National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

Fort Union National Monument

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2012/580

ON THE COVER
Local materials, such as sandstone exposed in nearby cliffs and clay from the "adobe fields," were used in the construction of Fort Union. Graneros Shale (geologic map unit Kgs), which underlies most of the national monument, yielded the clay. Dakota Sandstone (Kd) provided the building stone. Photograph by Katie KellerLynn (Colorado State University).

THIS PAGE
The Turkey Mountains fill the northern horizon at Fort Union National Monument. The mountains are composed of an igneous intrusion called a "laccolith." Photograph by Katie KellerLynn (Colorado State University).

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National Park Service
Geologic Resources Division
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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.

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Executive Summary

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 This report was prepared using available published and unpublished geologic information.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

Fort Union National Monument protects remnants of the Southwest's largest frontier fort, including earthworks, archeological deposits, and stabilized adobe ruins. In addition, a network of Santa Fe Trail ruts is still visible on the surrounding prairie. These cultural resources are part of a landscape developed over the last 100 million years, including deposition of sandstone and shale in the Western Interior Seaway, which extended from the Arctic to the Tropics, covering the entire west-central part of the North American continent. As the Western Interior Seaway advanced into New Mexico about 96 million years ago, Dakota Sandstone (map unit symbol Kd) was deposited. Nearby outcrops of Dakota Sandstone provided building stone for fort construction. Fort Union sits on a plain of Graneros Shale (Kgs), which yielded clay for the production of adobe used at the frontier fort. Like the Dakota Sandstone, Graneros Shale was deposited in the Western Interior Seaway.

Starting about 8 million years ago, a period of volcanic activity in the Ocaté volcanic field helped to shape the Fort Union landscape. Many well-known landmarks, including Black Mesa to the north and Maxson Crater to the east, have volcanic origins. Along with mesas and ridges composed of Dakota Sandstone, these volcanic features provide topographic relief in the broad Mora Valley, where Fort Union is located. Northeast of the fort, the valley is enclosed by the Turkey Mountains, a laccolith (dome-shaped igneous intrusion).

Established as part of the National Park System in 1954, the 292-ha (721-ac) national monument is separated into two units ("main" and "smaller") encompassing the sites of the three Fort Unions, constructed during the post's 40-year period of use from 1851 to 1891. The smaller unit, located west of Wolf Creek, contains the ruins of the first Fort Union, which was operational from 1851 to 1861, and the arsenal of the third Fort Union. East of Wolf Creek is the main unit, which contains the ruins of the second Fort Union, or Star Fort, which operated from 1861 to 1862. Also included in the main unit is the third Fort Union, which was operational from 1862 to 1891. Portions of the third fort are the largest and best preserved of the three forts within the national monument.

Fort Union was built to protect commerce and travel on the Santa Fe Trail, and the national monument preserves many Santa Fe Trail ruts. Fort Union served as a hub along this trail for the delivery of supplies and equipment to other military posts throughout the Southwest (Curran et al. 2005).

The NPS Geologic Resources Division held a Geologic Resources Inventory (GRI) scoping meeting for Fort Union National Monument on 28 March 2006. This report expands upon the scoping summary (National Park Service 2006b) and ties geologic issues, features, and processes to the digital geologic map of the national monument (see "Geologic Map Data" section). *Geologic Map of the Fort Union Quadrangle, Mora County, New Mexico* (Johnson 1974) was the source for the digital geologic data.

This GRI report was written for resource managers to assist in resource management and science-based decision making, but it may also be useful for interpretation. The report discusses geologic issues facing resource managers at Fort Union National Monument, distinctive geologic features and processes within the national monument, and the geologic history leading to the present-day landscape. The Geologic Map Overview Graphic illustrates the geologic data; the Map Unit Properties Table summarizes the main features, characteristics, and potential management issues for all rocks and unconsolidated deposits on the digital geologic map of Fort Union National Monument. This report also provides a glossary that contains explanations of technical, geologic terms, including terms on the Map Unit Properties Table. Additionally, a geologic time scale shows the chronologic arrangement of major geologic events, with the oldest events and time units at the bottom and the youngest at the top.

Geologic issues of particular significance for resource management at Fort Union National Monument were identified during a 2006 GRI scoping meeting. They include the following:

- Soil Ruts. The potential for present-day soil rutting is severe throughout the national monument. Rutting occurs when soil strength is not sufficient to support the applied load from vehicle traffic. In historic times, this susceptibility led to the creation of wagon ruts on the Santa Fe Trail. Protecting the ruts from erosion has long been a resource management concern at Fort Union National Monument. In 2007, investigators found that wagon ruts were fairly stable in terms of recent erosion and did not recommend taking any steps toward erosion control. However, investigators recommended that staff develop an erosion monitoring program at the national monument. Moreover, future infrastructure projects or any changes to present infrastructure at the national monument, including the construction of impermeable surfaces and culverts, should avoid increasing runoff or changing slope grades because such changes could induce erosion.

- Wolf Creek. Wolf Creek is the primary fluvial feature at Fort Union National Monument. Seepage from springs maintains its perennial flow. No large-scale groundwater pumping, such as that for irrigation or municipal wells, occurs in the area, and no significant water diversion has been employed in the Wolf Creek basin. Therefore, the perennial nature of Wolf Creek is not expected to change as a result of groundwater pumping. Flooding could occur along Wolf Creek or in arroyos originating outside but continuing inside the national monument. Flooding could impact some present-day infrastructure and the ruins of the third fort. In addition, the natural meandering of Wolf Creek could affect the integrity of the sewage lagoons in the main unit of the national monument over time.
- Landslides and Rockfall. Although mass wasting (gravity-driven processes) is not a major issue within Fort Union National Monument, rockfall does occur in the area, most notably along the cliffs on the western side of the smaller unit. Only a portion of this ridge, which is composed of Dakota Sandstone (Kd), intersects the national monument's boundary. However, repeated freeze-thaw cycles and seismic activity could dislodge rock fragments and blocks, potentially impacting resources at the smaller unit. Johnson (1974) mapped landslide deposits north of the national monument along Black Mesa.
- Seismic Activity. Earthquake activity in New Mexico is concentrated around Socorro, approximately 190 km (120 mi) southwest of Fort Union National Monument. However, investigators have mapped small earthquake epicenters in the vicinity of the national monument. The geologic map for Fort Union National Monument shows two faults: (1) the Fort Union fault, which lies along the western boundary of the smaller unit; and (2) the Los Gavilanes fault, located northwest of the national monument.
- Oil and Gas Development. Oil and gas production has occurred within the Las Vegas Basin, which is the structural basin in which Fort Union National Monument is situated. The primary target for oil and gas production in the vicinity of the national monument is the thick section of rocks from the Pennsylvanian Period (318 million–299 million years ago). Other strata with potential for oil and gas development are the Upper Cretaceous (100 million–65.5 million years ago) Carlile (Kc) and Graneros (Kgs) shales for shale gas, the Upper Cretaceous Greenhorn Limestone (Kgn) for shale gas and oil, the Upper Jurassic (161 million–145 million years ago) Morrison Formation (Jm) for natural gas, and the Lower Cretaceous (145 million–100 million years ago) Dakota Sandstone (Kd) for natural gas. Furthermore, the Upper Jurassic Entrada Sandstone (Je) and strata from the Triassic Period (251 million–200 million years ago) have significant potential for carbon-dioxide (CO_2) gas. This potential is particularly notable on the flanks of the Turkey Mountains uplift, including all reservoirs from the lowermost Pennsylvanian (approximately 318 million years ago) through the uppermost Permian (approximately 251 million years ago) strata.

Geologic features of particular significance for resource management at Fort Union National Monument include the following:

- Volcanic Features. Fort Union National Monument is surrounded by the Ocaté volcanic field, and the associated volcanic features are a prominent part of the Fort Union landscape. Features include the basalt of Black Mesa (Tbm), which caps nearby Black Mesa, and the basalt of Wolf Creek (QTw), which follows the Wolf Creek channel just north of the national monument.
- Dakota Sandstone. Made of resistant Dakota Sandstone (Kd), hogback ridges on the eastern edge of the uplifted Sangre de Cristo Mountains serve as a backdrop for Fort Union. A Dakota Sandstone ridge lines the western side of the smaller unit of Fort Union National Monument. This sandstone was used in fort construction, and is the source of the aquifer that supplies water to spring-fed Wolf Creek and the national monument's well.
- Turkey Mountains. This dome-shaped mountain uplift is the result of an igneous intrusion called a "laccolith." The Turkey Mountains are located on the east side of the Mora River Valley. They fill the northern horizon of Fort Union National Monument.
- Stream Terraces. Two levels of terraces, divided into older (Qto) and younger (Qty) deposits, line the Mora River Valley. Now isolated above the modern river channel, these deposits represent the floodplains of the Pleistocene Epoch (2.6 million–11,700 years ago).
- Caves. Scoping participants suggested that lava tubes—a type of cave that develops in lava flows—may be present near Fort Union National Monument. However, the New Mexico Bureau of Geology and Mineral Resources has not identified any such feature to date. *Fort Union National Monument Ethnographic Overview* (Sánchez et al. 2006) documented "caves" as places where prostitutes, gamblers, and whiskey sellers set up businesses near the fort, but the location of these caves is unknown.
- Eolian Features and Processes. Overgrazing in a region known for abundant wind led to the frequent occurrence of dust storms at Fort Union during its 40-year occupation (1851–1891). Today, however, dust storms occur rarely and are not a high-priority resource management issue.
- Building Materials. The primary building stone used at Fort Union was Dakota Sandstone (Kd), which was mined from the cliffs west of the first fort. In addition, clay from Graneros Shale (Kgs) in the "clay fields" northwest of the fort was used to make adobe. Lime

from local outcrops of Greenhorn Limestone (Kgn) was used in mortar production.

- Paleontological Resources. Although no fossil discovery has been reported from within the boundaries of Fort Union National Monument, paleontological resources from the Upper Cretaceous Graneros Shale (Kgs) have been found in other areas of New Mexico. Fossils in the Graneros Shale include oysters, ammonites, gastropods, and foraminifera, which lived in the Western Interior Seaway. Alluvium (Qa), which occurs in the main unit of the national monument, has the potential to contain Quaternary (≤2.6 million years old) fossils such as bison and musk ox. Terrace deposits (Qto and Qty) may also contain Quaternary fossils.

Acknowledgments

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 geological surveys, local museums, and universities in developing GRI products.

The GRI team would like to thank the following people for their assistance with this report:

- The participants at the 2006 scoping meeting (see Appendix);
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Introduction

This section briefly describes the National Park Service Geologic Resources Inventory Program and the regional geologic and historic setting of Fort Union National Monument.

Geologic Resources Inventory Program

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

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

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

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

Park Setting

Fort Union National Monument lies in the shadow of the Sangre de Cristo Mountains in the Mora River Valley of northeastern New Mexico. The national monument is located on the western edge of the Great Plains in a transition zone between the Southern Rocky Mountains and High Plains physiographic provinces (fig. 1). Typically, the Southern Rocky Mountains are characterized by steep escarpments bounded by inactive thrust or reverse faults and a summit plateau of generally subdued topography (Pazzaglia and Hawley 2004). The Southern Rocky Mountains of New Mexico formed about 70 million years ago during a mountain-building episode called the Laramide Orogeny (fig. 2). In the vicinity of Fort Union National Monument, a fault controls the pattern of outcrops and bounds the valley on the west. A dome-shaped uplift, the Turkey Mountains, bounds the valley on the east (Winograd 1956).

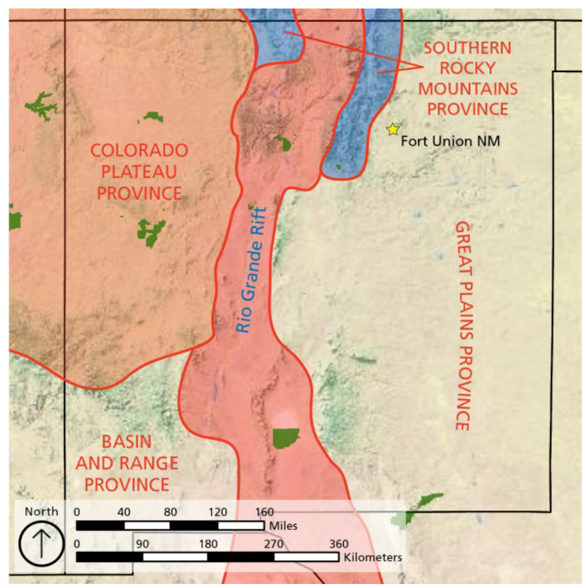

Figure 1. Physiographic provinces. Four provinces conjoin in New Mexico: the Colorado Plateau, Great Plains, Southern Rocky Mountains, and Basin and Range. Fort Union National Monument sits at the transition between the Great Plains and Southern Rocky Mountains. The Rio Grande rift represents the eastern extent of the Basin and Range. Graphic adapted from Price (2010) by Philip Reiker (NPS Geologic Resources Division).

Subsequent to the uplifting of the Rocky Mountains, extension (pulling apart of Earth's crust) along the Rio Grande rift has affected the region through further deformation and volcanism. The rift represents an ongoing episode of east–west crustal extension that began about 40 million years ago (Price 2010). In the Fort Union area, the Sangre de Cristo Mountains form the eastern flank of the rift.

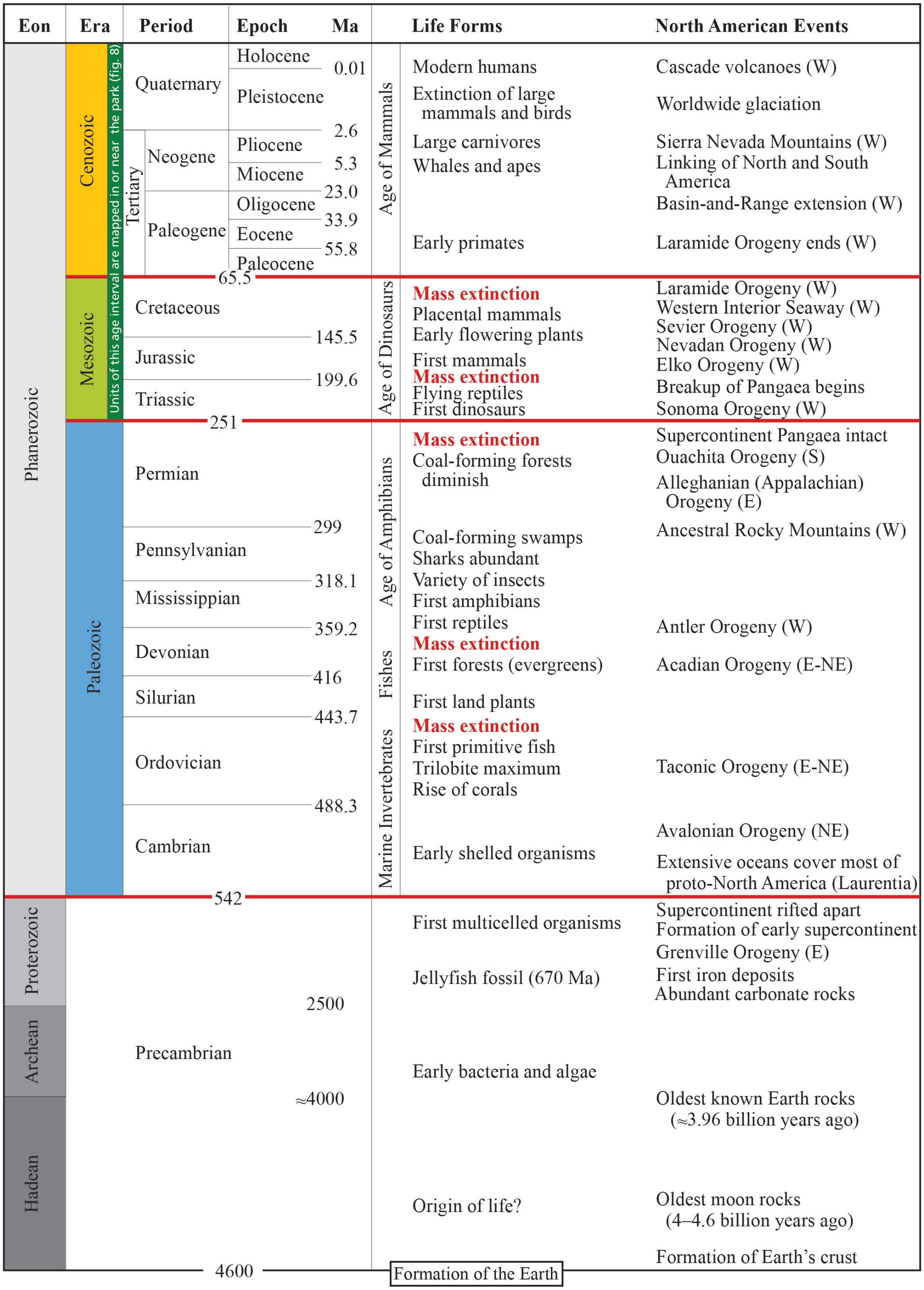

Figure 2. Geologic time scale. The divisions of the geologic time scale are organized stratigraphically, with the oldest at the bottom and youngest at the top. Boundary ages are in millions of years (Ma). Major life history and tectonic events occurring on the North American continent are included. Compass directions in parentheses indicate the regional locations of individual geologic events. Red lines indicate major boundaries between eras. The green bar indicates the span of time represented by rocks and deposits mapped within and near Fort Union National Monument (see fig. 8 for more detail). Graphic designed by Trista Thornberry-Ehrlich (Colorado State University) and modified by Philip Reiker (N), adapted from geologic time scales published by the U.S. Geological Survey (http://pubs.usgs.gov/fs/2010/3059/) and the International Commission on Stratigraphy (http://www.stratigraphy.org/ics%20chart/09_2010/StratChart2010.pdf).

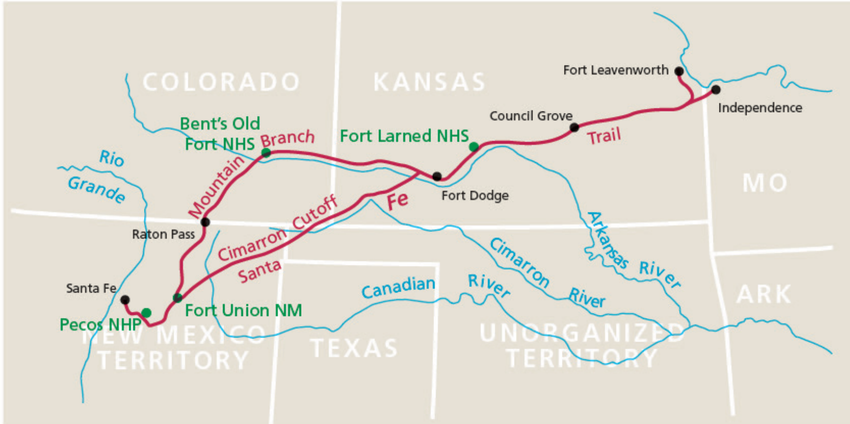

Figure 3. Santa Fe Trail. The Santa Fe Trail covered 1,450 km (900 mi), passing through five present-day states: Missouri, Kansas, Oklahoma, Colorado, and New Mexico. Green dots indicate the locations of National Park System units that preserve trail sites: Fort Larned National Historic Site (Kansas), Bent's Old Fort National Historic Site (Colorado), Fort Union National Monument (New Mexico), and Pecos National Historical Park (New Mexico). National Park Service graphic.

Situated near the junction of the northern Mountain Route and the southern Cimarron Cutoff of the Santa Fe Trail, Fort Union was one of the most significant stops along the entire trail (Curran et al. 2005) (fig. 3). The Santa Fe Trail served as a pathway of cultural exchange for more than a millennium, evolving from a network of indigenous trade routes to a major international highway between the United States and Mexico's northern frontier, and later (after the Mexican-American War), a national highway joining the United States to the new territory of New Mexico. Through much of its history, the Santa Fe Trail served as a route for military movement, namely during the Mexican-American War, Civil War, and Indian Wars. Officially opening in 1821, the Santa Fe Trail spanned 1,450 km (900 mi) across the Great Plains from Independence, Missouri, to Santa Fe in present-day New Mexico (National Park Service 2012). Generally, a journey along its entire length took about eight weeks. Today, Fort Union National Monument is one of nine federally managed areas preserving physical remains of the Santa Fe Trail; four National Park System units preserve trail sites. From east to west, these are Fort Larned National Historic Site (Kansas), Bent's Old Fort National Historic Site (Colorado), Fort Union National Monument (New Mexico), and Pecos National Historical Park (New Mexico) (fig. 3).

Figure 4. Aerial photograph of the second and third Fort Unions. The star-shaped earthworks of the second Fort Union, called "Star Fort," are apparent. The complex northeast of Star Fort is the third and final Fort Union, which was once the largest U.S. military installation on the southwestern frontier. The photograph also shows soil ruts of the Santa Fe Trail near Fort Union and "adobe fields" northwest of the third fort. Furrows resulting from excavation of clay from the fields are clearly visible. Graphic by Rebecca Port (Colorado State University). Aerial imagery from ESRI Imagery World 2D layer.

Between 1851 and 1891, Fort Union served as a garrison, arsenal, and supply depot. The frontier post helped to strengthen U.S. rule, presence, and influence in the American Southwest (National Park Service 2008). During its 40-year lifespan, three different Fort Unions were constructed close together in the Mora Valley. Natural features such as plentiful timber on adjacent ridges, mesas, and mountains; and water from spring-fed pools and Wolf Creek; influenced the U.S. military's choice of the fort's location (Curran et al. 2005). Construction of the first Fort Union began in August 1851. Hastily built with green logs, which warped as they dried, this fort served for 10 years. Also hastily constructed, the second Fort Union—a star-shaped earthen fortification ("Star Fort")—was built in 1861 to strengthen Federal defenses at the beginning of the Civil War. Earthworks were the major feature of the second fort (Curran et al. 2005), and the outline of the star is still readily apparent on aerial photographs (fig. 4). In what is now Pecos National Historical Park, the Battle of Glorieta Pass secured the region against the Confederate threat to the south, and no Civil-War fighting actually occurred at Star Fort. Because the partially subterranean fort was a dank, unpleasant place, plans to build a better post were underway within two years after its construction (Houk 2005). The third and final Fort Union was the largest military fortification on the southwestern frontier, with as many as 1,600 troops stationed there at its heyday. The third Fort Union was one of the first representations of the "Territorial" New Mexico architectural style, characterized by adobe structures topped with brick coping (Curran et al. 2005).

Figure 5. Hospital complex at the third Fort Union. The military hospital at Fort Union was one of the largest and best-equipped medical facilities on the southwestern frontier. Today, the hospital ruins are some of the most picturesque preserved buildings at Fort Union National Monument. Top photograph property of the National Park Service (taken in 1889). Bottom photograph by Katie KellerLynn (Colorado State University), taken in 2006.

By 1879, the railroad had arrived in Watrous, New Mexico, near Fort Union, and soon made travel on the Santa Fe Trail obsolete. Fort Union remained garrisoned until its closure in 1891. In the ensuing 63 years before the National Park Service became its steward, Fort Union fell into disrepair. The Union Land and Grazing Company, the private owner during this period, had little use for the buildings and left the fort unattended (Zhu 1992). Consequently, cattle grazing, local residents' use of the fort as a salvage yard, and the course of nature all contributed to the degradation of the fort structures (Zhu 1992). Today, the ruins typically seen by most visitors to Fort Union National Monument are those of the third fort (fig. 5). Although exposure to the elements has irreversibly eroded the adobe structures at Fort Union National Monument, some remaining walls rise more than 4 m (12 ft) and retain original architectural details, such as brick copings (Curran et al. 2005). As part of the enabling legislation for Fort Union National Monument, the remaining structures are to be preserved, not rebuilt (Zhu 1992).

The 292-ha (721-ac) Fort Union National Monument is separated into two units encompassing the sites of the three former forts. The main unit of the monument comprises 258 ha (637 ac) and includes the site of the second fort and remnants of 63 structures of the third fort. This unit contains the largest concentration of 19th-century adobe ruins in the United States (National Park Service 2008). The boundary of the main unit forms an almost perfect square, approximately 1.6 km (1 mi) long on each side (Curran et al. 2005). The 34-ha (84-ac) smaller unit encompasses the site of the first Fort Union, and adobe ruins and foundations of the arsenal connected with the third fort (National Park Service 2006a). This smaller unit is located approximately 610 m (2,000 ft) west of the main unit at the base of the faulted cliffs of Lower Cretaceous Dakota Sandstone (map unit symbol Kd) (fig. 6).

Figure 6. Dakota Sandstone ridge. Dakota Sandstone (Kd) makes up the cliffs/mesa behind the smaller unit of Fort Union National Monument. Soldiers quarried sandstone from the cliff to use as building stone at the fort. National Park Service photograph.

Figure 7. Dakota Sandstone cliff. Cretaceous Dakota Sandstone (Kd) crops out on the western side of the highway leading to Fort Union National Monument. This cliff at the turnoff to the national monument (Exit 366) exposes the sandstone. National Park Service photograph.

Fort Union National Monument is accessible from Interstate 25 via Exit 366 (New Mexico Highway 161), where a cliff exposes outcrops of Dakota Sandstone (fig. 7). The fort sits on younger (Upper Cretaceous) Graneros Shale (Kgs; fig. 8), which underlies the surrounding prairie. The Ocaté volcanic field lies to the north and east of the national monument. Cinder cones and lava flows associated with this field are a prominent part of the Fort Union setting. The flows nearest to Fort Union are around 2.4 million years old (Olmsted and McIntosh 2004).

Era	Period	Epoch	Age*	Rock/Sediment Unit	Description
Cenozoic	Quaternary	Holocene	0.01–present	Alluvium (Qa)	Unconsolidated gravel, sand, silt, and clay
				Lake deposits (Ql)	Clay, calcium carbonate, and carbonaceous material
				Alluvial cone deposits (Qac)	Basalt and shale fragments
				Alluvial fan deposits (Qaf)	Unconsolidated gravel, sand, silt, and clay
		Holocene and Pleistocene	2.6–present	Talus (Qt)	Broken blocks of basalt
		Pleistocene	2.6–0.01	Younger terrace deposits (Qty)	Unconsolidated gravel and sand
				Landslide deposits (Qls)	Basalt blocks resting on Carlile Shale (Kc)
				Older terrace deposits (Qto)	Semi-consolidated gravel and sand
	Quaternary; Tertiary: Neogene	Pleistocene; Pliocene	5.3–0.01	Basalt of Wolf Creek (QTw)	Vesicular basalt
	Tertiary: Neogene	Pliocene	5.5–2.6	Basalt of Black Mesa (Tbm)	Vesicular basalt
	Tertiary: Neogene	Miocene	65.5–5.3	Units of this age interval are absent in Fort Union National Monument area.	
	Tertiary: Paleogene	Oligocene			
		Eocene			
		Paleocene			
Mesozoic	Cretaceous	Upper	100–65.5	Carlile Shale (Kc)	Gray shale
				Greenhorn Limestone (Kgn)	Light-gray limestone
				Graneros Shale (Kgs)	Dark-gray shale
		Lower	145–100	Dakota Sandstone (Kd)	Sandstone, shale, and conglomeratic sandstone
	Jurassic	Upper	161–145	Morrison Formation (Jm)	Siltstone, shale, and conglomeratic sandstone
				Todilto Limestone (Jt)	Sandy limestone with some gypsum
				Entrada Sandstone (Je)	Sandstone
		Middle	175–161	Units of this age interval are absent in the Fort Union National Monument area.	
		Lower	200–175		
	Triassic	Upper	228–200	Chinle Formation (TRc)	Shale and sandstone with limestone lenses and pebbles

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

Figure 8. General stratigraphic column for Fort Union National Monument. Graneros Shale (Kgs) underlies the majority of the national monument. Dakota Sandstone (Kd) crops out in the mesa to the west of the smaller unit. Basalt erupted as lava flows from the Ocaté volcanic field, with the basalt of Wolf Creek (QTw) flow ending just north of the national monument. Alluvium (Qa) underlies the Wolf Creek channel and floodplain. Colors are standard colors approved by the U.S. Geological Survey to indicate different time periods on geologic maps; they also correspond to the colors on the Map Unit Properties Table. See the Map Unit Properties Table for more detail.

Geologic Issues

The Geologic Resources Division held a Geologic Resources Inventory scoping meeting for Fort Union National Monument on 28 March 2006 to discuss geologic resources, address the status of geologic mapping, and assess resource management issues and needs. This section synthesizes those discussions and highlights particular issues that may require attention from resource managers. Contact the Geologic Resources Division for technical assistance.

Participants at the 2006 scoping meeting (see Appendix for a list of participants) identified and discussed the following geologic issues:

- Soil Ruts
- Wolf Creek
- Landslides and Rockfall
- Seismic Activity

Since 2006, oil and gas development in the Las Vegas Basin—the structural basin in which Fort Union National Monument is situated—has become an additional geologic issue of resource management concern.

Resource managers may find *Geological Monitoring* (Young and Norby 2009) useful for addressing these geologic resource management issues. The manual provides guidance for monitoring vital signs—measurable parameters of the overall condition of natural resources. The NPS Geologic Resources Division initiated and funded the development of *Geological Monitoring* to provide guidance for resource managers seeking to establish the status and trends of geologic resources and processes within the National Park System, and to advance the understanding of how geologic processes impact ecosystem dynamics. Each chapter covers a different geologic resource and supplies detailed recommendations for resource managers, including monitoring methodologies, timing and frequency, and equipment and costs.

Soil Ruts

According to the soil survey for Fort Union National Monument (National Park Service 2009), the potential for soil rutting is severe throughout the national monument, except along the structural benches (soil map unit SB) in the smaller unit, where it is moderate, and along the terraces (TA) in the main unit, where it is slight (fig. 9).

From a natural resource perspective, the occurrence of 120-year-old soil ruts on the landscape underscores the long-term effects of human activities, namely the ability of vehicular traffic to modify soil properties for more than a century (Sharratt et al. 1998). From a cultural resource perspective, the severe susceptibility to soil rutting at Fort Union National Monument was beneficial. Superb remains of the Santa Fe Trail pass through the national monument (fig. 10), and visitors can view culturally significant ruts of both branches of the trail (National Park Service 2002).

The ruts of the Santa Fe Trail are of primary national significance, although other ruts, such as those running north along the mesa and west through Higgins Canyon, have local significance. The latter routes connected Fort Union to the towns of Loma Parda and Ocate, which were sources of produce and recreation. Ruts leading to the Turkey Mountains connected the fort to timber and hunting areas. Additionally, ruts show the route to a horse track east of the third fort (Curran et al. 2005). Ruts leading to the quarry that was the source of building materials also remain visible on the landscape and in aerial view (fig. 4).

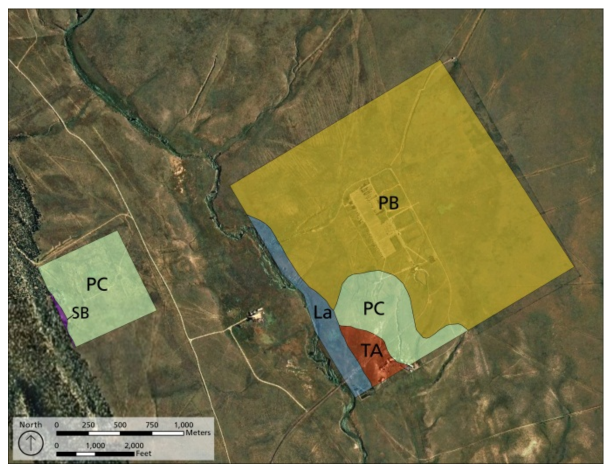

Figure 9. Soils at Fort Union National Monument. The smaller unit of Fort Union National Monument (left) contains two soil types: the undulating Partri-Camero-Bernal association (PC) and the very steep Sombordoro–rock outcrop–Tuloso complex (SB). PC is associated with the potential for severe soil rutting, but low potentials for water and wind erosion. SB is associated with the potential for slight soil rutting, a moderate potential for water erosion, and a low potential for wind erosion. The main unit of Fort Union National Monument (right) contains four soil types: gently sloping Partri loam (PB); undulating PC; La Bier silty clay loam (La), and Tinaja gravelly loam (TA). TA has a moderate potential for soil rutting, a high potential for water erosion, and a low potential for wind erosion. PB is associated with the potential for severe soil rutting, but low potentials for water and wind erosion. La is associated with the potential for severe soil rutting, high susceptibility to wind erosion, and a low potential for water erosion. Graphic by Rebecca Port (Colorado State University) using soils data from the Soil Resources Inventory Program (National Park Service 2009). Aerial imagery from ESRI Imagery World 2D layer.

Figure 10. Soil ruts. Fort Union National Monument is one of four National Park System units that preserves soil ruts of the Santa Fe Trail. These features have remained on the landscape for 120 years. National Park Service photograph.

The protection of these features has long been a resource management concern (Kruse 1982). The ruts have been photographed and mapped, but no data on how they might be preserved have been gathered (National Park Service 1985). Park managers currently rely on erosion control measures established in the 1980s and 1990s (Marie Frias Sauter, Fort Union National Monument, superintendent, e-mail communication, 7 February 2011).

In 2007, a team of NPS resource specialists from Fort Union National Monument, the Water Resources Division, and the Regional Support Office in Santa Fe inspected wagon ruts within and near Fort Union National Monument to assess the effects of erosion on this resource (Smillie et al. 2007). Overall, these specialists found that most wagon ruts were fairly stable in terms of recent erosion. Very few "raw" banks—channels with angular, unvegetated banks indicative of recent or active erosion—were observed. Many ruts were only slightly incised and had good grass cover. However, the team observed a few incised channels in four general areas: (1) south and west of the visitor center, (2) east of the housing area, (3) west of the northwestern corner of the fort complex, and (4) from the water tank to the northeast corner of the fort complex. Significantly, none of these incised channels is presently threatening the main fort area. A riprap grade-control structure prevents headcutting of the gully east of the housing area up into the fort area. This structure appears to be working well and may serve as a model for the future mitigation of headcutting in other areas. Smillie et al. (2007) did not recommend that park managers take any structural steps (e.g., riprap installation) toward erosion control at the time of the study. However, these investigators recommended that monument staff develop an erosion monitoring program. Moreover, future infrastructure projects or any change to present infrastructure, such as the installation of impermeable surfaces or culverts, should avoid increasing runoff or changing slope grades (Smillie et al. 2007) because such changes could induce erosion.

Wolf Creek

Wolf Creek is Fort Union's primary fluvial feature (fig. 11). Alluvium (map unit symbol Qa)—gravel, sand, silt, and clay—covers the Wolf Creek floodplain and channel (see "Geologic Map Data" section). Although sometimes identified as "Coyote Creek," for example in the national monument's cultural landscape inventory (Curran et al. 2005), this creek is denoted as Wolf Creek on the 1963 topographic map by the U.S. Geological Survey (USGS) and in the USGS Geographic Names Information System (GNIS). In addition to Wolf Creek, four intermittent fluvial channels (arroyos) intersect the main unit of Fort Union National Monument (fig. 12).

Wolf Creek, a tributary of the Mora River, is a perennial stream that flows along the southwestern side of the main unit of Fort Union National Monument. According to Winograd (1956), seepage from springs maintains the perennial flow in Wolf Creek. The source of the springs is an aquifer of Dakota Sandstone (Kd) (Winograd 1956; Martin 2009). Groundwater may be rising along the Fort Union fault, which separates the Dakota Sandstone from the strata of the "shaly sequence" or Graneros Shale (fig. 13) (Winograd 1956).

Figure 11. Wolf Creek. Wolf Creek is a perennial stream that flows along the western side of the main unit of Fort Union National Monument. It is the national monument's primary fluvial feature. The source of the spring-fed creek is the Dakota Sandstone (Kd) aquifer. National Park Service photograph.

The well that provides water for the national monument was drilled into Dakota Sandstone (Martin 2009). No large-scale groundwater pumping, such as that for irrigation or municipal wells, occurs in the area, and no significant water diversion has been employed in the Wolf Creek basin (Larry Martin, NPS Water Resources Division, hydrogeologist, e-mail communication, 9 February 2011). Therefore, water level in the national monument's well is not expected to change significantly (Martin 2009), and the perennial nature of Wolf Creek is not expected to change as a result of groundwater pumping (Larry Martin, e-mail communication, 9 February 2011).

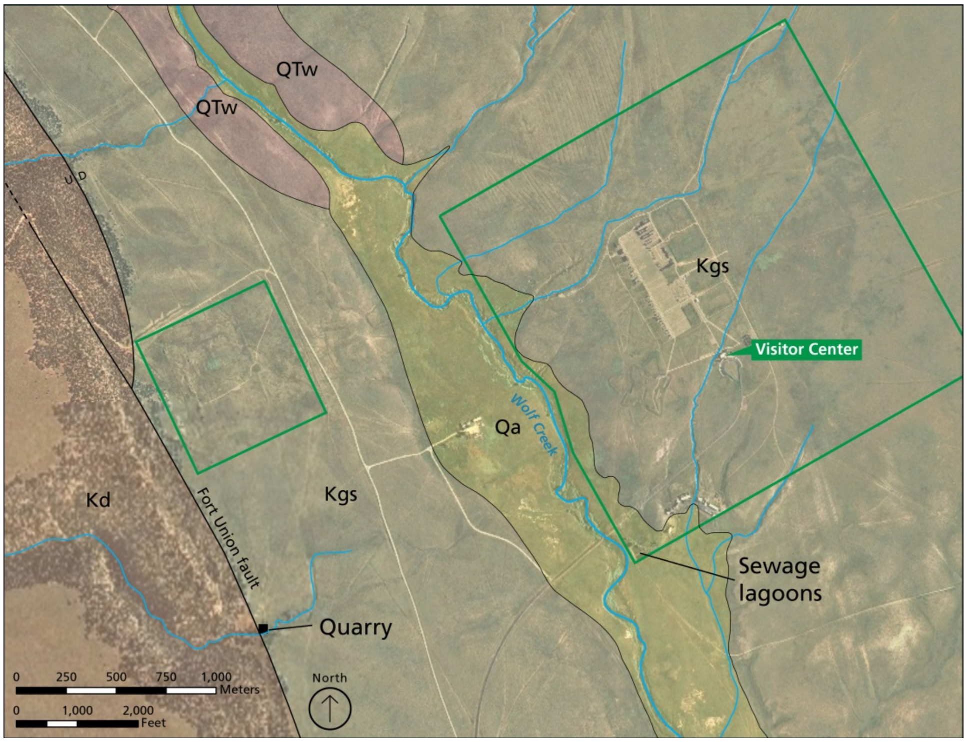

Figure 12. Geologic map and aerial image of Fort Union National Monument. Green outlines indicate the boundaries of the two units at Fort Union National Monument. The main unit encompasses the ruins of the second and third Fort Unions. The smaller unit encompasses the ruins of the first Fort Union and the arsenal of the third Fort Union. The approximate location of the sandstone quarry used for building stone is indicated south of the smaller unit, where an intermittent stream intersects the Dakota Sandstone (Kd) along the Fort Union fault (Tibor Remeyik, Fort Union National Monument, volunteer, telephone communication, 11 February 2010). Graphic by Rebecca Port (Colorado State University), and Philip Reiker (NPS Geologic Resources Division). Aerial imagery from ESRI Imagery World 2D layer.

Figure 13. Graneros Shale. Upper Cretaceous Graneros Shale (Kgs) was deposited in the Western Interior Seaway. The unit underlines the majority of Fort Union National Monument and the surrounding plain. Photograph by Richard Gonzales (Fort Union National Monument, volunteer).

Flooding could occur along Wolf Creek or in arroyos originating outside but continuing inside Fort Union National Monument (National Park Service 1987). The primary concern related to flooding is damage to historic structures, namely adobe and stone ruins of the third fort, but flooding could also damage modern facilities such as the employee quarters, maintenance shop, utility systems, and sewage lagoons, which are situated in the southern corner of the main unit (National Park Service 1987). In addition, the natural meandering of Wolf Creek could affect the integrity of the sewage lagoons over time (National Park Service 2006b) (fig. 12).

Lord et al. (2009)—the chapter about monitoring stream systems in *Geological Monitoring* (Young and Norby 2009)—described fluvial geomorphology and how to monitor changes over time. The authors suggested six methods and vital signs for such monitoring: (1) watershed landscape, (2) hydrology, (3) sediment transport, (4) channel cross section, (5) channel planform, and (6) channel longitudinal profile. This guidance may be of use for monitoring changes in the channel morphology and flow of Wolf Creek.

Landslides and Rockfall

Johnson (1974) mapped landslide deposits (map unit symbol Qls) north of Fort Union National Monument along the Los Gavilanes fault and on the eastern flank of Black Mesa, as well as talus deposits (Qt) at the base of Black Mesa (see “Geologic Map Data” section). Both of these deposit types are results of mass wasting (gravity-driven processes). Weathering, including repeated freeze-thaw cycles, caused blocks to dislodge and form talus slopes at the base of Black Mesa. Intense summer rainstorms and seismic activity also facilitate rockfall and the formation of talus slopes (Caine 1986). Movement within the talus slopes continues after the initial rockfall event (Caine 1986).

Although mass wasting is not a major issue at Fort Union National Monument, managers at the national monument are aware that some rockfall does occur in the area, in particular along the ridge on the western side of the smaller unit (National Park Service 2006b). These cliffs are composed of Dakota Sandstone (Kd). Only a small section of this ridgeline intersects the national monument boundary, but freeze-thaw cycles can dislodge rock fragments and blocks, which can move under the force of gravity in free fall and roll or bounce into the smaller unit, potentially impacting ruins of the first fort and the third fort's arsenal (National Park Service 2006b). Additionally, seismic activity can trigger mass wasting. Although the Fort Union fault, which runs along the western side of the smaller unit, currently appears to be stable, a small amount of displacement occurred during the Pleistocene Epoch (National Park Service 2006b) (see "Seismic Activity" section).

In the chapter about slope movements in *Geological Monitoring* (Young and Norby 2009), Wieczorek and Snyder (2009) described the various types of slope movement and mass-wasting triggers, and suggested five methods and vital signs for monitoring: (1) types of landslides, (2) landslide triggers and causes, (3) geologic materials in landslides, (4) measurement of landslide movement, and (5) assessing landslide hazards and risks

Seismic Activity

Johnson (1974) mapped two faults in the vicinity of Fort Union National Monument: the Fort Union fault, which lies along the western boundary of the smaller unit (fig. 12); and the Los Gavilanes fault, located northwest of the national monument (see "Geologic Map Data" section). Activity (slip rates) along these faults is not known; however, the major fault zone in the area—the 270-km- (170-mi-) long Sangre de Cristo normal fault system that forms the eastern margin of the Rio Grande rift—had a slip rate of 0.06 mm (0.002 in) per year in northern New Mexico during the middle and late Pleistocene Epoch (<750,000 years ago) (Ruleman et al. 2008).

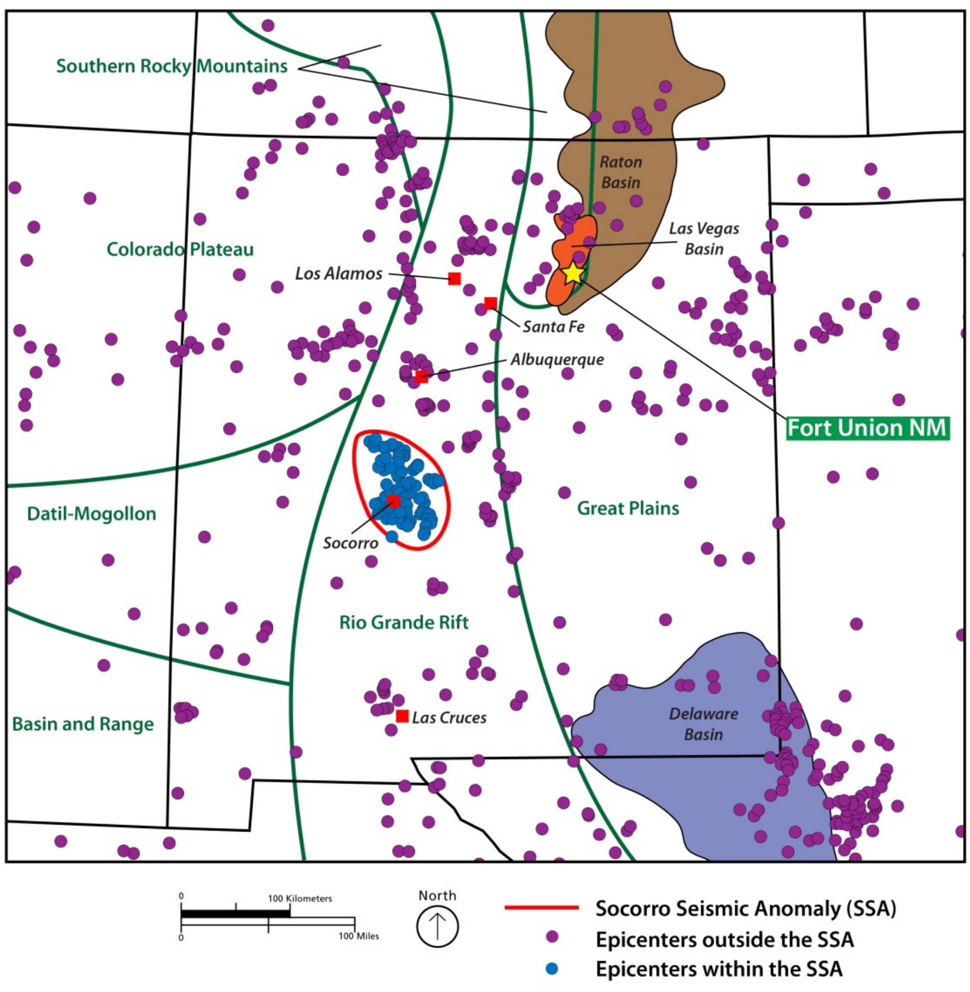

Figure 14. Seismic activity and structural basins in New Mexico. Earthquake activity in New Mexico is concentrated around Socorro, but some small earthquake epicenters occur in the vicinity of Fort Union National Monument. Two other "hot spots" of seismic activity are the Delaware and Raton basins. Swarms of earthquakes in these basins may be related to the disposal of water associated with the production of oil and gas. Fort Union lies in the Las Vegas Basin. Like the Delaware and Raton basins, the Las Vegas Basin is known to contain oil and gas resources. Modified from Sanford et al. (2002) by Philip Reiker (NPS Geologic Resources Division).

In the chapter about seismic activity in *Geological Monitoring* (Young and Norby 2009), Braile (2009) highlighted methods for seismic monitoring such as monitoring earthquake activity, analysis and statistics of earthquake activity, analysis of historical and prehistoric earthquake activity, earthquake risk estimation, and geomorphic and geologic indications of active tectonics. In addition, Braile (2009) provided a summary of seismic monitoring methods, including the required expertise, equipment, and personnel, and the cost and labor intensity of each method.

A disproportionate number of earthquakes in New Mexico are centered in the Rio Grande Valley near Socorro, in a tight cluster known as the Socorro Seismic Anomaly (fig. 14). Seismic activity in this area is likely the result of the stretching of the Earth's crust over a large body of magma that exists at a depth of 19 km (12 mi) below the surface (Fialko and Simons 2001). This magma is associated with the Rio Grande rift, but surprisingly, with the exception of the Socorro Seismic Anomaly, this rift is not defined by earthquake activity (Sanford et al. 2006). The Socorro Seismic Anomaly occupies less than 1% of New Mexico and bordering areas, but accounted for 23% of earthquakes of magnitude 2.0 or greater during a 37-year study period from 1962 through 1998 (Sanford et al. 2002), and 15% of magnitude 2.0 or greater earthquakes in a 6-year study period from 1999 through 2004 (Sanford et al. 2006). Although earthquake activity in New Mexico is concentrated around Socorro, Sanford et al. (2002) mapped some small earthquake epicenters in the vicinity of Fort Union National Monument (fig. 14).

Two other "hot spots" of seismic activity are located in the Delaware (southeastern New Mexico and West Texas) and Raton (northeastern New Mexico and southern Colorado) basins (fig. 14). Some observations suggest that swarms of earthquakes in the Delaware Basin were caused by disposal of large quantities of water related to the production of oil. Earthquakes swarms in the Raton Basin may have been caused by the removal and/or injection of water associated with the production of coalbed methane (Sanford et al. 2002, 2006).

The recorded history of seismic activity in New Mexico begins in 1869 (Sanford et al. 2002, 2006; U.S. Geological Survey 2009b). This long record aids researchers in evaluating seismic hazards and forecasting the location and magnitude of future earthquakes (Sanford et al. 2002). The largest recorded earthquake in New Mexico occurred on 15 November 1906; it was centered in the Socorro area and felt throughout most of New Mexico and in parts of Arizona and Texas (U.S. Geological Survey 2009a). This historic quake occurred before the Richter scale came into use and was measured using the Modified Mercalli scale as an intensity VII (on a scale of I to XII), indicating little damage to well-designed and well-constructed buildings, but considerable damage to poorly built or poorly designed structures, as well as breakage of some chimneys. Indeed, four chimneys were shaken off the Socorro County Courthouse, and two others were cracked severely. Plaster was shaken from walls in Santa Fe, about 200 km (120 mi) from the epicenter. A recent large earthquake (magnitude 4.1 on the Richter scale) in New Mexico occurred on 18 January 2010 in the Raton area (Winchester 2010).

Oil and Gas Development

At the time of the scoping meeting in 2006, the potential for hydrocarbon extraction was minimal in the vicinity of Fort Union National Monument. Since 2006, however, interest in shale gas production has increased and horizontal drilling technology has improved. Thus, staff members at the NPS Geologic Resources Division inquired with the New Mexico Bureau of Geology and Mineral Resources about the potential for oil and gas development near Fort Union National Monument (Bruce Heise, Geologic Resources Division, geologist, e-mail communication to Ron Broadhead, New Mexico Bureau of Geology and Mineral Resources, petroleum geologist, 4 January 2011). According to Ron Broadhead at the New Mexico Bureau of Geology and Mineral Resources, "there is considerable potential for hydrocarbons in the region [including the Las Vegas Basin], with natural gas the most likely resource." The Las Vegas Basin lies east of the Sangre de Cristo uplift and underlies Fort Union National Monument (fig. 14).

The primary target for oil and gas production in the Las Vegas Basin is the thick section of rocks from the Pennsylvanian Period (fig. 2). This section contains up to 3,050 m (10,000 ft) of shale and sandstone (Broadhead 2008). Black, organic-rich shales are likely to contain gas; interbedded sandstones offer considerable potential and have yielded hydrocarbon-rich gases to exploration wells (Ron Broadhead, e-mail communication, 10 January 2011). Other strata with potential for oil and gas development are the Carlile (map unit symbol Kc) and Graneros (Kgs) shales for shale gas, the Greenhorn Limestone (Kgn) for shale gas and oil, the Morrison Formation (Jm) for natural gas, and the Dakota Sandstone (Kd) for natural gas. Of these, the Graneros Shale, Greenhorn Limestone, Dakota Sandstone, and Morrison Formation are mapped in the vicinity of Fort Union National Monument (see "Geologic Map Data" section). Within Mora County, the Dakota Sandstone and Morrison Formation have produced natural gas from the now-abandoned Wagon Mound field, located on the eastern flank of the Las Vegas Basin (Ron Broadhead, written communication, 1 August 2012).

In addition, significant potential for carbon dioxide (CO_2) gas has been recognized in the Entrada Sandstone (Je) and in Triassic strata such as the Santa Rosa Sandstone, which was not mapped by Johnson (1974). This potential is particularly notable on the flanks of the Turkey Mountains uplift because the Tertiary laccolith that forms the uplift appears to be a major source of CO_2 in the Las Vegas Basin. On the uplift, all reservoirs from the lowermost Pennsylvanian through the uppermost Permian strata have the potential to be saturated with CO_2 (Ron Broadhead, written communication, 1 August 2012).

Geologic Features and Processes

Geologic resources underlie park ecosystems and geologic processes shape the landscape of every park. This section describes the most prominent and distinctive geologic features and processes in Fort Union National Monument.

Discussions during the scoping meeting in 2006 provided an opportunity to develop a list of geologic features and processes operating in Fort Union National Monument. These include the following:

- Volcanic Features
- Dakota Sandstone
- Turkey Mountains
- Caves
- Eolian Features and Processes
- Building Materials
- Stream Terraces
- Paleontological Resources

Figure 15. Basalt west of Wolf Creek. Vesicular basalt erupted in the Ocaté volcanic field and flowed down the Wolf Creek drainage. Another flow caps Black Mesa (fig. 16). National Park Service photograph.

Volcanic features of the Ocaté volcanic field; landforms associated with the Dakota Sandstone (map unit symbol Kd), such as hogbacks, cliffs, and ridges; and the Turkey Mountains on the northern horizon are all significant parts of the Fort Union landscape (Price 2010). These features appear much the same as they did during the fort's active period, from 1851 to 1891. Historical accounts indicate that nearby caves also played a role in the Fort Union story, and wind and windblown dust were common complaints and topics of conversation. Additionally, geologic materials such as building stone and clay for adobe were important resources for the fort's construction. Dakota Sandstone (Kd) provided building stone, while Graneros Shale (Kgs) yielded clay. Other geologic features include alluvium (Qa) that forms terraces along Wolf Creek in the main unit. Elsewhere, Graneros Shale (fig. 13) and alluvium are known to contain fossils.

Figure 16. Black Mesa. Capped by the basalt of Black Mesa (Tbm), Black Mesa is a prominent landmark north of Fort Union National Monument. National Park Service photograph.

Volcanic Features

The digital geologic map for Fort Union National Monument shows basalt of Wolf Creek (QTw), which is more than 24 m (80 ft) thick, near the northwestern corner of the main unit of the national monument (see fig. 15 and "Geologic Map Data"). In addition, basalt of Black Mesa (Tbm) caps Black Mesa north of the national monument and can be more than 37 m (120 ft) thick in the area (fig. 16). These basalt units are lava flows that issued from the Ocaté volcanic field. The majority of the Ocaté volcanic field lies north of the national monument, but Maxson Crater and associated flows are located to the east (fig. 17). Lava erupted from shield volcanoes, composite cones, fissures, and cinder cones (Nielson and Dungan 1985; O'Neill and Mehnert 1988).

The Ocaté volcanic field is one of a series of volcanic fields associated with the Jemez lineament, an east–west zone extending across New Mexico and into Arizona where concentrated volcanism has occurred during the past 10 million years (fig. 18). In New Mexico, the Raton–Clayton, Ocaté, and Zuni–Bandera volcanic fields, as well as the Valles Caldera, fall on the Jemez lineament (fig. 18). The National Park System is well represented on this lineament: Capulin Volcano National Monument is part of the Raton–Clayton volcanic field, Bandelier National Monument is in the Valles Caldera, and El Malpais and El Morro national monuments (KellerLynn 2012a, 2012b) are in the Zuni–Bandera volcanic field.

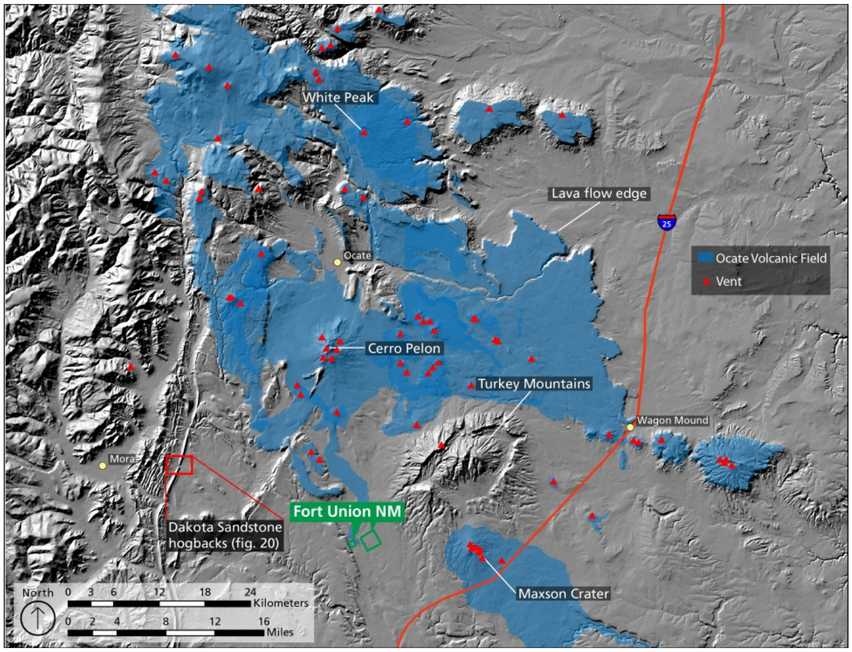

Figure 17. Topographic relief in the Fort Union area. Green boxes represent the main and smaller units of Fort Union National Monument, which are surrounded by the Ocaté volcanic field, shown in blue. The Ocaté volcanic field was active from about 8 million to 800,000 years ago (fig. 19). The total volume of exposed volcanic rocks in the Ocaté volcanic field is approximately 90 km^3 (22 mi^3) (Baldridge 1990). Volcanic features include lava flows, shield volcanoes, composite cones, fissures, and cinder cones. Volcanic vents of the Ocaté volcanic field are shown with red triangles. Note the Turkey Mountains, a large laccolith to the east of Fort Union NM. A more detailed view of hogbacks of Dakota Sandstone is shown in figure 20. Elevation imagery from U.S. Geological Survey, compiled by Rebecca Port (Colorado State University). Annotation and Ocaté Volcanic Field information adapted from Olmsted and McIntosh (2004) by Philip Reiker (NPS Geologic Resources Division)

The Ocaté volcanic field was active for 7 million years, erupting episodically in approximately 14 pulses between 8.2 million and 800,000 years ago (fig. 19). The lava flows nearest Fort Union National Monument are from eruptive pulse 10 (2.59 million–2.18 million years ago). In general, volcanism progressed from north to south during the evolution of the field (Olmsted and McIntosh 2004). The physiographic expressions of the resulting lava flows reflect their relative ages: the oldest flows cap the highest mesas, rising up to 600 m (1,970 ft) above the modern drainage, and successively younger lava flows cap correspondingly lower mesas. The youngest flows, approximately 800,000 years old (O'Neill and Mehnert 1988; Olmsted and McIntosh 2004), lie 10–30 m (30–100 ft) above the present drainage and cover surfaces representing the stream network at the time of eruption (Baldridge 1990).

Dakota Sandstone

First described by Meek and Hayden (1862), during an expedition into the Nebraska Territory, Dakota Sandstone (Kd) is named for Dakota, Nebraska, where prominent hills of this rock formation occur near the town. Since that time, Dakota Sandstone has been identified in Arizona, Colorado, Iowa, Kansas, Minnesota, Montana, North Dakota, New Mexico, Oklahoma, South Dakota, Texas, Utah, and Wyoming. The broad distribution of the sandstone reflects its depositional environment. Starting about 96 million years ago, Dakota sediments were deposited as the Western Interior Seaway advanced across western North America during the Cretaceous Period. Fossil leaves,

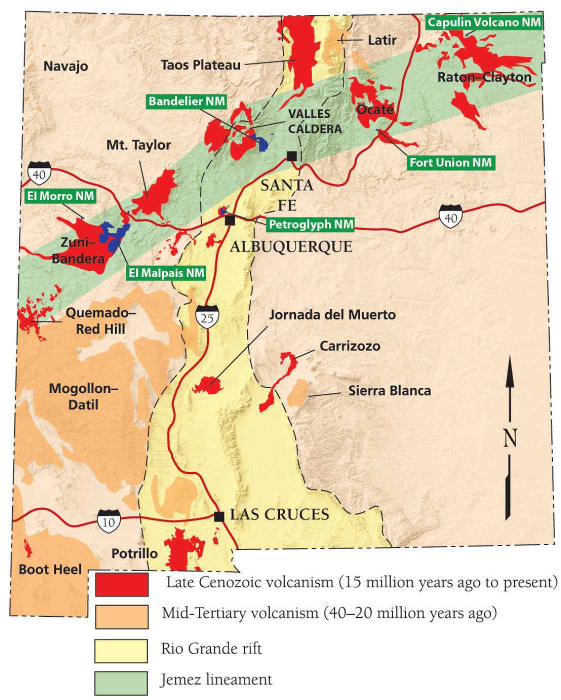

Figure 18. Major volcanic fields in New Mexico. Fort Union National Monument is surrounded by the Ocaté volcanic field. This volcanic field and numerous others lie on the Jemez lineament, a zone of crustal weakness and concentrated volcanism that stretches from central Arizona to northeastern New Mexico. The north–south-trending Rio Grande rift—a center of volcanic activity during an earlier episode of volcanism (40 million–20 million years ago)—intersects the Jemez lineament near Valles Caldera. Graphic by New Mexico Bureau of Geology and Mineral Resources, modified by Philip Reiker (NPS Geologic Resources Division).

wood, and coal were left as evidence of the unit's terrestrial origin; shell fragments document eventual transgression to marine conditions.

Dakota Sandstone is resistant to erosion and forms hills, ridges, and hogbacks. With outlines resembling the back of a hog, hogbacks are ridges with sharp summits and steep slopes of nearly equal inclination on both flanks. The term "hogback" is usually restricted to the description of ridges carved from strata dipping at angles greater than 20° (Neuendorf et al. 2005). Hogbacks are formed by differential erosion, with outcrops of steeply inclined resistant rocks making up the sharp-crested ridges. The eastern edge (frontal fault) of the uplifted Sangre de Cristo Mountains is marked by hogbacks (fig. 20).

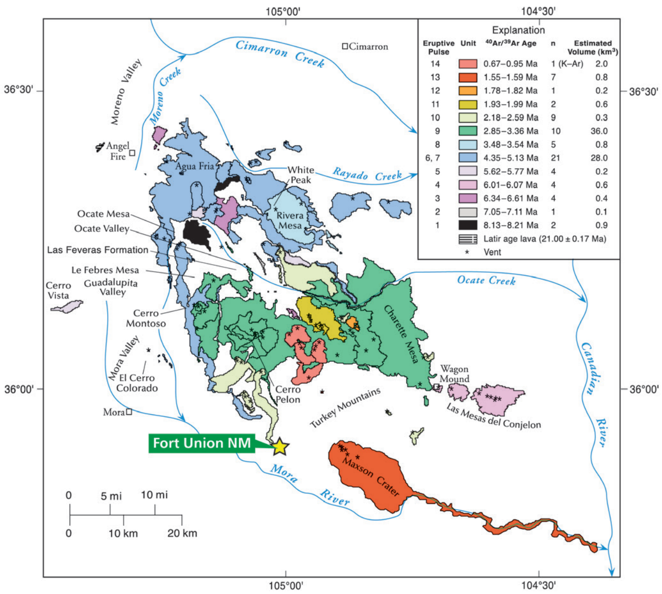

Figure 19. Lava flows of the Ocaté volcanic field. The Ocaté volcanic field erupted in 14 pulses, as shown on the figure. Olmsted and McIntosh (2004) radiometrically dated the lava flows using argon-40 (^{40}Ar) / argon-39 (^{39}Ar). The legend indicates the range of $^{40}Ar/^{39}Ar$ ages and the estimated volumes for each eruptive pulse. n = number of samples dated by Olmsted and McIntosh (2004). The flows closest to Fort Union National Monument are from eruptive pulse 10. Graphic from Olmsted and McIntosh (2004).

These features have served as a landmark and visual representation of the boundary between the Southern Rocky Mountains and the Great Plains physiographic provinces for many years (fig. 1). Lee (1921) was the first geologist to draw this boundary between the two provinces along the uplifted Cretaceous hogbacks.

In addition to hogbacks, Dakota Sandstone makes up the mesa west of the smaller unit of Fort Union National Monument (fig. 6) and can be observed along the western side of New Mexico Highway 161 (NM-161), which leads to the national monument from Interstate 25 (I-25). The cliff at the intersection of I-25 and NM-161 (Exit 366) also displays Dakota Sandstone (fig. 7).

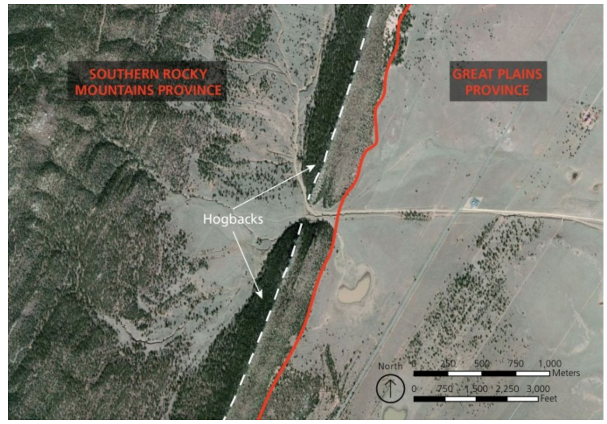

Figure 20. Dakota hogbacks. Hogbacks made of Upper Cretaceous Dakota Sandstone are a distinctive feature in the Fort Union area. Such features are regionally significant, as they mark the boundary between the Rocky Mountain and Great Plains physiographic provinces. The hogbacks shown in the image are approximately 19 km (12 mi) west of Fort Union National Monument. Aerial imagery from ESRI Bing Maps Aerial layer, modified by Rebecca Port (Colorado State University).

Turkey Mountains

Visible on the horizon to the northeast of Fort Union National Monument, the Turkey Mountains (fig. 21) are a result of an igneous intrusion called a "laccolith"—a mushroom-shaped body of magma with a flat floor and domed roof. The laccolith created the circular Turkey Mountains (fig. 17), uplifting and exposing Triassic strata at the center of the dome. Concentric bands of the Triassic Chinle Formation (TRc) and Jurassic Entrada Sandstone (Je) and Morrison Formation (Jm) encircle the central core of Triassic Santa Rosa Sandstone (not mapped on the digital geologic map for Fort Union). Cretaceous Dakota Sandstone (Kd) and Graneros Shale (Kgs) form surface exposures on the flanks of the uplift (Broadhead 2008).

The igneous rock of the laccolith is not exposed, but drilling during oil and gas exploration confirmed its presence (Boyd and Campbell 1983; Broadhead 2008). Moreover, dikes associated with the laccolith are exposed at the surface (Hayes 1957; Broadhead 2008). A potassium-argon date of 15.6 ± 0.7 million years for biotite from one of the dikes indicates that dike emplacement occurred during the Miocene Epoch (Boyd and Campbell 1983). Chemical analysis has suggested a common or similar magma source for these dikes and the surrounding Ocaté volcanic field (Lindline et al. 2007).

Figure 21. Turkey Mountains. An igneous intrusion called a "laccolith" created the domed Turkey Mountains. Triassic strata are exposed at the center of the dome, and concentric bands of Triassic, Jurassic, and Cretaceous rocks encircle the central core. Photograph by Richard Gonzales (Fort Union National Monument, volunteer).

Caves

Although no caves occur within Fort Union National Monument, scoping participants suggested that lava-tube caves may be present nearby (National Park Servcie 2006b). Two units of thick basalt—basalt of Wolf Creek (QTw) and basalt of Black Mesa (Tbm), 24 m (80 ft) and 37 m (120 ft) thick, respectively—are shown on the geologic map of Fort Union National Monument, and potentially contain lava tubes (National Park Service 2006b). However, no such feature has been identified to date (Greer Price, deputy director, and Nelia Dunbar, geochemist, New Mexico Bureau of Geology and Mineral Resources, e-mail communication, 24 January 2011).
Lava tubes are roofed conduits for molten material that form when the surface of an active lava flow cools. Below the insulating roof or crust, molten lava continues to flow until its source is depleted or diverted, leaving behind an empty space or cave. Some lava tubes extend for tens of kilometers, although these features are generally fragmented into shorter stretches (Neuendorf et al. 2005). For example, lava tubes at El Malpais National Monument are up to 29 km (47 mi) long and are some of the most striking morphological features within the Zuni–Bandera volcanic field (Wood and Kienle 1990; KellerLynn 2012a).

Although no lava tubes have been identified in the Ocaté volcanic field, Sánchez et al. (2006, Appendix C, p. 124) mentioned the historic role of "caves" at Fort Union, noting that "officials had difficulty maintaining order and discipline among [the fort's] enlisted men" because prostitutes, gamblers, and whiskey sellers arrived in the vicinity shortly after the fort's establishment, and many set up businesses in nearby caves. Furthermore, these caves were found to be a hidden repository for thousands of dollars–worth of military supplies and equipment used as compensation for items received and services rendered (Sánchez et al. 2006).

It is not known whether the caves mentioned in Sánchez et al. (2006) are lava tubes, but other cave-forming rock units are limited in the vicinity, so they may be. These caves may also be "talus caves" formed within talus (Qt) deposits along the flanks of Black Mesa (see "Geologic Map Data" section).

Eolian Features and Processes

In contrast to 1851–1891, when as many as 1,600 people occupied Fort Union and more than 2,000 horses grazed the surrounding lands (fig. 22), today's landscape is well vegetated (National Park Service 2006b). In the historic past, however, the construction of buildings, gardens, corrals, and the parade ground gradually turned the rich grassland into a barren, dusty area (Zhu 1992).

Construction, grazing, and military activities in a region known for abundant wind led to the frequent occurrence of dust storms at the frontier post. Residents commonly complained about the wind and windblown dust, and referred to the fort as "Fort Windy" (Oliva 1993). One of the first residents of the post, Catherine Cary (Mrs. Isaac) Bowen, wrote to her parents that "in this territory nearly all the time we have high winds and the soil becomes so dry and powdered that the air is filled with clouds of the most disagreeable kind of dust" (Oliva 1993, p. 8). Frances A. (Mrs. Orsemus B.) Boyd, an officer's wife who resided at the post in 1872, reported that the fine soil and sand drifted like driven snow, especially against the buildings at the fort. According to Boyd's account, the deposits of migrating sand were popular playgrounds for children (Miller 1894).

Figure 22. The third Fort Union. During its active period (1851–1891), as many as 1,600 troops were stationed at Fort Union, which was the largest frontier fort in the Southwest. Note the lack of vegetation in the compound, which provided ample dust for dust storms. National Park Service photograph.

After the closing of Fort Union as a frontier post, a commercial grazing operator—Union Land and Grazing Company—replaced the military as the primary land user (Zhu 1992). Grazing continued for 63 years, ending when Fort Union National Monument was established in 1954.

At the present time, dust storms occur rarely and are not a high-priority resource management issue at Fort Union National Monument (National Park Service 2006b). Furthermore, at the scale of geologic mapping, Johnson (1974) did not include any recent eolian deposit on the surface of the national monument. Nevertheless, ample ancient eolian deposits occur within the rock units in the area, primarily the Entrada Sandstone (Je), which formed 160 million years ago as sand dunes in a sabkha environment similar to those of the modern Persian Gulf and Gulf of California.

Lancaster (2009)—the chapter about eolian features and processes in *Geological Monitoring* (Young and Norby 2009)—provided a brief introduction to eolian processes and landforms and their deposits, and highlighted 10 vital signs: (1) frequency and magnitude of dust storms, (2) rate of dust deposition, (3) rate of sand transport, (4) wind erosion rate, (5) changes in total area occupied by sand dunes, (6) areas of stabilized and active dunes, (7) dune morphology and morphometry, (8) dune field sediment state, (9) rates of dune migration, and (10) erosion and deposition patterns of dunes. The discussion of each vital sign provided estimated costs of monitoring methods, a complexity rating for each method, an explanation of methodologies, and recommended timing of monitoring activity. In times of drought and drying climatic conditions, these vital signs may be useful for resource management at Fort Union National Monument.

Figure 23. Building stone. Fort Union National Monument preserves building stone, primarily Dakota Sandstone (Kd), in walkways, chimneys, and building foundations. This sandstone was also used in the construction of the stone guard house and prisoners' cells (shown here). Photograph by Katie KellerLynn (Colorado State University).

Building Materials

Fort Union was built using local geologic materials. Stone mined from nearby quarries was used in the foundations of the barracks, shops, storerooms, and stables; the foundation and steps of the hospital; fireplaces and chimneys of the officers' quarters; the stone guard house and prisoners' cells (fig. 23); and the flagstone walkways in front of the laundress's quarters, prison, and guard house (Oliva 1993). Local stone was also used to construct the latrines (National Park Service 2006b). The sundial on the parade ground (fig. 24) and U.S. Geological Survey markers are also made of stone (Tibor Remeyik, Fort Union National Monument, volunteer, telephone communication, 11 February 2011).

Figure 24. Sundial. This small sundial on the parade grounds is a contributing feature of the Fort Union cultural landscape. The sundial was constructed in 1873 (Oliva 1993). National Park Service photograph.

Although no thorough inventory of the building stones at the national monument has been conducted, most of the stone is likely Dakota Sandstone (Kd) (Sean Habgood, Fort Union National Monument, exhibits specialist, e-mail communication, 8 February 2011; Tibor Remeyik, telephone communication, 11 February 2011). Quarries for building stone occur on private lands outside the national monument (Marie Frias Sauter, Fort Union National Monument, superintendent, e-mail communication, 2 February 2011). One known quarry is located in an outcrop of Dakota Sandstone behind the first fort (figs. 6 and 12). About 10 years ago, 19th-century tools used for stone extraction were still there (Tibor Remeyik, telephone communication, 11 February 2011). The basalts of Black Mesa (Tbm) and Wolf Creek (QTw) may have been used as decorative materials. At this time, however, their use at the fort is unknown (Tibor Remeyik, telephone communication, 11 February 2011).

Other local materials include clay and lime for adobe and mortar production, respectively. Clay fields are located within and outside the monument's boundaries (Marie Frias Sauter, e-mail communication, 2 February 2011) and are visible on aerial photographs at the northwestern side of the main unit (fig. 4). These fields contributed to the cultural landscape's significance and inclusion on the Natural Register of Historic Places (Curran et al. 2005). Two lime kilns used for mortar production during the fort's construction are located on private land south of Fort Union National Monument, near an outcrop of Greenhorn Limestone (Kgn) southwest of Wheeler Lake

(Tibor Remeyik, telephone communication, 11 February 2011). Greenhorn Limestone was the source of the lime.

Some materials used in the construction of Fort Union were not local. For example, bricks stamped “St. Louis” were used in chimneys and the blacksmith shop (Tibor Remeyik, telephone communication, 11 February 2011). The presence of materials quarried elsewhere and transported along the Santa Fe Trail highlights the significance of the trail as a corridor of commerce and transportation of supplies.

Stream Terraces

Terraces composed of alluvial material (sand and gravel) represent former floodplains. Higher terrace levels were deposited before lower levels, and are, thereby, older. Terraces thus chronicle a river’s downward erosion to the modern floodplain.

Johnson (1974) mapped two units of terrace deposits in the Mora River Valley. The older terrace deposits (Qto) are semi-consolidated, stream-deposited gravel and sand above the Mora River (southwestern corner of the map area). Younger terrace deposits (Qty) are unconsolidated, stream-deposited gravel. Soil data also indicate the presence of terrace deposits within Fort Union National Monument (National Park Service 2009). Tinaja gravelly loam (soil map unit TA) covers the terrace deposits in the southern corner of the main unit (figs. 9 and 12).

The older (Qto) and younger (Qty) terraces in the Fort Union area were deposited during the Pleistocene Epoch (2.6 million–11,700 years ago), when glaciers filled the surrounding valleys. Although the terraces are fluvial in origin, they received sediment deposited by rivers flowing from the glaciated Sangre de Cristo Mountains. During glacial advances, excessive debris in meltwater streams led to rapid aggradation of streambeds through deposition of thick accumulations of sand and gravel. When glaciers retreated, streams swollen with meltwater cut trenches into the accumulated material, thereby deepening channels and producing terraces. Terrace tops are thus built during glacial advances; terrace faces are cut during glacial retreats (Harris and Tuttle 1990). Uplift or a change in base level also may induce erosional cycles that cut terraces (Neuendorf et al. 2005).

Paleontological Resources

Koch and Santucci (2003) completed a paleontological resource inventory for the Southern Plains Network, including Fort Union National Monument. The primary geologic formation exposed at the national monument is the Upper Cretaceous Graneros Shale (Kgs; figs. 12 and 13). Kues and Lucas (1987) determined the age of this marine-deposited transgressive (sea level rising) unit using fossil oysters (*Ostrea beloiti*). Sediments of the Graneros Shale were deposited in a variety of marine environments, ranging from offshore, low-energy waters at the midrange of the continental shelf to moderately active waters below the wave base (Kauffman et al. 1969).

Although no fossil discovery has been reported from within the boundaries of Fort Union National Monument, paleontological resources from the Graneros Shale have been found in other areas of New Mexico and surrounding states (Koch and Santucci 2003). Fossils include marine bivalves, gastropods, and foraminifera, which lived in the Western Interior Seaway (see “Geologic History” section). Other Cretaceous units in the area also contain fossils: the Greenhorn Limestone (Kgn) and Carlile Shale (Kc) contain ammonites, bivalves, foraminifera, and fish bones and teeth; and the Dakota Sandstone (Kd) contains terrestrial fossils, including wood, leaves, and pollen, as well as marine fossils such as ammonites and pelecypods.

Johnson (1974) also mapped Triassic (251 million–200 million years ago) and Jurassic (200 million–145.5 million years ago) rocks exposed northwest of Fort Union National Monument (see “Geologic Map Data” section). These units comprise some of the most famous rock formations in the western United States. The Triassic Chinle Formation (TRc), known for petrified wood, is particularly well exposed at Petrified Forest National Park in Arizona (KellerLynn 2010). The Jurassic Morrison Formation (Jm), known for dinosaur remains, is the source of spectacular fossil discoveries within Dinosaur National Monument in Colorado and Utah (Graham 2006). Additionally, the Jurassic Todilto Limestone (Jt) contains dinosaur tracks, algal structures, fish scales, ostracodes, and worm burrows.

In extremely rare cases, lava can also preserve fossils such as tree molds (impressions of tree bark), like those within El Malpais National Monument (KellerLynn 2012a). Quaternary fossils of bison or musk ox can also occur in alluvium (Qa) and other alluvial deposits such as terraces (Qto and Qty), as well as in cave sediments (see “Caves” section). Of these, only alluvium occurs within the boundaries of Fort Union National Monument, along Wolf Creek.

Santucci et al. (2009)—the chapter about monitoring in situ paleontological resources in *Geological Monitoring* (Young and Norby 2009)—outlined potential threats to fossil resources and suggested monitoring vital signs to qualitatively and quantitatively assess the potential impacts of these threats. Paleontological vital signs include the following: (1) erosion (geologic factors), (2) erosion (climatic factors), (3) catastrophic geohazards, (4) hydrology/bathymetry, and (5) human access/public use. The authors of this chapter also presented detailed methodologies for monitoring each of these vital signs. If fossils are discovered at Fort Union National Monument, this guidance may be useful for resource management.

Geologic History

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

The geologic history of Fort Union National Monument is revealed in its scenic setting. The sedimentary rocks underlying the national monument were laid down in a seaway that spread from the Arctic to the Tropics and advanced into New Mexico about 96 million years ago. This seaway prevailed for 30 million years and reached its maximum extent about 90 million years ago (Price 2010). Beginning 70 million years ago, uplift of the Rocky Mountains created the Sangre de Cristo Mountains, which lie west of the national monument. Starting about 40 million years ago, Rio Grande rifting further uplifted the range. About 15 million years ago, the Turkey Mountains to the northeast rose as a result of an igneous intrusion called a "laccolith." About 8 million years ago, lava from the Ocaté volcanic field flowed north and east of the national monument. Black Mesa, which is capped by basalt from the Ocaté field, is a prominent landmark in the Fort Union landscape, serving as a visible reminder of relatively recent volcanic activity in the area. Today, rivers and streams, rockfall, and weathering are the primary geologic agents transforming the cultural and natural features at Fort Union National Monument.

Mesozoic Era: From Land to Seaway

The Mesozoic Era (251 million–65.5 million years ago) incorporates the Triassic, Jurassic, and Cretaceous periods (fig. 2). Although Fort Union National Monument lies on Cretaceous Graneros Shale (map unit symbol Kgs), Triassic and Jurassic rocks are exposed in the upper northwestern corner of the map area (see "Geologic Map Data" section). These rocks include the Triassic Chinle Formation (TRc) and three Jurassic units: Entrada Sandstone (Je), Todilto Limestone (Jt), and the Morrison Formation (Jm).

The Chinle Formation is a sequence of terrestrial sediments that was deposited in a vast basin extending north–south from Wyoming to Texas, and east–west from western Oklahoma to southeastern Nevada—an area of about 2.3 million km^2 (0.9 million mi^2) (Lucas 1992). The sedimentary layers of the Chinle Formation consist of shale, sandstone, and (nonmarine) limestone. These rocks preserve a suite of lowland environments, including river channels, floodplains, swamps, and small lakes (Dubiel 1994; Blakey and Raucci 2006).

Well-known Delicate Arch and other arches in Arches National Park in Utah are made of the Entrada Sandstone (Je; Graham 2004). In the Fort Union area, the Entrada Sandstone is buff to gray colored, rather than reddish, and forms sheer cliffs. The Entrada Sandstone was deposited by the wind about 160 million years ago in a vast coastal desert called a "sabkha" (Condon 1992).

The Todilto Limestone (Jt) was deposited in a restricted marine embayment with an ephemeral connection to the sea. Late in its development, the embayment became a completely enclosed, gypsum-rich body of water. Fossils such as ostracodes document life in ephemeral gypsiferous ponds, whereas marine calcareous algae in the rock unit represent short periods of near-normal marine water (Armstrong 1995). The limestone is part of a shoaling (shallowing) upward sequence deposited in a tidal environment under hot, arid conditions. The marine waters fluctuated from brackish to gypsiferous (Armstrong 1995).

Known for dinosaur fossils throughout the western United States, the Upper Jurassic Morrison Formation (Jm) has served an important role in the reconstruction of past ecosystems. Turner et al. (2004) showed that environmental conditions at the time of this formation's deposition resembled a modern savannah, with perennial and intermittent streams.

During the Cretaceous Period, the extensive Western Interior Seaway covered the western United States (fig. 25) and left thick deposits of sandstone, shale, and limestone, including the Dakota Sandstone (Kd), Graneros Shale (Kgs), Greenhorn Limestone (Kgn), and Carlile Shale (Kc). The Dakota Sandstone represents the initial advance of the seaway into New Mexico, about 96 million years ago. These rock units represent four suites of environments that changed through time as sea level rose and shorelines retreated landward: (1) coastal-plain fluvial, lagoonal, estuarine, and marginal marine sand environments; (2) a shallow, sandy and silty inner sublittoral (below low tide) shelf; (3) offshore mud environments at midshelf depth; and (4) a shallow midbasin carbonate platform (Kauffman et al. 1969). As sea level fell, these environmental suites repeated in reverse order (Kauffman et al. 1969).

The well-known and widespread Dakota Sandstone (U.S. Geological Survey 2007b) was deposited in the Western Interior Seaway as marine waters advanced from the north/northwest. The sediments preserve a diverse collection of terrestrial and marine fossils (see "Paleontological Resources" section). Today, the Dakota Sandstone forms distinctive hogbacks and cliffs that are part of the Fort Union landscape. Furthermore, most of the building stone used at the fort is likely Dakota Sandstone.

Dark-gray Graneros Shale underlies most of Fort Union National Monument. This unit can be up to 67 m (220 ft) thick in the area (Lucas et al. 2001). Like the Dakota Sandstone, Graneros Shale is widespread, cropping out in parts of Colorado, Iowa, Kansas, Minnesota, Montana, North Dakota, Oklahoma, South Dakota, and Wyoming (U.S. Geological Survey 2007c). As the shoreline of the Western Interior Seaway migrated south/southwest, the Graneros Shale was deposited as mud in slightly deeper waters than the Dakota Sandstone (Price 2010).

The Greenhorn Limestone overlies the Graneros Shale. Like its predecessors in the Cretaceous seaway (i.e., Graneros Shale and Dakota Sandstone), this unit is widespread, cropping out in Colorado, Iowa, Kansas, Montana, Nebraska, New Mexico, North Dakota, Oklahoma, South Dakota, and Wyoming (U.S. Geological Survey 2007d). Usually, the base of the Greenhorn Limestone is distinctly separated from the dark shales of the underlying Graneros strata. The upper portion of the limestone grades into the Carlile Shale (Darton 1901). Greenhorn Limestone formed in shallow marine waters (Shurr 1980), where ammonites, oysters, foraminifera, and fish lived.

Like the other Cretaceous units in the area, the Carlile Shale documents the expanse of the Western Interior Seaway, extending to Colorado, Iowa, Kansas, Minnesota, Montana, North Dakota, Nebraska, New Mexico, Oklahoma, South Dakota, and Wyoming (U.S. Geological Survey 2007a). Fossils such as bivalves, ammonites, and shark teeth are evidence of its marine origin. This gray shale unit is more than 61 m (200 ft) thick in the Fort Union area.

Mesozoic and Cenozoic Eras: Laramide Orogeny

At the end of the Mesozoic Era, the western margin of North America was tectonically active. Oceanic crust was being subducted under the North American continent. Active tectonism fueled Rocky Mountain uplift during a period of mountain building known as the "Laramide Orogeny," which began about 70 million years ago. Mountain building and uplift created the Sangre de Cristo Mountains and ultimately displaced the Western Interior Seaway (Smith and Siegel 2000).

Cenozoic Era: The End of Laramide Mountain Building and Beginning of Rio Grande Rifting

Following the Laramide Orogeny, volcanism was widespread, and volcanic rocks cover Laramide sediments in many areas of New Mexico. This period of volcanic activity peaked in the Oligocene Epoch (34 million–23 million years ago). Huge volcanic fields associated with this period cover parts of New Mexico, but they are not present in the Fort Union area. These fields developed during the transition from Laramide subduction–related magmatism to Rio Grande rifting (Chapin et al. 2004). Associated with this transition to rifting was a change in volcanic "style," from volcanism of intermediate compositions characterizing the widespread Oligocene volcanic fields to volcanism of basaltic compositions characterizing the Rio Grande rift (Lipman and Mehnert 1975). Rio Grande rifting began about 40 million years ago (Price 2010), and in the Fort Union area resulted in further uplifting of the Sangre de Cristo Mountains and increased elevation of the adjacent Great Plains (O'Neill 1988; O'Neill and Mehnert 1988). Rifting also resulted in the (re)activation of zones of weakness (Kellogg 1999), including the Fort Union and Los Gavilanes faults.

The Turkey Mountains, visible on the northern horizon at Fort Union National Monument, are an expression of uplift after the Western Interior Seaway receded from the area. Approximately 15 million years ago, a relatively shallow igneous intrusion, called a "laccolith," built up the Turkey Mountains and deformed the Cretaceous sedimentary strata of the interior seaway, as well as older/underlying Triassic and Jurassic strata (Price 2010).

Cenozoic Era: Volcanism Abounds

Soon after the Turkey Mountains were domed upward and dikes were emplaced, the Ocaté volcanic field began to erupt episodically in approximately 14 pulses between 8.2 million and 800,000 years ago (Olmsted and McIntosh 2004). Johnson (1974) mapped two basaltic rock units from the field in the vicinity of Fort Union: (1) basalt of Black Mesa (Tbm) and (2) basalt of Wolf Creek (QTw) (see "Geologic Map Data" section).

Cenozoic Era: The Present-Day Landscape

During the Pleistocene Epoch (2.6 million–11,700 years ago), valley glaciers flowed in the Sangre de Cristo Mountains. Glacial advances produced excessive debris, leading to rapid aggradation of streambeds with thick accumulations of sand and gravel. When the glaciers retreated, streams swollen with meltwater cut trenches into the accumulated material, which deepened the stream channels and produced terraces. Southwest of Fort Union National Monument along the Mora River, Johnson (1974) mapped two terrace levels: older (Qto) and younger (Qty) terrace deposits.

Quaternary deposits mapped by Johnson (1974) are evidence of geologic activity to the present day. The blocks of broken basalt that cover the slopes of Black Mesa are composed of talus (Qt), which was deposited during the Pleistocene and Holocene epochs. During the Pleistocene Epoch, landslides (Qls) occurred on the slopes of Black Mesa.

Rivers and streams continue to transform the landscape in the Fort Union area. Fluvial deposits include an alluvial fan (Qaf) at the mouth of Higgins Canyon and an alluvial cone deposit (Qac) that emanates from the southeastern slope of Black Mesa. The cone is composed of basalt and shale debris, which fluvial processes redistributed away from the volcanic field (Davies et al. 1978). Streams transported and deposited alluvium (Qa)—gravel, sand, silt, and clay—within Higgins Canyon and along Wolf Creek and the Mora River.

In addition to Holocene alluvium (Qa), Johnson (1974) mapped Holocene lake deposits (Ql). These deposits are carbonaceous (rich in organic material) and appear as ephemeral lakes in the uplifted Dakota Sandstone (Kd) west of the national monument. Little is known about the origins of these lakes (Greer Price, New Mexico Bureau of Geology and Mineral Resources, deputy director, e-mail communications, 19 and 24 January 2011).

Today, Fort Union National Monument contains a cultural landscape of earthworks, archeological deposits, and stabilized adobe ruins within the geologic setting of the Mora River Valley. At the time of the fort's occupation, the U.S. Army valued the abundant surface water in the valley (Curran et al. 2005), namely streams fed by artesian springs. The source of these springs is the Dakota Sandstone aquifer. The army also used Dakota Sandstone as building stone in the construction of Fort Union. An uplifted ridge of Dakota Sandstone borders the valley on the west and exposes the sandstone. The plain on which Fort Union sits is composed of Graneros Shale, which yielded clay for adobe used at the fort. Today, weathering is impacting these earthen materials, but many impressive historic ruins remain on the landscape.

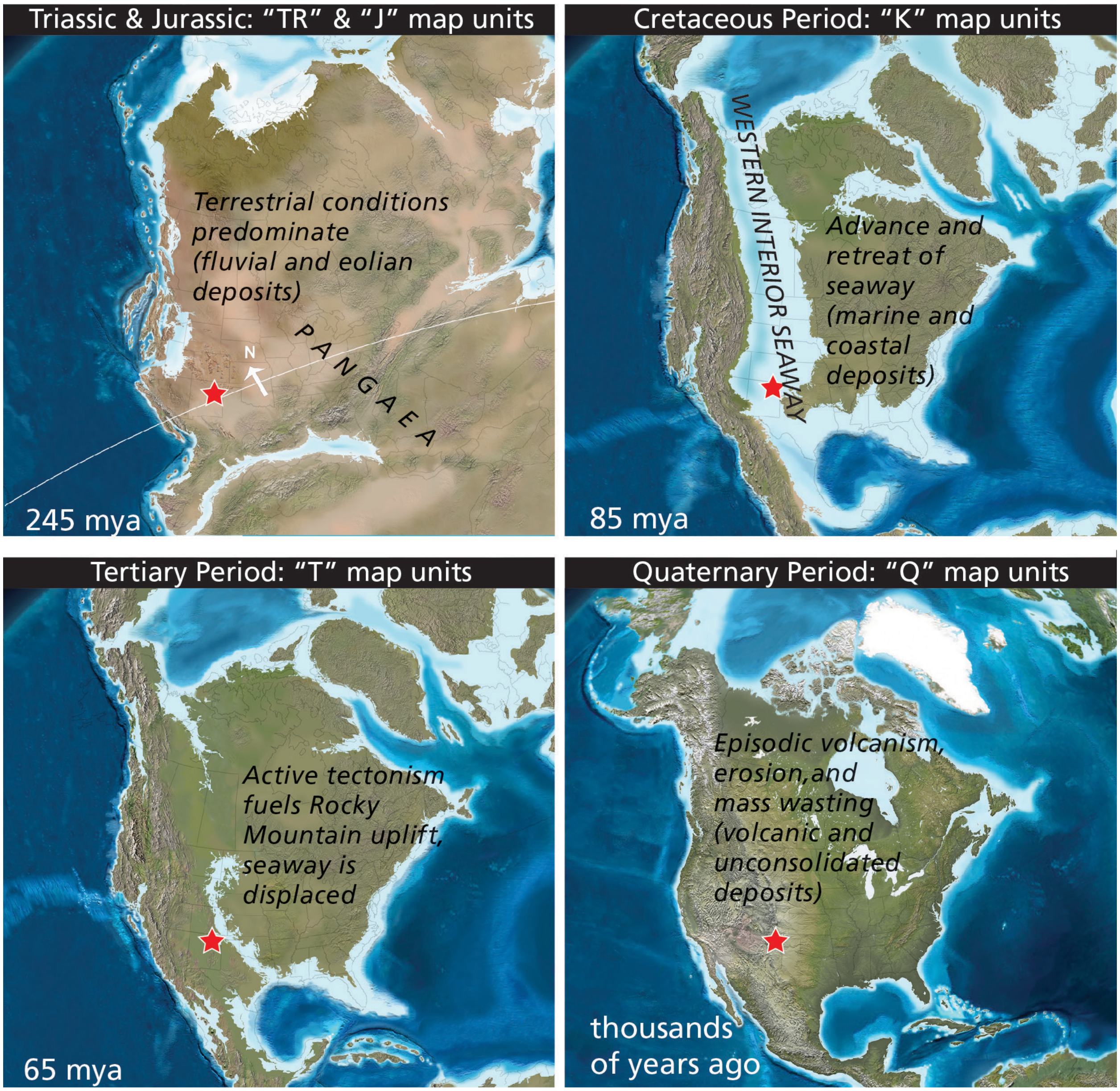

Figure 25. Paleogeographic maps for Fort Union National Monument. These images of North America represent the Mesozoic (Triassic, Jurassic, and Cretaceous periods) and Cenozoic (Tertiary time and Quaternary Period) geologic eras. The geologic history of Fort Union National Monument encompasses repeated inundation by seas during the Mesozoic, mountain uplifting and sediment deposition in basins during the Mesozoic and Cenozoic, and crustal extension (pulling apart of Earth's crust) and volcanism during the Cenozoic. Stars represent the approximate location of Fort Union National Monument during various points in geologic time. The white line represents the approximate location of the equator. mya = million years ago. Map units refer to those on the geologic map (Johnson 1974). Base paleogeographic maps created by Ron Blakey (Colorado Plateau Geosystems, Inc.), available at http://cpgeosystems.com/index.html (accessed 25 January 2012). Graphic complied by Jason Kenworthy (NPS Geologic Resources Division) and Rebecca Port (Colorado State University).

Geologic Map Data

This section summarizes the geologic map data available for Fort Union National Monument. The Geologic Map Overview Graphic displays the geologic map data draped over a shaded relief image of the national monument and surrounding area. The foldout Map Unit Properties Table summarizes this report's content for each geologic map unit. Complete GIS data are included on the accompanying CD and are also available at the GRI publications website (http://www.nature.nps.gov/geology/inventory/gre_publications.cfm).

Geologic Maps

Geologic maps facilitate an understanding of an area's geologic framework and the evolution of its present landscape. Using designated colors and symbols, geologic maps portray the spatial distribution and relationships of rocks and unconsolidated deposits. There are two primary types of geologic maps: surficial and bedrock. Surficial geologic maps encompass deposits that are frequently unconsolidated and formed during the past 2.6 million years (the Quaternary Period). Surficial map units are differentiated by geologic process or depositional environment. Bedrock geologic maps encompass older, generally more consolidated sedimentary, metamorphic, and/or igneous rocks. Bedrock map units are differentiated based on age and/or rock type. For reference, a geologic time scale is included as figure 2. Bedrock and surficial geologic map data are provided for Fort Union National Monument.

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

Source Maps

The Geologic Resources Inventory (GRI) team converts digital and/or paper source maps into GIS formats that conform to the GRI GIS data model. The GRI digital geologic map product also includes essential elements of the source maps, including unit descriptions, map legend, map notes, references, and figures. The GRI team used the following source map to produce the digital geologic data for Fort Union National Monument. This source map provided information for the "Geologic Issues," "Geologic Features and Processes," and "Geologic History" sections of this report.

Johnson, R. B. 1974. Geologic map of the Fort Union quadrangle, Mora County, New Mexico (scale 1:24,000). Geologic quadrangle map GQ-1164. U.S. Geological Survey, Washington, D.C., USA.

Geologic GIS Data

The GRI team implements a GIS data model that standardizes map deliverables. The data model is included on the enclosed CD and is also available online (http://science.nature.nps.gov/im/inventory/geology/GeologyGISDataModel.cfm). This data model dictates GIS data structure, including layer architecture, feature attribution, and relationships within ESRI ArcGIS software. The GRI team digitized the data for Fort Union National Monument using data model version 1.3.1.

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

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

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

Geology data layers in the Fort Union National Monument GIS data.

Data Layer	Data Layer Code	On Overview Graphic?
Geologic Attitude and Observation Points	ATD	No
Fault Symbology	SYM	Yes
Faults	FLT	Yes
Geologic Contacts	GLGA	Yes
Geologic Units	GLG	Yes

Geologic Map Overview Graphic

The Geologic Map Overview Graphic (in pocket) displays the GRI digital geologic data of the national monument and surrounding area. For graphic clarity and legibility, not all GIS feature classes may be visible on the overview, as indicated in the above table. Cartographic elements and basic geographic information have been added to the overview. Digital elevation data and geographic information, which are part of the overview graphic, are not included with the GRI digital geologic GIS data for the national monument, 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 (in pocket) correspond to the accompanying digital geologic data. Following the structure of the report, the table summarizes the geologic issues, features, and processes, and geologic history associated with each map unit. The table also lists the geologic time period, map unit symbol, and a simplified geologic description of the unit. Connections between geologic units and park-specific stories are also summarized.

Use Constraints

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

Please contact GRI with any questions.

Glossary

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

aggradation. The building-up of Earth's surface by depositional processes, specifically the upbuilding performed by a stream in order to establish or maintain uniformity of grade or slope.

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.

ammonite. Any ammonoid belonging to the suborder Ammonitina, characterized by a thick, strongly ornamental shell with sutures having finely divided lobes and saddles. Range—Jurassic to Cretaceous.

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.

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.

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

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

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.

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

bituminous limestone. A dark, dense limestone containing abundant organic matter, believed to have accumulated under stagnant conditions and emitting a fetid odor when freshly broken or vigorously rubbed.

bivalve. Having a shell composed of two distinct and usually movable valves, equal or subequal, that open and shut.

burrow. A tubular or cylindrical hole or opening, made in originally soft of loose sediment, by a mud-eating worm, a mollusk, or other invertebrate, extending along a bedding plane or penetrating a rock, and often later filled with clay or sand and preserved as a filling; it may be straight or sinuous, and vertical, horizontal, or inclined.

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

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.

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

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

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

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

composite cone. Another term for "stratovolcano." A volcano that is constructed of alternating layers of lava and pyroclastic deposits, along with abundant dikes and sills. Viscous, acidic lava may flow from fissures radiating from a central vent, from which pyroclastics are ejected.

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

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

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

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.

dome. General term for any smoothly rounded landform or rock mass. More specifically refers to an elliptical uplift in which rocks dip gently away in all directions.

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

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

ephemeral lake. A short-lived lake.

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

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.

fissure vent. The opening at the Earth’s surface of a volcanic conduit having the form of a crack or fissure.

fissure volcano. One of a series of volcanic vents in a pattern of eruption along a fissure.

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.

fluvial. Of or pertaining to a river or rivers.

foraminifer. Any protozoan belonging to the subclass Sarcodina, order Foraminiferida, characterized by the presence of a test of one to many chambers composed of secreted calcite (rarely silica or aragonite) or of agglutinated particles. Most foraminifers are marine but freshwater forms are known. Range—Cambrian to Holocene.

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).

freeze-thaw. Also called “frost action.” The mechanical weathering process caused by alternate or repeated cycles of freezing and thawing water in pores, cracks, and other opening, usually at the surface.

gastropod. Any mollusk belonging to the class Gastropoda, characterized by a distinct head with eyes and tentacles and, in most, by a single calcareous shell that is closed at the apex, sometimes spiraled, not chambered, and generally asymmetrical (e.g., a snail). Range—Upper Cambrian to the present.

gypsiferous. Gypsum-bearing.

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

hogback. Any ridge with a sharp summit and steep slopes of nearly equal inclination on both flanks, and resembling in outline the back of a hog.

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.

jasper. A variety of chert associated with iron ores and containing iron-oxide impurities that give it various colors, especially red.

laccolith. A mushroom- or arcuate-shaped pluton that has intruded sedimentary strata and domed up the overlying sedimentary layers. Common on the Colorado Plateau.

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

lime. Calcium oxide (used in building and in agriculture).

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.

loam. A rich permeable soil composed of a mixture of clay, silt, sand, and organic matter.

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

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

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.

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

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.

ostracode. Any aquatic crustacean belonging to the subclass Ostracoda, characterized by a two-valved (shelled), generally calcified carapace with a hinge along the dorsal margin. Most ostracodes are of microscopic size.

outcrop. Any part of a rock mass or formation that is exposed or “crops out” at Earth’s surface.

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

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

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

pelecypod. Any benthic aquatic mollusk belonging to the class Pelecypoda, characterized by a bilaterally symmetrical bivalve shell, a hatchet-shaped foot, and sheetlike gills. Range—Ordovician to present.

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

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

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

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

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

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

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

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).

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

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

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

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

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

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

shelf (continental). 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).

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

shoaling. To become shallow gradually; to cause to become shallow; to fill up or block off with a shoal; to proceed from a greater to a lesser depth of water.

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.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

tree mold. A trace fossil formed when molten lava flows around a tree and subsequently cools, creating an impression of the tree or bark in the lava.

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.

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).

wave base. The depth at which wave action no longer stirs the sediments; it is usually about 10 m (33 ft) to 20 m (66 ft).

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

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Additional References

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

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

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

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

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

NPS Views Program (geology-themed modules are available for geologic time, paleontology, glaciers, caves and karst, coastal geology, volcanoes, and a wide variety of geologic parks): http://www.nature.nps.gov/views/layouts/Main.html#/Views/.

NPS Resource Management Guidance and Documents

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

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

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

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

Geologic Monitoring Manual:
Young, R., and L. Norby, editors. 2009. Geological monitoring. Geological Society of America, Boulder, Colorado, USA. http://nature.nps.gov/geology/monitoring/index.cfm

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

Geological Surveys and Societies

New Mexico Bureau of Geology and Mineral Resources: http://geoinfo.nmt.edu/

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/

U.S. Geological Survey Reference Tools

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

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

U.S. Geological Survey Geographic Names Information System (GNIS; official listing of place names and geographic features): 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 (USGS publications, many available online): http://pubs.er.usgs.gov

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

Appendix: Scoping Meeting Participants

The following people attended the GRI scoping meeting for Fort Union National Monument, held on 28 March 2006. The scoping summary document is available on the GRI publications website (http://www.nature.nps.gov/geology/inventory/gre_publications.cfm).

Name	Affiliation	Position
Doug Bland	New Mexico Bureau of Geology and Mineral Resources	Geologist
Tim Connors	NPS Geologic Resources Division	Geologist
Dennis Ditmanson	Fort Union National Monument and Pecos National Historical Park	Superintendent
Bruce Heise	NPS Geologic Resources Division	Geologist
Dan Jacobs	Pecos National Historical Park	Chief Ranger
Katie KellerLynn	Colorado State University	Research Associate/Geologist
Ron Kerbo	NPS Geologic Resources Division	Cave Specialist
Virgil Lueth	New Mexico Bureau of Geology and Mineral Resources	Geologist

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