fobosec	Yes
Geologic Attitude Observation Localities	foboatd	No
Geologic Observation Localities	fobogol	No
Geologic Sample Localities	fobogsl	No
Mine Point Features	fobomin	No
Linear Geologic Units	fobogln	Yes
Linear Dikes	fobodke	Yes
Map Symbology	fobosym	Yes
Folds	fobofld	Yes
Faults	foboflt	Yes
Surficial Contacts	fobosura	Yes
Surficial Units	fobosur	Yes
Geologic Contacts	foboglga	Yes
Geologic Units	foboglg	Yes

Note: All data layers may not be visible on the geologic map overview graphic.

Geologic Map Overview

The fold-out geologic map overview displays the GRI digital geologic data draped over a shaded relief image of Fort Bowie National Historic Site and includes basic geographic information. For graphic clarity and legibility, not all GIS feature classes are visible on the overview. The digital elevation data and geographic information are not included with the GRI digital geologic GIS data for the park, but are available online from a variety of sources.

Map Unit Properties Table

The geologic units listed in the fold-out map unit properties table correspond to the accompanying digital geologic data. In addition to geologic descriptions of each unit, the table highlights resource management considerations for each unit. The units, their relationships, and the series of events the created them are highlighted in the "Geologic History" section. Please refer to the geologic timescale (fig. 20) for the geologic period and age associated with each unit.

Use Constraints

Graphic and written information provided in this section is not a substitute for site-specific investigations, and ground-disturbing activities should neither be permitted nor denied based upon the information provided here. Minor inaccuracies may exist regarding the location of geologic features relative to other geologic or geographic features on the overview graphic. Based on the source map scale (1:24,000) and U.S. National Map Accuracy Standards, geologic features represented here are within 12 meters / 40 feet (horizontally) of their true location.

Please contact GRI with any questions.

Glossary

This glossary contains brief definitions of technical geologic terms used in this report. Not all geologic terms used are referenced. For more detailed definitions or to find terms not listed here please visit: http://geomaps.wr.usgs.gov/parks/misc/glossarya.html. Definitions are based on those in the American Geological Institute Glossary of Geology (fifth edition; 2005).

absolute age. The geologic age of a fossil, rock, feature, or event in years; commonly refers to radiometrically determined ages.
abyssal plain. A flat region of the deep ocean floor, usually at the base of the continental rise.
accretion. The gradual addition of new land to old by the deposition of sediment or emplacement of landmasses onto the edge of a continent at a convergent margin.
active margin. A tectonically active margin where lithospheric plates come together (convergent boundary), pull apart (divergent boundary) or slide past one another (transform boundary). Typically associated with earthquakes and, in the case of convergent and divergent boundaries, volcanism. Compare to "passive margin."
alluvial fan. A fan-shaped deposit of sediment that accumulates where a hydraulically confined stream flows to a hydraulically unconfined area. Commonly out of a mountainous area into an area such as a valley or plain.
alluvium. Stream-deposited sediment.
amphibole. A common group of rock-forming silicate minerals. Hornblende is the most abundant type.
aphyric. Describes the texture of fine-grained or aphanitic igneous rocks that lack coarse (large) crystals.
aquifer. A rock or sedimentary unit that is sufficiently porous that it has a capacity to hold water, sufficiently permeable to allow water to move through it, and currently saturated to some level.
arc. See "volcanic arc" and "magmatic arc."
arenite. A general term for sedimentary rocks composed of sand-sized fragments with a pure or nearly pure chemical cement and little or no matrix material between the fragments.
arkose. A sandstone with a large percentage of feldspar minerals, commonly coarse-grained and pink or reddish.
arête. A rocky sharp-edged ridge or spur, commonly present above the snowline in rugged mountains sculptured by glaciers. The feature results from the continued backward growth of the walls of adjoining cirques.
arroyo. A small, deep, flat-floored channel or gully of an ephemeral or intermittent stream in the arid and semiarid regions of the southwestern United States.
ash (volcanic). Fine material ejected from a volcano (also see "tuff").
ash flow. A density current, generally a hot mixture of volcanic gases and volcanic material that travels across the ground surface.
ash-flow tuff. A tuff deposited by an ash flow.
asthenosphere. Earth's relatively weak layer or shell below the rigid lithosphere.
augen. Describes large lenticular mineral grains or mineral
barchan dune. A crescent-shaped dune with arms or horns of the crescent pointing downwind. The crescent or barchan type is most characteristic of inland desert regions.
basalt. A dark-colored, often low-viscosity, extrusive igneous rock.
basement. The undifferentiated rocks, commonly igneous and metamorphic, that underlie rocks exposed at the surface.
basin (structural). A doubly plunging syncline in which rocks dip inward from all sides.
basin (sedimentary). Any depression, from continental to local scales, into which sediments are deposited.
bed. The smallest sedimentary strata unit, commonly ranging in thickness from one centimeter to a meter or two and distinguishable from beds above and below.
bedding. Depositional layering or stratification of sediments.
bedrock. A general term for the rock that underlies soil or other unconsolidated, surficial material.
block (fault). A crustal unit bounded by faults, either completely or in part.
breccia. A coarse-grained, generally unsorted sedimentary rock consisting of cemented angular clasts greater than 2 mm (0.08 in).
calcareous. Describes rock or sediment that contains the mineral calcium carbonate ($CaCO_3$).
calcite. A common rock-forming mineral: $CaCO_3$ (calcium carbonate).
calcrete. Pedogenic calcareous soil, e.g., limestone consisting of surficial sand and gravel cemented into a hard mass by calcium carbonate precipitated from solution.
caldera. A large bowl- or cone-shaped depression at the summit of a volcano. Formed by explosion or collapse.
carbonaceous. Describes a rock or sediment with considerable carbon content, especially organics, hydrocarbons, or coal.
carbonate. A mineral that has CO_3^{-2} as its essential component (e.g., calcite and aragonite).
carbonate rock. A rock consisting chiefly of carbonate minerals (e.g., limestone, dolomite, or carbonatite).
cementation. Chemical precipitation of material into pores between grains that bind the grains into rock.
chemical sediment. A sediment precipitated directly from solution (also called nonclastic).
chemical weathering. Chemical breakdown of minerals at Earth's surface via reaction with water, air, or

dissolved substances; commonly results in a change in chemical composition more stable in the current environment.

chert. A extremely hard sedimentary rock with conchoidal (smooth curved surface) fracturing. It consists chiefly of interlocking crystals of quartz Also called "flint."

cinder. A glassy pyroclastic fragment that falls to the ground in an essentially solid condition.

cinder cone. A conical volcanic feature formed by the accumulation of cinders and other pyroclasts, normally of basaltic or andesitic composition.

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

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

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

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

clinopyroxene. A group name for pyroxene minerals crystallizing in the monoclinic system. Important rock-forming minerals; common in igneous and metamorphic rocks.

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

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

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

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

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

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

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

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

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

craton. The relatively old and geologically stable interior of a continent (also see "continental shield").

crinoid. A marine invertebrate (echinoderm) that uses a stalk to attach itself to a substrate. "Arms" are used to capture food. Rare today, they were very common in the Paleozoic. Crinoids are also called "sea lilies."

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

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

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

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

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

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

differential erosion. Erosion that occurs at irregular or varying rates, caused by differences in the resistance and hardness of surface material.

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

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

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

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

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

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

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

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

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

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

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

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

epicontinental. Describes a geologic feature situated on the continental shelf or on the continental interior. An "epicontinental sea" is one example.

erg. An regionally extensive tract of sandy desert; a "sand sea."

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

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

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

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

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

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

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

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

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

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

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

granite. An intrusive igneous (plutonic) rock composed primarily of quartz and feldspar. Mica and amphibole minerals are also common. Intrusive equivalent of rhyolite.

graben. A down-dropped structural block bounded by steeply dipping, normal faults (also see "horst").

greenschist. A metamorphic rock, whose green color is due to the presence of the minerals chlorite, epidote, or actinolite, corresponds with metamorphism at temperatures in the 300–500°C (570–930°F) range.

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

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

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

hornblende. The most common mineral of the amphibole group. Hornblende is commonly black and occurs in distinct crystals or in columnar, fibrous, or granular forms.

horst. Areas of relative "up" between grabens, representing the geologic surface left behind as grabens drop. The best example is the Basin and Range province of Nevada. The basins are grabens and the ranges are weathered horsts. Grabens become a locus for sedimentary deposition (also see "graben").

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

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

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

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

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

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

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

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

lamination. Very thin, parallel layers.

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

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

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

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

limb. Either side of a structural fold.

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

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

llithification. The conversion of sediment into solid rock.

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

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

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

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

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

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

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

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

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

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

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

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

mesa. A broad, flat-topped erosional hill or mountain bounded by steeply sloping sides or cliffs.

meta–. A prefix used with the name of a sedimentary or igneous rock, indicating that the rock has been metamorphosed.

metamorphic. Describes the process of metamorphism or its results. One of the three main classes of rocks—igneous, metamorphic, and sedimentary.

mica. A prominent rock-forming mineral of igneous and metamorphic rocks. It has perfect basal cleavage meaning that it forms flat sheets.

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

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

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

monument. An isolated pinnacle, column, or pillar of rock resulting from erosion and resembling an anthropogenic monument or obelisk.

muscovite. A mineral of the mica group. It is colorless to pale brown and is a common mineral in metamorphic rocks such as gneiss and schist, igneous rocks such as granite, pegmatite, and sedimentary rocks such as sandstone.

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

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

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

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

orogeny. A mountain-building event.

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

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

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

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

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

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

parent rock. Rock from which soil, sediments, or other rocks are derived.

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

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

pediment. A gently sloping, erosional bedrock surface at the foot of mountains or plateau escarpments.

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

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

plastic. Describes a material capable of being deformed permanently without rupture.

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

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

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

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

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

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

potassium feldspar. A feldspar mineral rich in potassium (e.g., orthoclase, microcline, sanidine, adularia).

pumice. Solidified "frothy" lava. It is highly vesicular and has very low density.

pumiceous. Volcanic vesicular texture involving tiny gas holes such as in pumice. Finer than scoriaceous.

pyroclast. An individual particle ejected during a volcanic eruption.

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

pyroxene. A common rock-forming mineral. It is characterized by short, stout crystals.

quartzite. Metamorphosed quartz sandstone.

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

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

recharge. Infiltration processes that replenish groundwater.

red beds. Sedimentary strata composed largely of sandstone, siltstone, and shale that are predominantly red due to the presence of ferric iron oxide (hematite) coating individual grains.

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

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

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

rhyolite. A group of extrusive volcanic rocks, typically porphyritic and commonly exhibiting flow texture, with phenocrysts of quartz and alkali feldspar in a glassy to cryptocrystalline groundmass. The fine-grained extrusive equivalent of granite.

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

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

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

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

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

sabkha. A coastal environment in an arid climate just above high tide. Characterized by evaporate minerals, tidal-flood, and eolian deposits. Common in the Persian Gulf.

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

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

sandstone. Clastic sedimentary rock of predominantly sand-sized grains.

schist. A strongly foliated metamorphic rock that can be readily be split into thick flakes or slabs. Micas are arranged in parallel, imparting a distinctive sheen, or "schistosity" to the rock.

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

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

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

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

shale. A clastic sedimentary rock made of clay-sized particles that exhibit parallel splitting properties.

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

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

silicate. A compound whose crystal structure contains the SiO_4 tetrahedra.

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

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

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

sinkhole. A circular depression in a karst area with subterranean drainage and is commonly funnel-shaped.

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

spatter cone. A low, steep-sided cone of spatter built up on a fissure of vent, usually composed of basaltic material.

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

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

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

stratification. The accumulation, or layering of sedimentary rocks in strata. Tabular, or planar, stratification refers to essentially parallel surfaces. Cross-stratification refers to strata inclined at an angle to the main stratification.

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

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

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

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

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

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

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

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

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

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

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

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

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

terrace. A relatively level bench or step-like surface breaking the continuity of a slope (also see "stream terrace").

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

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

terrigenous. Derived from the land or a continent.

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

tongue (stratigraphy). A member of a formation that extends and wedges out away from the main body of a formation.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

volcanogenic. Describes material formed by volcanic processes.

wash. A term used especially in the southwestern United States for the broad, gravelly dry bed of an intermittent stream, generally in the bottom of a canyon; it is occasionally swept by a torrent of water.

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

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

xenolith. A rock particle, formed elsewhere, entrained in magma as an inclusion.

Literature Cited

This section lists references cited in this report. A more complete geologic bibliography is available from the National Park Service Geologic Resources Division.

Armstrong, A.K., B.L. Mamet, and J.E. Repetski. 1980. The Mississippian System of New Mexico and southern Arizona. Pages 82-100 in T.D. Fouch and E.R. Magathan, editors. Paleozoic paleogeography of west-central United States. Society of Economic Paleontologists and Mineralogists, Rocky Mountain Section, Denver, Colorado, USA.

Bezy, J.V. 2001. Rocks in the Chiricahua National Monument and the Fort Bowie National Historic Site. Arizona Geologic Survey, Down-to-Earth 11, Tucson, Arizona, USA.

Bezy, J.V. 2005. A guide to the geology of Saguaro National Park. Arizona Geologic Survey, Down-to-Earth 18, Tucson, Arizona, USA.

Bilodeau, W.L., and F.A. Lindberg. 1983. Early Cretaceous tectonics and sedimentation in southern Arizona, southwestern New Mexico, and northern Sonora, Mexico. Pages 173-188 in M.W. Reynolds and E.D. Dolly, editors. Mesozoic paleogeography of west-central United States. Society of Economic Paleontologists and Mineralogists (SEPM), Rocky Mountain Section, Symposium 2, Denver, Colorado, USA.

Blakey, R. C. 1980. Pennsylvanian and Early Permian paleogeography, southern Colorado Plateau and vicinity. Pages 239-258 in T.D. Fouch and E.R. Magathan, editors. Paleozoic paleogeography of west-central United States. Society of Economic Paleontologists and Mineralogists, Rocky Mountain Section, Denver, Colorado, USA.

Cloues, P. 1998. Fort Bowie National Historic Site abandoned mine land field trip. Trip report. Geologic Resources Division (GRD), Lakewood, Colorado, USA. On file at GRD.

Drewes, H. 1980. Tectonic map of southeast Arizona. U.S. Geological Survey Miscellaneous Investigations Series Map I-1109 (scale 1:125,000).

Drewes, H. 1981. Geologic map and sections of the Bowie Mountain South quadrangle, Cochise County, Arizona. Geological Survey Miscellaneous Investigations Series Map I-1363 (scale 1:24,000).

Drewes, H. 1982. Geologic map and sections of the Cochise Head quadrangle and adjacent areas, southeastern Arizona. U.S. Geological Survey Miscellaneous Investigations Series Map I-1312 (scale 1:24,000).

Drewes, H. 1984. Geologic map and sections of the Bowie Mountain North quadrangle, Cochise County, Arizona. U.S. Geological Survey Miscellaneous Investigations Series Map I-1492 (scale 1;24,000).

Dubiel, R.F. 1994. Triassic deposystems, paleogeography, and paleoclimate of the Western Interior. Pages 133-168 in M.V. Caputo, J.A. Peterson, and K.J. Franczyk, editors. Mesozoic systems of the Rocky Mountain region, USA. Society for Sedimentary Geology, Rocky Mountain Section, Denver, Colorado, USA.

Elder, W.P., and J.I. Kirkland. 1994. Cretaceous paleogeography of the southern Western Interior Region. Pages 415-440 in M.V. Caputo, J.A. Peterson, and K.J. Franczyk, editors. Mesozoic systems of the Rocky Mountain region, USA. Society for Sedimentary Geology, Rocky Mountain Section, Denver, Colorado, USA.

Gardner, M. 1994. Fort Bowie National Historic Site. Southwest Parks and Monuments Association, Tucson, Arizona, USA.

Graham, J. 2006. Geologic Resource Evaluation scoping summary Fort Bowie National Historic Site, Arizona. National Park Service Geologic Resources Division, Lakewood, Colorado, USA. http://www.nature.nps.gov/geology/inventory/publications/s_summaries/FOBO_scoping_summary_2006-0621.pdf (accessed 15 February 2011).

Graham, J. 2009. Chiricahua National Monument Geologic Resources Inventory Report. Natural Resource Report NPS/NRPC/GRD/NRR—2009/081. National Park Service, Denver, Colorado, USA. http://www.nature.nps.gov/geology/inventory/gre_publications.cfm (accessed 15 February 2011).

Graham, J. 2010. Saguaro National Park geologic resources inventory report. Natural Resource Report NPS/NRPC/GRD/NRR—2010/233. National Park Service, Denver, Colorado, USA. http://www.nature.nps.gov/geology/inventory/gre_publications.cfm (accessed 15 February 2011).

Graham, J. 2011a. Coronado National Memorial geologic resources inventory report. Natural Resource Report NPS/NRPC/GRD/NRR—2011/438. National Park Service, Fort Collins, Colorado, USA. http://www.nature.nps.gov/geology/inventory/gre_publications.cfm (accessed 16 September 2011)

Graham, J. 2011b. Tumacácori National Historical Park geologic resources inventory report. Natural Resource Report NPS/NRPC/GRD/NRR—2011/439. National Park Service, Fort Collins, Colorado, USA. http://www.nature.nps.gov/geology/inventory/gre_publications.cfm (accessed 16 September 2011).

Hoffman, P. F. 1989. Precambrian geology and tectonic history of North America. Pages 447-512 in A.W. Bally and A.R. Palmer, editors. The geology of North America: An overview, Vol. A. Geological Society of America, Boulder, Colorado, USA.

Johnson, J.G., C.A. Sandberg, and F.G. Poole. 1991. Devonian lithofacies of western United States. Pages 83-106 in J.D. Cooper and C.H. Stevens, editors. Paleozoic paleogeography of the Western United States-II, Volume 1. Society of Economic Paleontologists and Mineralogists, Pacific Section, Los Angeles, California, USA.

Kring, D. A. 2002. Desert heat – volcanic fire: The geologic history of the Tucson Mountains and southern Arizona. Arizona Geological Society Digest 21, Tucson, Arizona, USA.

Morrison, R.B. 1991. Quaternary geology of the southern Basin and Range province. Pages 353-371 in R.B. Morrison, editor. Quaternary nonglacial geology; conterminous U.S, Vol. K-2. Geological Society of America, Boulder, Colorado, USA.

Pallister, J.S., E.A. du Bray, and D.B. Hall. 1997. Guide to the volcanic geology of Chiricahua National Monument and vicinity, Cochise County, Arizona. U.S. Geological Survey Miscellaneous Investigations Series Map I-2541 and Pamphlet (scale 1:24,000).

Peterson, J. A. 1980. Permian paleogeography and sedimentary provinces, west central United States. Pages 271-292 in T.D. Fouch and E.R. Magathan, editors. Paleozoic paleogeography of west-central United States. Society of Economic Paleontologists and Mineralogists, Rocky Mountain Section, Denver, Colorado, USA.

Poole, F. G., and C. A. Sandberg. 1991. Mississippian paleogeography and conodont biostratigraphy of the western United States. Pages 107-136 in J.D. Cooper and C.H. Stevens, editors. Paleozoic paleogeography of the Western United States-II, Volume 1. Society of Economic Paleontologists and Mineralogists, Pacific Section, Los Angeles, California, USA.

Sabins, F.F., Jr. 1957. Stratigraphic relations in Chiricahua and Dos Cabezas Mountains, Arizona. American Association of Petroleum Geologists Bulletin 41 (3):466-510.

Santucci, V.L., J.P. Kenworthy, and A.L. Mims. 2009. Monitoring in situ paleontological resources. Pages 189–204 in R. Young and L. Norby, editors. Geological Monitoring. Geological Society of America, Boulder, Colorado, USA. http://nature.nps.gov/geology/monitoring/paleo.cfm (accessed 16 September 2011).

Tweet, J.S., V.L. Santucci, and J.P. Kenworthy. 2008. Paleontological resource inventory and monitoring—Sonoran Desert Network. Natural Resource Technical Report NPS/NRPC/NRTR—2008/130. National Park Service, Fort Collins, Colorado, USA.

Wieczorek, G.F. and J.B. Snyder. 2009. Monitoring slope movements. Pages 245–271 in R. Young and L. Norby, editors. Geological Monitoring. Geological Society of America, Boulder, Colorado, USA. http://nature.nps.gov/geology/monitoring/slopes.cfm (accessed 16 September 2011).

Additional References

This section lists additional references, resources, and web sites that may be of use to resource managers. Web addresses are current as of August 2011.

Geology of National Park Service Areas

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

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

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

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

Lillie, R. J. 2005. Parks and Plates: The geology of our national parks, monuments, and seashores. W.W. Norton and Co., New York, New York, USA. [Geared for interpreters].

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

Resource Management/Legislation Documents

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

NPS-75: Natural Resource Inventory and Monitoring Guideline: http://www.nature.nps.gov/nps75/nps75.pdf

NPS Natural Resource Management Reference Manual #77: http://www.nature.nps.gov/Rm77/

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

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

Geological Survey and Society Websites

Arizona Geological Survey: http://www.azgs.state.az.us/

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

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

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

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

Other Geology/Resource Management Tools

Bates, R. L. and J. A. Jackson, editors. American Geological Institute dictionary of geological terms (3rd Edition). Bantam Doubleday Dell Publishing Group, New York.

U.S. Geological Survey National Geologic Map Database (NGMDB): http://ngmdb.usgs.gov/

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

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

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

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

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

Appendix: Scoping Session Participants

The following is a list of participants from the GRI scoping session for Fort Bowie National Historic Site, held on April 5, 2006. The contact information and email addresses in this appendix may be outdated; please contact the Geologic Resources Division for current information. The scoping meeting summary was used as the foundation for this GRI report. The original scoping summary document is available on the GRI publications web site: http://www.nature.nps.gov/geology/inventory/gre_publications.cfm.

Name	Affiliation	Position	Phone	E-mail
Covington, Sid	Geologist	NPS Geologic Resources Division	303-969-2154	sid_covington@nps.gov
Dennett, Carrie	Ecologist	NPS Chiricahua National Monument & Fort Bowie National Historic Site	520-824-3560 ext. 601	carrie_Dennett@nps.gov
du Bray, Ed	Geologist	U.S. Geological Survey	303-236-5591	edubray@usgs.gov
Filippone, Colleen	Hydrologist	NPS Intermountain Region	520-546-1607	colleen_filippone@nps.gov
Graham, John	Geologist	Colorado State University		
Kerbo, Ron	Cave Specialist	NPS Geologic Resources Division	303-969-2097	Ron_Kerbo@nps.gov
Moody, Suzanne	Park Ranger, Interpretation	NPS Chiricahua National Monument	520-824-3560 ext. 305	suzanne_moody@nps.gov
Olsen, Ruth	Biological Science Tech	NPS Chiricahua National Monument & Fort Bowie National Historic Site	520-824-3560 ext. 602	ruth_olsen@nps.gov
O'Meara, Stephanie	Geologist	Colorado State University	970-225-3584	Stephanie_O'Meara@partner.nps.gov
Shipman, Todd	Geologist	Arizona Geological Survey	520-770-3500	todd.shipman@azgs.az.gov
Whalon, Alan	Superintendent	NPS Chiricahua National Monument & Fort Bowie National Historic Site	520-824-3560 ext. 202	alan_whalon@nps.gov

NPS 424/109950, September 2011

National Park Service
U.S. Department of the Interior

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

www.nature.nps.gov

EXPERIENCE YOUR AMERICA ™