National Park Service
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Natural Resource Stewardship and Science

Aztec Ruins National Monument

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2016/1245

ON THE COVER: Terraces cut by the Animas River dominate the landscape at Aztec Ruins National Monument. As mapped by Gillam (1998a), three primary terrace levels occur in the monument. The West Ruin is situated on the lowest and youngest terrace level. Two other terrace levels step up from this level and compose the "North Mesa" in the monument. That mesa covers the upper left corner of the photograph. Photograph by Kimberly Miskell-Gerhardt, taken from a plane piloted by Dan Gerhardt on 22 December 2002. Used with permission.

THIS PAGE: The bedrock of Aztec Ruins National Monument is the Nacimiento Formation, which consists of gray, green, and purple claystone, shale, and siltstone, as well as gray and yellow sandstone. The formation was used in construction of Aztec Ruins. In the West Ruin, green claystone makes up a distinctive band of a sandstone wall. National Park Service photograph available at http://www.nps.gov/media/photo/gallery.htm?id=572EFF35-155D-451F-67AE9343238A8B8E.

Aztec Ruins National Monument

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2016/1245

Katie KellerLynn

Colorado State University Research Associate
National Park Service Geologic Resources Division
Geologic Resources Inventory
PO Box 25287
Denver, CO 80225

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Contents

Contents (continued)

Figures

Tables

Executive Summary

The Geologic Resources Inventory (GRI) is one of 12 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 inventory. This report synthesizes discussions from a scoping meeting for Aztec Ruins National Monument (New Mexico) on 13 February 2007 and a follow-up conference call on 28 May 2015, which were held by the Geologic Resources Division to identify significant geologic resources and geologic resource management issues, as well as determine the status of geologic mapping. It is a companion document to previously completed GRI GIS data.

This GRI report was written for resource managers at Aztec Ruins National Monument to support science-informed decision making. It also may be useful for interpretation. The report was prepared using available geologic information, and the NPS Geologic Resources Division conducted no new fieldwork in association with its preparation. The report discusses distinctive geologic features and processes within the monument, highlights geologic issues facing resource managers, describes the geologic history leading to the present-day landscape, and provides information about the GRI GIS data that accompany this report.

The GRI team used three source maps to compile the GRI GIS data for the monument. Data from Brown and Stone (1979) covers the western side of the monument; data from Ward (1990) covers the eastern side of the monument. These data are illustrated on a GRI poster (in pocket) and referred to as the "bedrock and surficial map." Data from Gillam (1998a) covers the entire monument. A GRI poster (in pocket) illustrating those data is referred to as the "geomorphic map." In addition, two Map Unit Properties Tables (in pocket) summarize report content for the GRI GIS data. One of these tables highlights bedrock and surficial deposits as mapped by Brown and Stone (1979) and Ward (1990); the other highlights geomorphic features, namely terraces and the modern floodplain, as mapped by Gillam (1998a).

Aztec Ruins National Monument was established in 1923 to preserve the remarkable remnants of a large ancestral Puebloan community, which flourished from 1050 to 1150 CE (common era [preferred to AD]). At that time, it was one of the largest Puebloan settlements of the American Southwest. The pueblo was strategically situated between Mesa Verde to the north and Chaco Canyon to the south.

Aztec Ruins National Monument is in the San Juan Basin—a structural depression that formed as the Rocky Mountains were rising during the Laramide Orogeny (75 million–40 million years ago). The bedrock of the monument—the Nacimiento Formation (map unit **Tn**)—lies near the top of a thick sedimentary package of rocks that fills the San Juan Basin. The strata are as much as 4,600 m (15,000 ft) thick. The sediments that make up the Nacimiento Formation were deposited 64.5 million–61.0 million years ago (Paleocene Epoch) in floodplains, river channels, swamps, and lakes.

The ruins themselves sit on a Quaternary terrace that was cut into the valley floor by the Animas River. The river appeared on the scene after the Laramide Orogeny but before the Pleistocene ice ages. The terrace upon which the West and East Ruins lies and two other terraces rise step-like above the modern floodplain and record the geologically recent but complex history of the Animas River valley. Meltwater from the enormous Animas Glacier in the upper valley transported glacial sediments, called "outwash," downvalley, while the Animas River channeled into unconsolidated material and bedrock, creating numerous terraces in the process. At some counts, 34 different terrace levels were cut within the valley. Some rise as high as 660 m (2,170 ft) above the valley floor. Terraces record climate-related or other depositional cycles, probably reaching back at least 3 million years (late Pliocene Epoch). Terraces indicate that incision was not uniform but punctuated by periods when downcutting stopped and the river system either stayed at the same elevation or aggraded (built up). Each terrace level represents a past floodplain and marks the former course of the Animas River. These landforms dominate the monument and the surrounding viewshed.

During the 2007 scoping meeting and 2015 conference call, participants (see Appendix A) identified the following geologic features and processes of significance for Aztec Ruins National Monument:

- **Nacimiento Formation**. The bedrock underlying the monument lies towards the top of the San Juan Basin sequence of sedimentary rocks. It is the Paleocene Nacimiento Formation of primarily sandstone and shale. Elsewhere, the formation contains fossils significant for the beginning of the "Age of Mammals." No such fossils have been found in the monument to date.
- **Building Stone and Lithic Resources**. Ancestral Puebloans used blocks of Nacimiento Formation in construction. They also used materials deposited by the Animas River that range in size from cobbles (used in foundations) to silt (used for mortar). Lithic resources found at the monument include a variety of local and nonlocal materials.
- **Terraces**. As mapped by Gillam (1998a), the monument contains three primary terrace levels. Investigators have traced these terrace deposits to at least three ages of glacial moraines (ridge-like landforms composed of rock fragments deposited directly from glacial ice) at Durango, Colorado. The oldest terrace level (map unit **Qt5a**) formed approximately 340,000–250,000 years ago and is associated with the Durango moraines. The middle terrace level (**Qt6a**) formed approximately 160,000–140,000 years ago and is associated with the Spring Creek moraines. The youngest terrace level (**Qt7u**) formed approximately 25,000–19,000 years ago and is associated with the Animas City moraines. These moraines developed during the pre-Bull Lake, Bull Lake, and Pinedale glaciations, respectively.
- **Alluvium**. The variety of rock types found in the monument reflects the course of the Animas River. Material transported and deposited by a river is referred to as "alluvium." It ranges in size from boulders to silt. In addition to Animas River ("main river") alluvium, tributary streams and arroyos also contributed alluvium to the landscape. Animas River and tributary alluviums comprise a complex record of fluvial activity that took place before, during, and after the Animas Glacier advanced and retreated in the Animas River valley.
- **Eolian Features**. Deposits of windblown dust, called "loess," occur within the monument. These deposits may be as thick as 1 m (3 ft). Ancestral Puebloans mined the loess for its use as a primary ingredient in mortar and may have dug subsurface structures into thick loess layers. The Lava Creek B ash is another eolian feature of interest for the monument. This volcanic ash layer, which erupted from the Yellowstone caldera about 639,000 years ago, is a stratigraphic marker that investigators used to estimate the ages of terraces in the area. No ash occurs in the monument, but Gillam (1998b) found 17 locales of Lava Creek B ash in Animas River valley.

Geologic resource management issues identified during the GRI scoping meeting and follow-up conference call include the following. They are listed more-or-less by management priority:

- **Oil and Gas Development and Production**. Oil and gas development is a primary concern for resource managers at the monument. Four active, nonfederal oil and gas operations and two associated gathering lines occur within the boundaries. The source of the produced hydrocarbons is Upper Cretaceous sedimentary rocks, which lie below the surface.
- **Directional Drilling and Hydraulic Fracturing**. Technological improvements in directional drilling and hydraulic fracturing, commonly called "fracking," have spurred renewed interest by the oil and gas industry in the San Juan Basin. At present, all the wells in the monument are conventional, but directional drilling and fracking could be applied to enhance production from these wells in the future. Impacts to cultural resources, including archeological structures, as a result of vibrations from transportation and drilling are specific concerns. The approximate "safe distance" for directional drilling and fracking is unknown at this time.
- **Adjacent Development**. The monument is surrounded by the developing City of Aztec, resulting in a paucity of open space and concerns of trespass and access-related vandalism to monument resources. The primary area of concern is a proposed subdivision, Mesa Escondido, at the northern boundary of the monument. Impacts from development include loss of archeological resources, such as the destruction of a Chacoan road, as well as runoff-related erosion and visual impairments.

- **Water Impacts on Monument Resources**. Structural deterioration associated with water at Aztec Ruins has been a problem for many decades. In an effort to create a mitigation plan for protecting archeological sites at the monument, a hydrologic study began in 2005. Investigators completed a final report in 2014. Issues include past irrigation of agricultural fields, transport of water through Farmers Ditch, and soil moisture related to groundwater levels.
- **Localized and Regional Subsidence**. Localized subsidence is occurring near East Ruin. The origin of these small depressions is not apparent, though some causes were proposed by GRI scoping participants. Additionally, since the late 1980s, methane has been produced from coal beds, predominantly within the Fruitland Formation. Large amounts of groundwater are extracted during methane production, causing centimeter-scale subsidence across the San Juan Basin. Because this type of subsidence does not produce differential surface movements over short distances, it is unlikely to directly affect the ruins.
- **Piping**. The formation of soil pipes, as a result of percolating subsurface water and the removal of soil material, is another hydrologic issue of concern. Soil pipes have formed in the banks along the Animas River. Piping could affect the stability of archeological sites via subsidence but may also have cultural significance. Ancestral Puebloans may have excavated soil pipes to create kivas (subsurface ceremonial chambers).
- **Bank Erosion and Landscape Restoration**. In order to prevent bank erosion (and deterioration of an archeological site), the former owner of the "Fallon property" installed concrete slabs as rip-rap along the Animas River channel. The National Park Service acquired this property in 2009. The goal for this property and other lands acquired within the monument's legislative boundary is to restore natural function and appearance while protecting cultural resources.
- **Recreation and Land Use in the Animas River Corridor**. A trail and bridge now connect downtown Aztec with the monument. Monument managers have added buck-and-rail fencing in this area to minimize the proliferation of social trails. Because no park infrastructure has been built on the floodplain, flooding of the Animas River is a minor management concern.
- **Abandoned Mineral Lands**. Resource management of abandoned mineral lands (AML) requires an accurate inventory and reporting of features in the servicewide AML database. During the scoping process, participants identified two abandoned gas wells at the monument. These wells were plugged in the 1970s. One additional plugged and abandoned gas well occurs within the expanded boundaries of the monument. The National Park Service has not yet acquired the land upon which this well is located, so no mitigation has been conducted to date.
- **Paleontological Resource Inventory, Monitoring, and Protection**. Aztec Ruins National Monument was included in the 2009 paleontological resource inventory and monitoring report for the Southern Colorado Plateau Network. In 2015, an investigator completed a reconnaissance level field survey at the monument. No fossils have been discovered within bedrock (Nacimiento Formation) at the monument to date, but elsewhere the formation has yielded fossils that are significant for the "Age of Mammals." Limestone cobbles in the terraces contain reworked Paleozoic fossils, including brachiopods, crinoids, and horn corals. The monument's collections contain petrified wood associated with archeological artifacts. Terrace deposits also contain pieces of reworked petrified wood of unknown origin.

Products and Acknowledgments

The NPS Geologic Resources Division partners with institutions such as Colorado State University, the US Geological Survey, state geological surveys, local museums, and universities to develop GRI products. This chapter describes those products and acknowledges contributors to this report.

GRI Products

The objective of the Geologic Resources Inventory is to provide geologic map data and pertinent geologic information to support resource management and science-informed decision making in more than 270 natural resource parks throughout the National Park System. To realize this objective, the GRI team undertakes three tasks for each natural resource park: (1) conduct a scoping meeting and provide a summary document, (2) provide digital geologic map data in a geographic information system (GIS) format, and (3) provide a GRI report (this document). These products are designed and written for nongeoscientists.

Scoping meetings bring together park staff and geologic experts to review and assess available geologic maps, develop a geologic mapping plan, and discuss geologic features, processes, and resource management issues that should be addressed in the GRI report. Following the scoping meeting, the GRI map team converts the geologic maps identified in the mapping plan to digital geologic map data in accordance with the GRI data model. After the map is completed, the GRI report team uses these data, as well as the scoping summary and additional research, to prepare the GRI report.

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

Additional information regarding the GRI, including contact information, is available at http://go.nps.gov/gri. The current status and projected completion dates of products are available at http://go.nps.gov/gri_status.

Acknowledgments

The GRI team would like to thank the participants of the 2007 scoping meeting and 2015 conference call (see Appendix A) for their assistance with this inventory. In addition, thanks to **Edward Kassman**, **Jeremiah Kimbell**, and **Steve Simon** (NPS Geologic Resources Division) for their input about oil and gas issues at the monument. Also, thanks to **Phil Varela** (Chaco Culture National Historical Park) for his input, timely field survey, and photographs of paleontological resources. Finally, thanks very much to **Mary Gillam** (independent consultant and researcher) for her follow-up on various geologic features and issues and her thorough review of the GRI report. Her comments greatly helped to clarify and improve the final product.

Review

Aron Adams (Aztec Ruins National Monument)
Mary Gillam (independent consultant and researcher)
Dana Hawkins (Aztec Ruins National Monument)
Jason Kenworthy (NPS Geologic Resources Division)
Jeremiah Kimbell (NPS Geologic Resources Division)
Phil Varela (Chaco Culture National Historical Park)

Editing

Rebecca Port (NPS Geologic Resources Division)

Report Formatting and Distribution

Jason Kenworthy (NPS Geologic Resources Division)
Rebecca Port (NPS Geologic Resources Division)

Source Maps

D. R. Brown and W. J. Stone (New Mexico Bureau of Mines and Mineral Resources)
M. L. Gillam (University of Colorado, dissertation)
A. W. Ward (US Geological Survey)

GRI GIS Data Production

Heather Stanton (Colorado State University)
Jason Isherwood (Colorado State University)
David Plume (NPS Geologic Resources Division)
Tim Cleland (Colorado State University)
Stephanie O'Meara (Colorado State University)
Georgia Hybels (Colorado State University)

GRI Poster Design
Georgia Hybels (Colorado State University)

GRI Poster Editing
Georgia Hybels (Colorado State University)
Rebecca Port (NPS Geologic Resources Division)
Jason Kenworthy (NPS Geologic Resources Division)

Geologic Setting and Significance

This chapter describes the regional geologic setting of Aztec Ruins National Monument and summarizes connections among geologic resources, other park resources, and park stories.

Aztec Ruins National Monument protects an exceptionally well-preserved great house community, also referred to as a "pueblo," along the banks of the Animas River in northwestern New Mexico (National Park Service 2015). The monument, which provides opportunities for greater understanding of the evolution of the Chacoan culture, is nationally and internationally significant. It is listed in the National Register of Historic Places and is part of a world heritage site that includes Chaco Culture National Historical Park in the National Park System and five smaller Chacoan sites managed by the Bureau of Land Management. Located between two major cultural centers—Chaco Canyon to the south (see GRI report about Chaco Culture National Historical Park by KellerLynn 2015b) and Mesa Verde to the north (see GRI report about Mesa Verde National Park by Graham 2006)—Aztec Ruins was one of the largest ancestral Puebloan settlements in the Southwest (Thybony 1992). The complex consisted of several great houses, tri-walled and great kivas, small residential pueblos, earthworks, and roads. Far from being uncontrolled urban sprawl, however, the formal layout of the settlement, purposeful landscape modifications, and the orientation and visual relationships among the buildings all indicate planning of a grand design (National Park Service 2003).

Contrary to the name of the monument, the Aztecs of central Mexico did not inhabit this place. Inspired by popular histories about Cortez's conquest of Mexico and thinking that Aztecs built these structures, early Anglo settlers named the site "Aztec," and the nearby city eventually took its name from the site (National Park Service 2003). The Aztecs lived centuries after the structures at "Aztec Ruins" were built. Ancestral Puebloans lived at Aztec for nearly 200 years, from 1098 to 1265 CE.

Since its proclamation in 1923, Aztec Ruins National Monument had has various boundary changes but now encompasses 129 ha (318 ac). The monument preserves a primary group of ruins consisting of the West Ruin and East Ruin complexes. The West Ruin encloses a central plaza that prominently contains the Great Kiva—a partly subterranean ceremonial structure

Figure 1. Photograph of the Great Kiva. The Great Kiva in the West Ruin plaza is the only reconstructed great kiva in the American Southwest. National Park Service photograph available at http://www.nps.gov/azru/learn/photosmultimedia/index.htm.

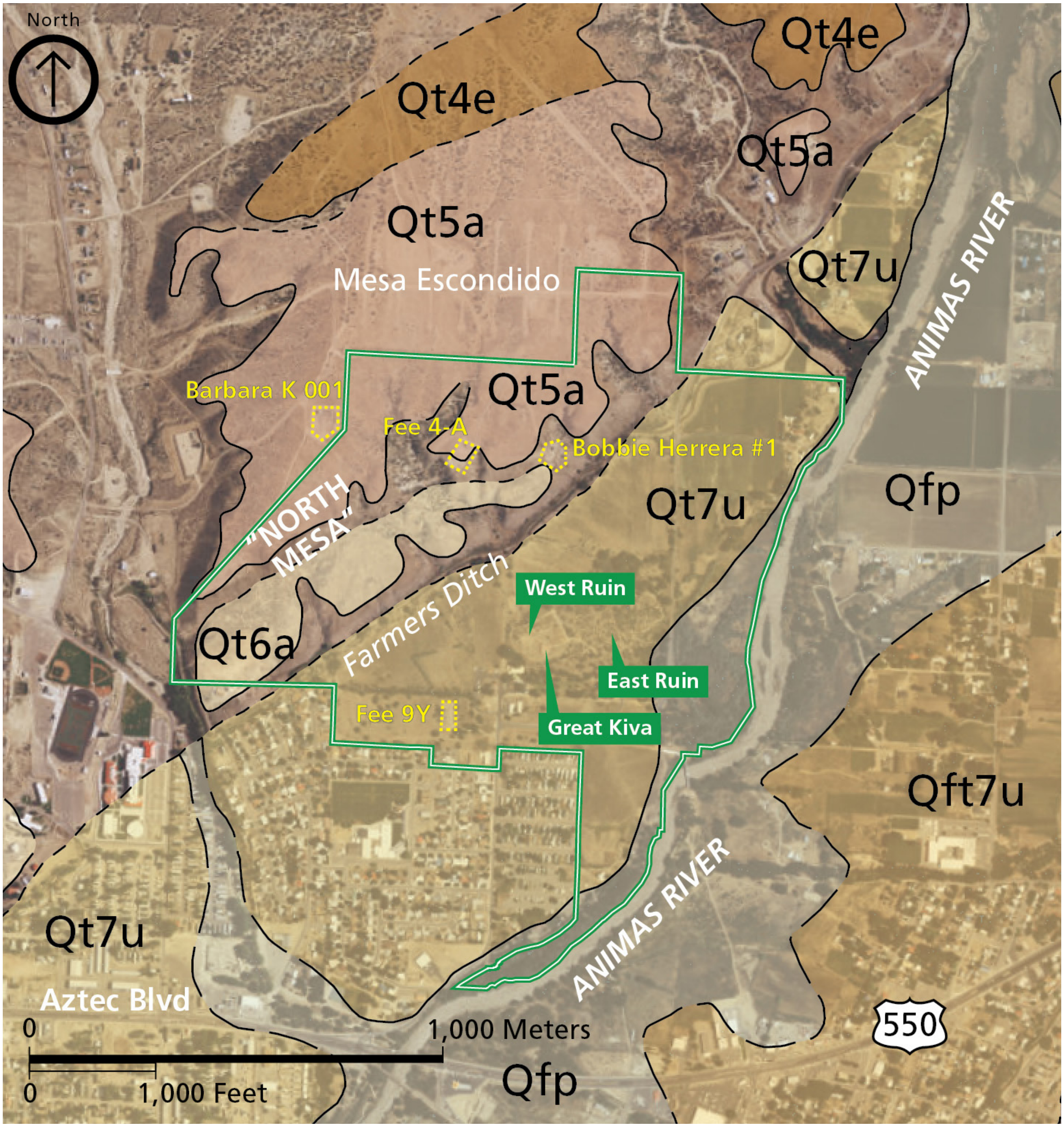

Figure 2. Satellite imagery of Aztec Ruins National Monument. The City of Aztec, New Mexico, and urban development surround the monunment (green outline). Gillam (1998a) mapped three primary terraces in the monument: Qt5a, Qt6a, and Qt7u, as well as the modern floodplain (Qfp). A proposed subdivision, Mesa Escondido, is directly north of the monument. Four active nonfederal oil and gas wells (yellow outlines and labels) and two associated gathering lines (not shown on figure) are within or adjacent to the monument. Graphic compiled by Jason Kenworthy (NPS Geologic Resources Division). Imagery from ESRI "World Imagery" ArcMap basemap (accessed 28 April 2016) with data from Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community.

14 m (46 ft) across (fig. 1). This is the only Chacoan great kiva to have been completely reconstructed. The ruins also host original intact masonry, wood and earthen roofs, artifacts, and earthworks. Surrounding the ruins, prehistoric roadways and the overall landscape are other significant resources associated with the monument (National Park Service 2010).

The Animas River flows along the eastern boundary of the monument (fig. 2). Many modern Puebloans know the monument as the "Place by Flowing Waters," though other names exist (KellerLynn 2007). Ancestral Puebloans took advantage of the accessible river water for farming and other uses. This source of water allowed for the development of fertile bottomlands during prehistoric times. The first European visitors to the area reported seeing signs of prehistoric irrigation features (Price 2010).

The Animas River valley is roughly 165 km (100 mi) long (Gillam 1998b), starting at the crest of the western San Juan Mountains in Colorado and ending where the Animas River joins the San Juan River (a major tributary of the Colorado River) near Farmington, New Mexico. The valley covers approximately 3,525 km^2 (1,360 mi^2) (Denis et al. 1985).

The Animas River valley is significant as the site of one of the largest former glaciers in the US Rocky Mountains (fig. 3; Gillam 1998b). The glacier produced massive amounts of debris that the river reworked, sometimes aggrading (building up) and sometimes incising (cutting into), forming a series of terraces that dominates the landscape and viewshed of the monument. The morphologically complex terraces represent hundreds of thousands of years of fluvial and glacial activity. The highest terraces in the valley (not in the monument) developed before periodic glaciations began. The modern floodplain formed after the last glaciation ended.

The Animas River valley and Aztec Ruins National Monument are situated within the San Juan Basin, which is the dominant structural feature in northwestern New Mexico and southwestern Colorado. The basin is roughly 160 km (100 mi) long, north–south, and 145 km (90 mi) wide, east–west; it extends across an area of about 19,400 km^2 (7,500 mi^2). The basin formed as the Rocky Mountains rose (and adjacent basins subsided) during the Laramide Orogeny (75 million–40 million years ago; see fig. 4 for a geologic time scale).

In cross section, the asymmetrical San Juan Basin resembles a set of nested mixing bowls (fig. 5). The sequence of rocks is as much as 4,600 m (15,000 ft) thick (Fassett and Hinds 1971) and ranges in age from 500 million (Cambrian Period; fig. 4) to 50 million years ago (Eocene Epoch; fig. 4). The strata dip from the margin toward the deepest part of the basin. Crystalline rocks more than a billion years old line the perimeter of the basin in uplifted mountain ranges such as the Nacimiento and Zuni mountains in New Mexico and the San Juan Mountains in Colorado (fig. 6). These mountain ranges have ancient cores, approximately 1.7 billion to 1.4 billion years old (Proterozoic Era or Precambrian; fig. 4). Thus, the rocks are progressively older away from the center of the basin where the strata are thickest and the youngest strata are exposed.

Bedrock at the monument consists of the 60-million-year-old (Paleocene Epoch; fig. 4) Nacimiento Formation (**Tn**), which is one of the youngest sedimentary layers in the San Juan Basin. The youngest sedimentary-rock unit, the San Jose Formation (**Tsj**), is exposed in the vicinity of the monument (see GRI GIS data). The San Jose Formation contains a world-famous fossil record of early mammals and associated plants, fishes, and reptiles (Lucas 2010). Minor volcanic rocks of mid-Tertiary age (35 million–18 million years old) and various Quaternary deposits (less than 2.6 million years old) also are present in the basin (Levings et al. 1990).

Upper Cretaceous rocks in the basin, which are more than 1,800 m (6,000 ft) thick, were deposited in the Western Interior Seaway, which spread across the North American continent from the Arctic to the Gulf of Mexico (fig. 7). The seaway advanced and retreated for 30 million years (approximately 100 million–70 million years ago), depositing sediments in marine and coastal settings. Related continental deposits accumulated on surrounding lowlands. The final retreat of the seaway is represented by the Pictured Cliffs Sandstone, which crops out in Chaco Culture National Historical Park (see GRI report by KellerLynn 2015b). Excellent exposures of Upper Cretaceous rocks occur in Chaco Canyon.

The remains of organisms (organic matter) deposited along with sediments in the Wester Interior Seaway would later be converted to hydrocarbons as the basin subsided during the Laramide Orogeny and more

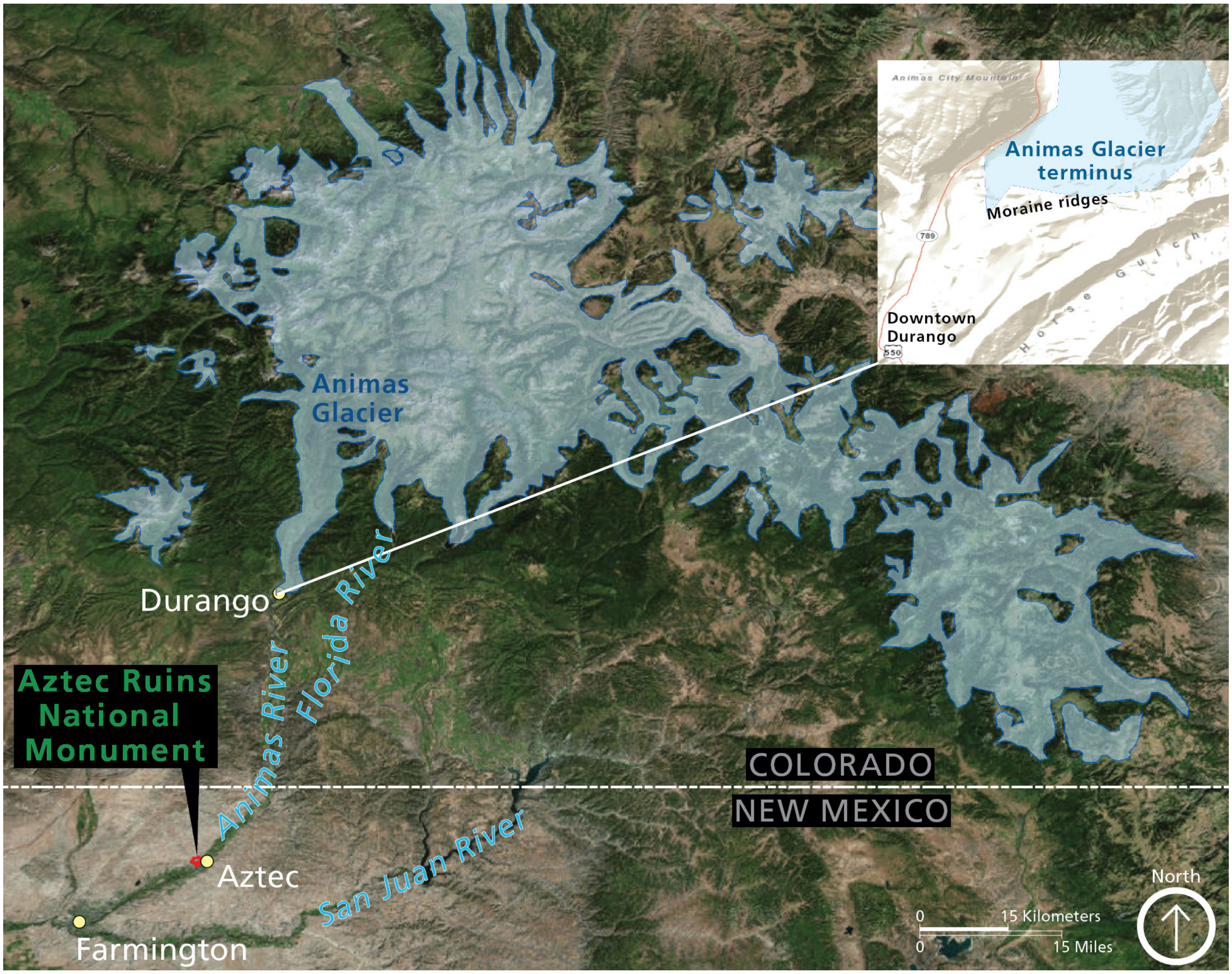

Figure 3. Map of the Animas Glacier and Animas River valley. The Animas River has its headwaters in the San Juan Mountains of Colorado and flows southward into New Mexico. During past glaciations, the upper valley contained the Animas Glacier. Its farthest advance is marked by ridge-like moraines at Durango, Colorado. The lower valley is filled with outwash transported beyond these glacial moraines. The Animas River episodically cut terraces into the valley floor/outwash plain. Graphic byTrista Thornberry-Ehrlich (Colorado State University) after Gillam (1998b, figure 2.3). Imagery from ESRI "World Imagery" ArcMap basemap (accessed 28 April 2016) with data from Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community. Shaded relief inset from ESRI "World Terrain Base" ArcMap basemap with data from Esri, USGS, and NOAA.

sediments accumulated atop previously deposited Upper Cretaceous rocks. By the end of the Laramide Orogeny, these rocks had reached a maximum depth of burial, and following the orogeny, regional heating of deeply buried organic matter resulted in the generation of oil and gas. The combination of thick Cretaceous source rocks and a large area covered by suitable reservoir rocks made the San Juan Basin one of the most important gas-producing basins in the United States (Engler et al. 2001; Brister and Hoffman 2002).

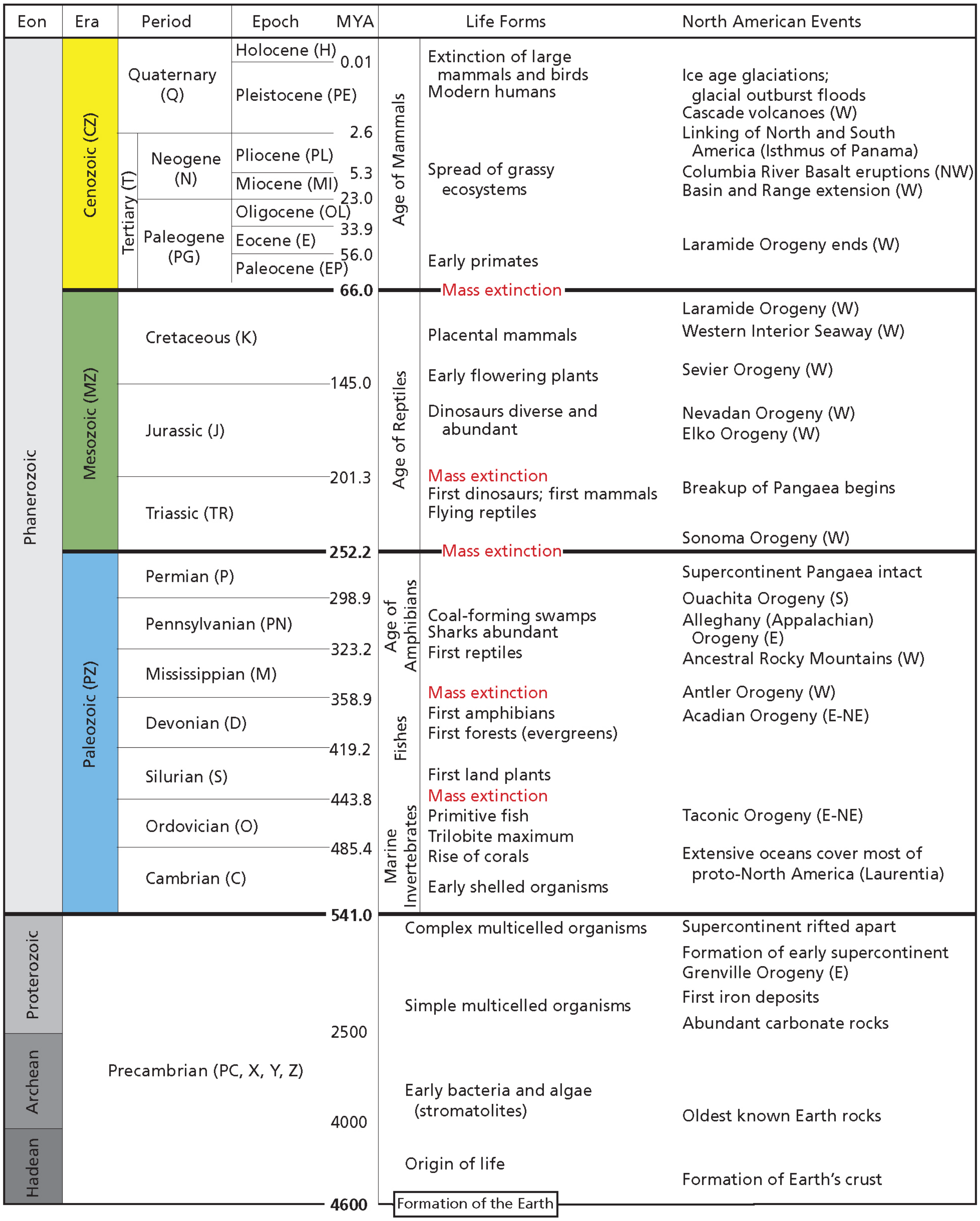

Figure 4. Geologic time scale. The divisions of the geologic time scale are organized stratigraphically, with the oldest divisions at the bottom and the youngest at the top. GRI map abbreviations for each period are in parentheses. The bedrock underlying the monument was deposited during the Paleocene Epoch. The Animas River cut terraces into glacial outwash during the Pleistocene Epoch. The river continues to incise today (Holocene Epoch). The Pleistocene and Holocene epochs are in the Quaternary Period so the geomorphic map units within the monument begin with a "Q". Compass directions in parentheses listed with "North American Events" indicate regional locations. Boundary ages are millions of years ago (MYA). National Park Service graphic using dates from the International Commission on Stratigraphy (http://www.stratigraphy.org/index.php/ics-chart-timescale).

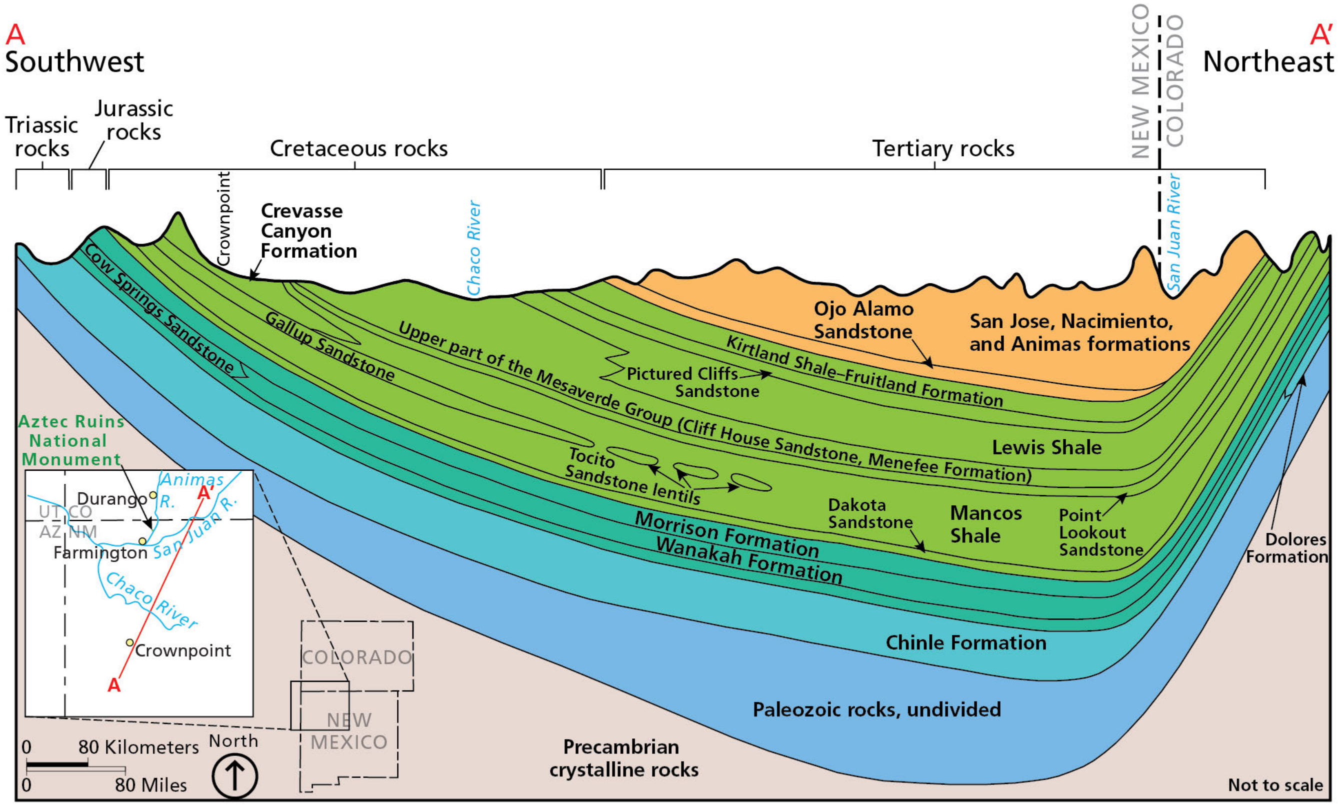

Figure 5. Illustration of San Juan Basin stratigraphy. During the Cretaceous Period, the San Juan Basin occupied a small area on the western edge of the Western Interior Seaway where sediments were deposited in marine, coastal, and terrestrial settings and include the Crevasse Canyon Formation, Cliff House Sandstone, Menefee Formation, Lewis Shale, and Pictured Cliffs Sandstone (shown as Cretaceous rocks in light green on the illustration). These rocks are exposed along the Chaco River in Chaco Culture National Historical Park. During the Laramide Orogeny, the basin began to subside and thousands of feet of additional terrestrial sediment accumulated (shown as Tertiary rocks in orange). The Nacimiento Formation underlies Aztec Ruins National Monument. The San Jose Formation is exposed in the vicinity. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Lyford (1979, figure 3).

Figure 6. Photograph of the San Juan Mountains. A Precambrian core of ancient metamorphic rock (gneisses and schists) was lifted up during the Laramide Orogeny and is now beautifully exposed in the San Juan Mountains of Colorado. The Animas River has its headwaters in these mountains. Wikimedia Commons photograph by John Fowler [CC BY 2.0 (http://creativecommons.org/licenses/by/2.0)] available at https://commons.wikimedia.org/wiki/File%3ASan_Juans_north_of_Durango.jpg.

Figure 7. Paleogeographic map of the Western Interior Seaway. During the Cretaceous Period, an expansive seaway spread across the North American continent. The seaway inundated New Mexico about 96 million years ago. This map represents the maximum extent of the seaway at about 85 million years ago. The red star indicates the approximate location of Chaco Culture National Historical Park, where Upper Cretaceous rocks are now exposed in Chaco Canyon about 85 km (53 mi) south of Aztec Ruins National Monument. These same rocks lie below the surface at Aztec Ruins National Monument. Graphic compiled by Jason Kenworthy (NPS Geologic Resources Division). Base paleogeographic map by Ron Blakey (Colorado Plateau Geosystems, Inc.) available at http://cpgeosystems.com/index.html.

Geologic Features and Processes

This chapter describes noteworthy geologic features and processes in Aztec Ruins National Monument.

Geologic features and processes of significance for the monument include the following. They are discussed more or less stratigraphically (oldest to youngest).

- Nacimiento Formation
- Building Stone and Lithic Resources
- Terraces
- Alluvium
- Eolian Features

Information about many of these features came from the three source maps used in compiling the GRI GIS data (see "Geologic Data" section). Brown and Stone (1979; scale 1:62,000) mapped the Aztec 15' quadrangle, which covers the eastern side of the monument. Ward (1990; scale 1:100,000) mapped the Farmington 30' × 60' quadrangle, which covers the western side of the monument. Both maps show bedrock (Nacimiento Formation) and selected Quaternary deposits such as terraces and alluvium. Mapping by Gillam (1998a; working scale 1:24,000, compiled at 1:50,000) delineated all major terraces and the modern floodplain in the monument.

Nacimiento Formation

The bedrock underlying the monument is the Nacimiento Formation (**Tn**), which was deposited about 64.5 million–61.0 million years ago (Paleocene Epoch; fig. 4). It consists of sedimentary rocks such as claystone, shale, siltstone, and sandstone (Brown and Stone 1979) of primarily continental origins such as floodplains, river channels, swamps, and lakes (Lucas and Ingersoll 1981a, 1981b; Williamson 1996). The sediments that make up these rocks were shed from the rising San Juan and Brazos–Sangre de Cristo uplifts to the north and east of the monument during the Laramide Orogeny (Lucas 1984; see "Geologic History" chapter). The Nacimiento Formation can be as much as 525 m (1,720 ft) thick (Williamson and Lucas 1992). Where exposed at the surface near the monument, the formation typically erodes to low, rounded hills or badlands (Levings et al. 1990).

Although the Nacimiento Formation was mapped by Ward (1990) throughout much of the western portion of the monument (the Flora Vista quadrangle), the formation is almost entirely covered by alluvium (stream deposits), colluvium (foot-of-slope or cliff deposits), or terrace gravel (see "Terraces" and "Alluvium" sections). Christensen (1979) measured a depth to bedrock of 23 m (77 ft) in the water well at the monument's visitor center. Ward (1990) disregarded many surface sediments in order to emphasize the underlying bedrock (Mary Gillam, independent consultant and researcher, written communication, 5 January 2016).

Noting exposures of bedrock is significant for the geologic resources inventory, especially in parks where they are rare. During the 2007 scoping meeting and site visit, participants thought that the Nacimiento Formation was exposed at only a single outcrop in the monument (KellerLynn 2007). Since then, however, additional exposures have been discovered; for example, during a field survey for paleontological resources, an investigator identified five exposures of the Nacimiento Formation in drainages on the mesa locally known as "North Mesa," which rises to the north and west above Farmers Ditch in the monument (fig. 2). These "exposed areas" vary from 45 to 250 m^2 (480 to 2,700 ft^2) but in actuality are not completely bare; they are covered by patches of overlying sediment and vegetation. These areas are located in deeply cut drainages on North Mesa where erosion has exposed the bedrock (Phil Varela, Chaco Culture National Historical Park, paleontology technician, email communication, 2 February 2016).

With so few bedrock exposures in the monument, the likelihood of finding in situ fossils is slim (Tweet et al. 2009), and no fossils have been found in the Nacimiento Formation within the monument to date (Phil Varela, Chaco Culture National Historical Park, paleontology technician, written communication, 5 November 2015). Elsewhere in the San Juan Basin, however, the Nacimiento Formation yields a diversity of vertebrate, invertebrate, and plant fossils indicative of a variety of depositional settings (see Tweet et al. 2009). Because of its age, which is contemporaneous with the beginning of the "Age of Mammals," the Nacimiento Formation is of interest for understanding the species that survived the Cretaceous–Tertiary (K–T) mass extinction event, which marks the loss of an estimated 50% of all species, including dinosaurs, living at that time. The mammals preserved in the Nacimiento Formation were mostly archaic forms that were later replaced (Williamson and Lucas 1992). They are important because they provide a record of mammalian evolution immediately after the K–T extinction, in an area with few other contemporaneous faunas (Weil and Williamson 2007).

Building Stone and Lithic Resources

Blocks of the Nacimiento Formation were used prehistorically in construction at Aztec Ruins. Ancient builders carried these blocks by hand from quarries several kilometers away, then used stone hammers, mauls, and pecking tools to break and dress (put the finishing touches on) the stone (Cajete and Nichols 2004). Ancient builders dabbled with the variety of finer and coarser grained rock types and colors that comprise the Nacimiento Formation. For example, the distinctive "greenstone" bed was incorporated as a decorative band in the wall of the West Ruin (see inside front cover). The greenstone was quarried outside of the monument at a site near Tucker Canyon, about 5 km (3 mi) northeast of the monument (KellerLynn 2007). Interestingly, outer walls were probably plastered with mud, obscuring any detailed stonework beneath, but this practice shielded mortar from the eroding forces of wind, rain, and snow (Cajete and Nichols 2004).

The Great Kiva contains large limestone disks (fig. 8). Each disk weighs about 160 kg (355 lbs) (Cajete and Nichols 2004). The source of these disks is unknown, but in October 2015, Gary Gianniny (professor and carbonate rock expert at Fort Lewis College) visited the monument and conducted a cursory examination of these disks. Gianniny found the limestone comprising the disks "atypical" of marine limestone known from the Hermosa Formation and Leadville Limestone, which are exposed in the region. Furthermore, the continental Nacimiento Formation is not known to contain lacustrine limestone (Mary Gillam, independent consultant and researcher, written communication, 5 January 2016). With permission, Gianniny took a small chip from a broken interior edge of one of the disks to examine under a microscope; his findings are forthcoming (Mary Gillam, independent consultant and researcher, written communication, 5 January 2016).

Figure 8. Photograph of the Great Kiva interior. Morning light breaks into the darkness of the Great Kiva. The kiva was excavated in 1921 and reconstructed in 1934. Note the limestone disks on either side of the staircase. National Park Service photograph available at http://www.nps.gov/azru/learn/photosmultimedia/index.htm.

The terraces (see "Terraces" section) at the monument were a source of local material used in construction and tool making. This material was reworked from elsewhere and brought to Aztec Ruins by glacial meltwater and the Animas River. Cobbles in the terraces, which are from a variety of upstream sources (see "Alluvium" section), are plentiful: they were used for wall foundations (Cajete and Nichols 2004). Limestone cobbles in the terraces yield notable fossils (see "Paleontological Resource Inventory, Monitoring, and Protection" section).

Petrified wood of unknown origin occurs in the terraces. It was a lithic resource found along with other artifacts at the ruins (see "Paleontological Resource Inventory, Monitoring, and Preservation" section).

Nonlocal materials utilized by ancestral Puebloans include obsidian ("volcanic glass") and chert (microcrystalline quartz; also known as "flint" or "jasper"). These lithic materials were traded throughout the Southwest and transported by humans to Aztec Ruins. Obsidian was used for making tools and projectile points. The conchoidal (smoothly curved like a "conch" shell) fracturing of chert made it suitable for cutting and scraping.

A likely source area of obsidian and chert was the Jemez Mountains, which make up a volcanic field that started erupting episodically about 14 million years ago (Miocene Epoch; fig. 4) and culminated during two caldera-forming events—1.62 million and 1.25 million years ago (Pleistocene Epoch; see GRI report about Bandelier National Monument by KellerLynn 2015a). Three source locations of obsidian appear to have been the most important for lithic raw material: (1) El Rechuelos, (2) Cerro Toledo, and (3) Valle Grande (fig. 9). Each has a distinctive chemical signature and can be differentiated by x-ray florescence or neutron activation (Baugh and Nelson 1987; Glascock and Neff 1993). Some chert found in the monument probably came from Narbona Pass in the Chuska Mountains southwest of the monument (KellerLynn 2007). Another source of chert was Cerro Pedernal, meaning "Flint Hill" in Spanish, which is a mesa on the northern

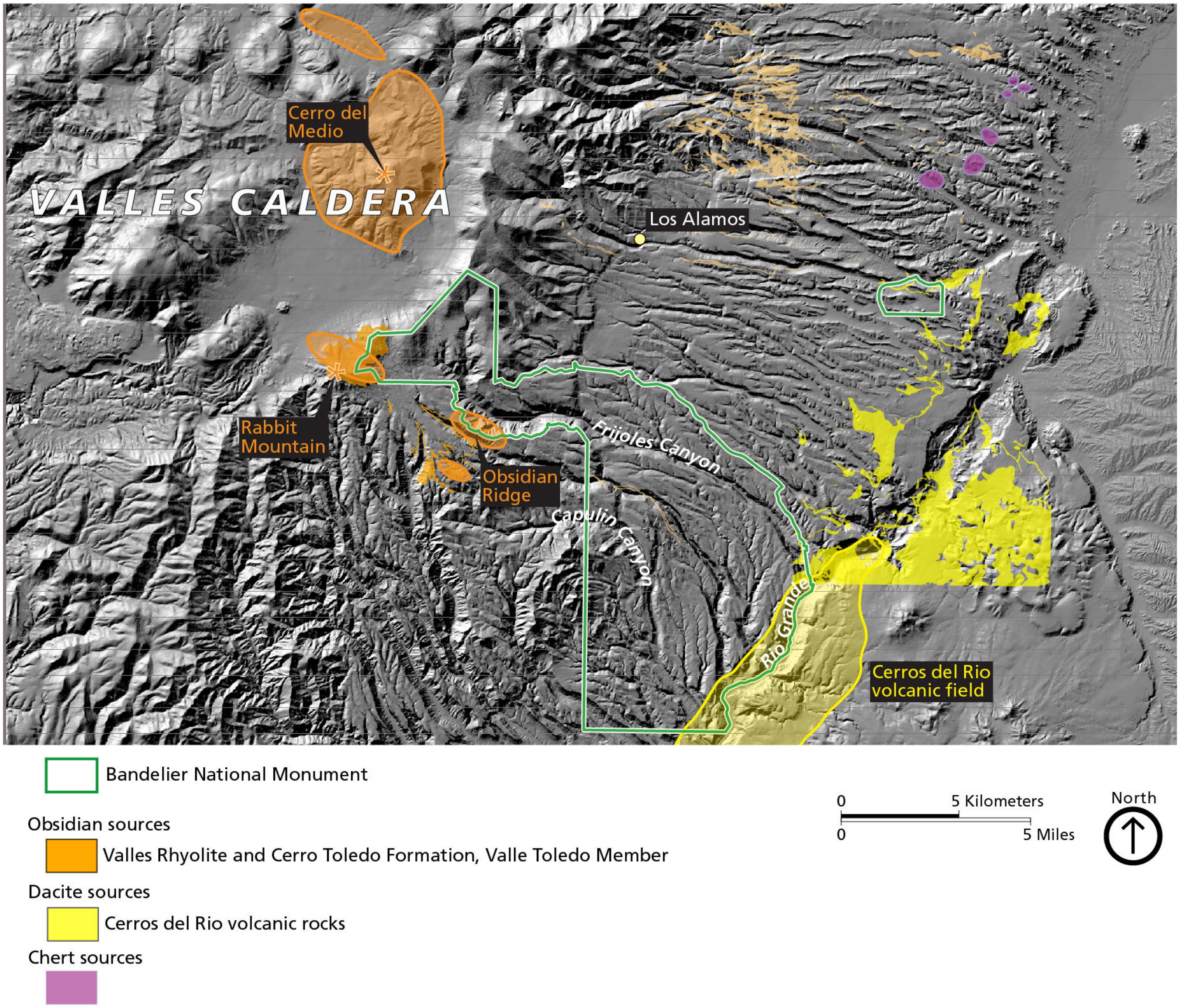

Figure 9. Map of lithic resources in the Jemez Mountains. The Jemez Mountains were a source area of lithic resources for ancestral Puebloans. The map shows source areas of obsidian (orange), including Cerro del Medio, Rabbit Mountain, and Obsidian Ridge at Valles caldera, as well as source areas of chert (pink). At the mouths of tributaries to the Rio Grande (within yellow area on the map), Cerros del Rio volcanic rocks yielded dacite (erroneously referred to as "basalt" in some archeological studies; see Shackley 2011) suitable for tool making. Bandelier National Monument contains a dacite quarry that exploited this material. Graphic by Trista Thornberry-Ehrlich (Colorado State University) using GRI GIS data for Bandelier National Monument and information from Baugh and Nelson (1987), Kilby and Cunningham (2002), Walsh (2005), Gauthier et al. (2007), and Civitello and Gauthier (2013).

flank of the Jemez Mountains (fig. 9; Kilby and Cunningham 2002). That chert was obtained from Miocene sedimentary deposits of the Santa Fe Group (Wilks 2005).

Terraces

During the Pleistocene ice ages, the San Juan Mountains were draped in a 5,000 km^2 (2,000 mi^2) ice cap (fig. 3; Atwood and Mather 1932). The Animas Glacier drained into the Animas River valley and was the longest outlet glacier of that ice cap. The glacier produced huge amounts of debris, some of which built into ridge-like moraines (see "Geologic History" section). Downvalley of these moraines, meltwater streams spread debris across the valley floor. This material is known as "outwash" because it "washed out" beyond the terminus of the glacier. Layers of outwash, composed of mostly gravel but also larger and smaller rock fragments, once spread continuously southward from the moraines at Durango, Colorado.

In time, the Animas River cut down through the layers of outwash into bedrock to create broad terraces, which once extended 80 km (50 mi) downvalley to the junction with the San Juan River (Gillam 1998a, 1998b). Later, erosion removed parts of the outwash plain, including in places, the parts next to moraines, so these layers are now discontinuous. The landscape of the monument is dominated by three terraces. These features step up from the modern floodplain and represent downward incision of the Animas River through time. As such, the highest terrace level is the oldest.

As mapped by Gillam (1998a; see fig. 2 and poster [in pocket]), the three principal terrace levels at the monument are terrace 5a (**Qt5a**; fig. 10), which is 49–50m (160–165 ft) above the modern floodplain (**Qfp**); terrace 6a (**Qt6a**; fig. 11), which is 30–34 m (100–110 ft) above the modern floodplain; and terrace 7, undivided (**Qt7u**; fig. 12), which includes at least two benches with an elevation of roughly 3–6 m (15–20 ft) above the modern floodplain (Mary Gillam, independent consultant and researcher, email communication, 4 June 2007). Numbers associated with terraces (e.g., 5, 6, and 7) indicate relative-age groups; the smaller the number, the older and higher the terrace above the present-day floodplain. A letter associated with a group number, for example "a," indicates a single level within a group; "u" indicates an "undivided" group comprising at least two closely spaced levels.

Figure 10. Photograph of terrace 5a. The highest and oldest terrace at Aztec Ruins National Monument is middle Pleistocene terrace 5a (Qt5a). It makes up the upper part of North Mesa in the monument. The Fee 4-A oil and gas operation, including well and pad (shown here), covers a portion of terrace 5a (Qt5a; see fig. 2). National Park Service photograph from Filippone and Martin (2014, photograph 10).

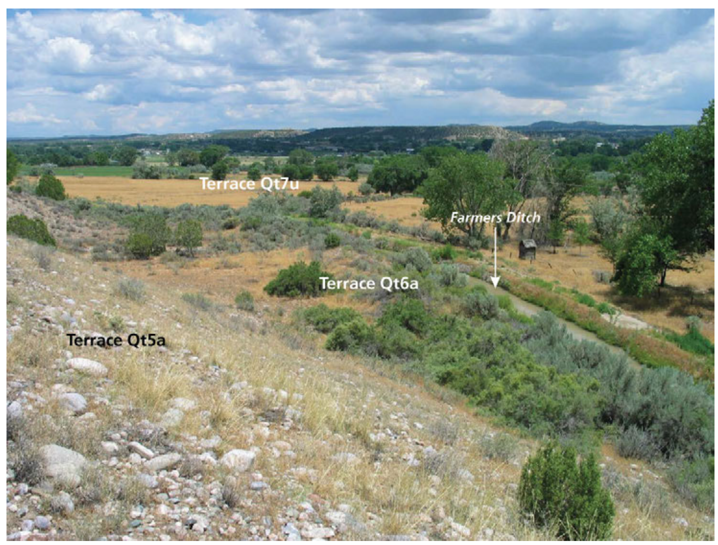

Figure 11. Photograph of terrace 6a. The intermediate or middle-aged terrace at Aztec Ruins National Monument is the late–middle Pleistocene terrace 6a (Qt6a). It is shown at the center of the photograph (northwest side of Farmers Ditch). It makes up the lower bench of North Mesa. National Park Service photograph from Filippone and Martin (2014, photograph 11).

Figure 12. Photograph of terrace 7u. Upper Pleistocene terrace 7, undivided (Qt7u) is the lowest and youngest terrace in the monument. It is pictured on the far (southeast) side of Farmers Ditch. Terrace 6a (Qt6a) is directly above Farmers Ditch. A portion of terrace 5a (Qt5a) is shown in the foreground. National Park Service photograph from Filippone and Martin (2014, photograph 12).

In the western part of the monument, Ward (1990) mapped two units of terrace gravel (**Q4d** and **Q5b**; table 1); these correlate to the two higher of Gillam's three terrace levels. Brown and Stone (1979) combined terrace deposits in the eastern part of the monument into a single unit—terrace and pediment deposits (**Qtp**). Neither Brown and Stone (1979) nor Ward (1990) mapped a low terrace level above the modern floodplain, similar to Gillam's lowest terrace (**Qt7u**); instead, they grouped this material with younger valley-floor alluvium (**Qal**; Brown and Stone 1979) or with younger tributary stream alluvium and bedrock (**Qnt** and **Tn**, Ward 1990), respectively. These differences in map treatment arose because the earlier two maps show geologic units that either occur at the land surface or are shallowly buried by younger deposits. In contrast, Gillam's map shows all terraces whether at the surface or more deeply buried (Mary Gillam, independent consultant and researcher, written communication, 5 January 2016). The three mapping projects also had different objectives and areas of emphasis. Table 1 provides a correlation of units as mapped by Brown and Stone (1979), Ward (1990), and Gillam (1998a); these three source maps comprise the GRI GIS data for the monument (see "Geologic Data" section).

Terraces in the monument range in age from approximately 340,000 to 19,000 years old (see "Geologic History" section). The age of a terrace reflects the timing of channel incision. Each individual terrace level may represent thousands of years or more of activity. The age of a terrace is inferred from its height above a river, relative dating methods that involve soil and weathering development, available numeric ages, and correlation to dated glacial deposits (Gillam 1998a, 1998b; Mary Gillam, independent consultant and researcher, written communication, 5 January 2016).

Alluvium

Since appearing on the landscape sometime between 18 million and 3 million years ago (see "Geologic History" section), the Animas River has been eroding, transporting, and depositing material, referred to as "alluvium," from its headwaters in the San Juan Mountains in Colorado to its junction with the San Juan River near Farmington, New Mexico. The variety of

Table 1. GRI GIS unit correlation

<table>
<tr><th>Monument Landform</th><th>Gillam (1998a)</th><th colspan="2">Ward (1990)</th><th>Brown and Stone (1979)</th></tr>
<tr><td>Floodplain and active alluvial fans</td><td>Qfp (modern floodplain) (Holocene)</td><td colspan="2">Qcf (channel and floodplain alluvium) (Holocene)</td><td rowspan="2">Qal (alluvium) (Holocene and late Pleistocene)</td></tr>
<tr><td>Bench at level of East Ruin and West Ruin</td><td>Qt7u (terrace 7, undivided) (Late Pleistocene)</td><td>Qnt (Naha and Tsegi Alluviums, ndifferentiated) (Holocene)</td><td>Tn (Nacimiento Formation) (Paleocene)</td></tr>
<tr><td>North Mesa, lower bench</td><td>Qt6a (terrace 6a) (Late–middle Pleistocene)</td><td colspan="2">Q5b (terrace gravel, unit 5, lowest terrace [of group 5]) (Pleistocene)</td><td rowspan="2">Qtp (terrace and pediment deposits) (Pleistocene)</td></tr>
<tr><td>North Mesa, higher bench</td><td>Qt5a (terrace 5a) (Middle Pleistocene)</td><td colspan="2">Q4d (terrace gravel, unit 4, intermediate terrace [of group 4]) (Pleistocene)</td></tr>
</table>

Figure 13. Photographs of alluvium on the North Mesa. Since appearing on the landscape between 18 million and 3 million years ago, the Animas River has transported colorful and varied alluvium that reflects the landscapes through which the river flowed. Note pen for scale in the upper photograph. Photographs by Katie KellerLynn (Colorado State University).

rock types at the monument reflects the course of the Animas River and the landscapes through which it flowed (fig. 13; Gillam 1998b; Scott and Moore 2007).

Quartzite (metamorphosed sandstone) is common in the terraces at the monument. This rock, which is 1.7 billion years old (middle Proterozoic; fig. 4), originated as part of the Uncompahgre Formation that crops out in the San Juan Mountains of Colorado. Also, rocks from the San Juan volcanic field in Colorado are common. This field was active about 35 million to 22 million years ago. These rocks are chiefly porphyry (an igneous rock with conspicuous crystals, called "phenocrysts," in a fine-grained matrix) and volcanic tuff (consolidated volcanic ash) and lesser amounts of basalt. Varied sandstones are common near Durango but rarer downstream because soft rocks disintegrate readily when tumbled in a river with harder rocks. The alluvial mix also contains lesser amounts of the mineral quartz; sedimentary rocks such as limestone, mudstone, shale, chert, and jasper; metamorphic rocks such as hornblende gneiss, biotite schist, and some fine-grained varieties; and several different granitoid rocks that originated as igneous plutons below Earth's surface (Mary Gillam, independent consultant and researcher, written communication 5 January 2016).

In addition to alluvium transported by the Animas River, tributary channels and arroyos also deposited alluvium. The complex recent history of the river valley is recorded in main-river alluvium (outwash and post-glacial alluvium) and tributary or arroyo alluvium (see "Geologic History" section).

Brown and Stone (1979) recorded alluvium (**Qal**) as covering most of the eastern half of the monument. They described the alluvium as valley-fill deposits of gravel, sand, silt, and clay. Ward (1990) mapped channel and floodplain alluvium (**Qcf**) along the Animas River in the western part of the map area (see GRI GIS data). This material consists of yellow-brown and gray-brown, poorly sorted clay, silt and sand containing pebbles, cobbles, and boulders.

Alluvium deposited as alluvial fans conceals most of the lowest terrace (**Qt7u**) mapped by Gillam (1998a) near the middle of the valley. During mapping, Gillam was able to identify exposed edges of this terrace in some places but not in others (Mary Gillam, independent consultant and researcher, written communication, 5 January 2016). By contrast, Ward (1990) lumped fan, low terrace, and river floodplain deposits along the middle of the valley (unit **Qcf**), and Brown and Stone (1979) lumped deposits of various types and ages in both their "terrace" (**Qtp**) and "valley-floor" units (**Qal**) (Mary Gillam, written communication, 5 January 2016). Table 1 provides a correlation of these units.

Clarification of "Pediments"

As a point of clarification, unit **Qtp** of Brown and Stone (1979) was named "terrace and pediment deposits"; however, their use of "pediment" in this instance is not commonly accepted (Mary Gillam, independent consultant and researcher, written communication, 5 January 2016).

Pediments are a characteristic erosional feature of arid terranes (Wyckoff 1999). They are eroded into bedrock or occasionally into old alluvial deposits. They may be bare but are more commonly partly mantled by a thin, discontinuous veneer of alluvium. No bare bedrock or alluvium-mantled bedrock slopes matching this definition are within the area that Brown and Stone (1979) mapped as terrace and pediment deposits (**Qtp**) within and near the monument (Mary Gillam, independent consultant and researcher, written communication, 5 January 2016). That area essentially matches the distribution of higher terraces mapped by Gillam (1998a). Many parts of these terraces are buried by alluvial fans that mostly conceal the narrow bedrock slopes (former river cutbanks) between different terrace levels. Presumably, Brown and Stone (1979) interpreted the depositional alluvial-fan surfaces as erosional pediments because pediments do occasionally flank the upslope sides of older terraces in the region, for example, at the rear edge of terrace 3a (**Qt3a**) on the southern side of the Animas River downstream from the monument (Gillam 1998a; see GRI GIS data). However, this relationship does not occur at the monument (Mary Gillam, independent consultant and researcher, written communication, 5 January 2016).

Clarification of "Naha and Tsegi Alluviums"

In an area that Gillam (1998a) mapped as the upper Pleistocene terrace (**Qt7u**) in the western part of the monument, Ward (1990) mapped areas of Naha and Tsegi Alluviums, undifferentiated (**Qnt**) and the Nacimiento Formation (**Tn**) (see bedrock and surficial map, in pocket). Unit **Qnt** consists of well-stratified, yellowish gray and grayish brown silt and sand. As mapped by Ward (1990), the **Qnt** material in the monument appears to be a "finger" of the Estes Arroyo, probably consisting of locally derived fan alluvium that Ward (1990) interpreted as more similar to **Qnt** than to his other mapping units (Mary Gillam, independent consultant and researcher, written communication, 5 January 2016).

The terminology "Naha and Tsegi Aluviums" originated in Arizona's "Navajo Country" (Hack 1941). Hack's system of alluvium in ascending order (oldest to youngest) is Jeddito, Tsegi, and Naha. According to Hack (1941), the Jeddito Alluvium contains remains of proboscidian (elephants and their extinct relatives) of late Pleistocene age, the Tsegi Alluvium contains evidence of human occupation deposited before the 13th century, and the Naha Alluvium contains Pueblo IV pottery (i.e., older than 1300 CE).

Hack's terminology has been applied to areas in New Mexico (and Utah; e.g., Hereford 1988). Weide et al. (1980), Scott et al. (1984), and Mytton and Schneider (1987) used this terminology in the Chaco Canyon area (see GRI report about Chaco Culture National Historical Park by KellerLynn 2015b), and Ward (1990) used it in the monument and surrounding area. Correlation of this material to Hack's type locality in northern Arizona is uncertain, and some investigators have questioned its use, preferring to apply local stratigraphic names (see Hall 1990, 2010).

Eolian Features

Throughout New Mexico, the wind has eroded bedrock and alluvium and deposited eolian (windblown) sand and silt on upland areas. Eolian sand covers significant portions of the San Juan Basin, where large dunes are still active. Eolian silt, referred to as "loess," overlies much of the northern part of the San Juan Basin, where it forms sheets. Some of the best grazing and cropland on the uplands consists of loess (Scott and Moore 2007).

The uppermost deposits on most terraces and older moraines in the Animas River valley consist partly or entirely of loess. Scott and Moore (2007) observed that older loess has been strongly weathered so it contains more clay and is oxidized to a moderate reddish brown.

Younger loess, where it is thick enough to form a distinct layer, contains less clay and is usually yellowish brown. Small deposits of dune sand also overlie outwash on some terraces (Gillam 1998b).

Deposits of Quaternary loess, as much as 1 m (3 ft) thick, occur within the monument (KellerLynn 2007). Loess deposits have cultural significance; ancestral Puebloans dug subsurface structures into them (Paul Carrara, US Geological Survey, research geologist, personal communication, 8 March 2007). They also mined the loess for its use as a primary ingredient for mortar (Dana Hawkins, Aztec Ruins National Monument, biological technician, written communication, 20 October 2015).

During scoping, participants suggested that findings of a study by the US Geological Survey of the surficial deposits at Mesa Verde National Park may be applicable to Aztec Ruins National Monument (see Carrara 2009, 2012; and http://esp.cr.usgs.gov/archive/mverde/). The geologic resources of Mesa Verde National Park played a key role in the lives of the ancient people who lived there (see GRI report by Graham 2006). For example, thick, red loess on mesa tops was significant for prehistoric farming. The loess' particle-size distribution has good moisture-retention properties. Soil that developed in this loess, along with seasonal rains, allowed ancient farmers to grow crops such as corn, beans, and squash (Carrara 2012).

Lava Creek B ash is another eolian feature of interest for the monument. This ash erupted from the Yellowstone caldera approximately 639,000 years ago (Lanphere et al. 2002) and was transported by the wind throughout the Southwest, southern Rocky Mountains, and Great Plains. Deposits of Lava Creek B ash serve as a time-stratigraphic marker, that is, a distinctive, widespread layer of rock or sediment that has been numerically dated and helps to date other rocks and deposits with respect to their relative position to this layer.

The Lava Creek B ash is not exposed within the boundaries of the monument (KellerLynn 2007), but remnants of the formerly widespread blanket of ash occur in the area. In the Flora Vista quadrangle, Ward (1990) mapped an "observation locality" of the ash about 11 km (7 mi) southwest of the monument near the Hargis Arroyo (see GRI GIS data). Gillam (1998a, 1998b) located lenses of Lava Creek B ash at 17 sites in the Animas River valley and used it to estimate the ages of some terraces in the Animas River valley (see Appendix C in Gillam 1998b). The nearest outcrops of Lava Creek B ash to the monument are the aforementioned Hargis Arroyo site and in Miller Canyon, which is on the south side of the valley about 14 km (9 mi) northeast of the monument.

Local residents can attest to ongoing eolian processes that transport sediment and induce dust storms (Mary Gillam, independent consultant and researcher, written communication, 5 January 2016). These modern processes, including potential "sand blasting" of the ruins, are not a management concern, however (KellerLynn 2007).

Geologic Resource Management Issues

This chapter describes geologic features, processes, or human activities that may require management for visitor safety, protection of infrastructure, and preservation of natural and cultural resources in Aztec Ruins National Monument. The NPS Geologic Resources Division provides technical and policy assistance for these issues.

During the 2007 scoping meeting (see scoping summary by KellerLynn 2007) and 2015 conference call, participants (see Appendix A) identified the following geologic resource management issues. They are listed more-or-less by management priority.

- Oil and Gas Development and Production
- Directional Drilling and Hydraulic Fracturing
- Adjacent Development
- Water Impacts on Monument Resources
- Localized and Regional Subsidence
- Piping
- Bank Erosion and Landscape Restoration
- Recreation and Land Use in the Animas River Corridor
- Abandoned Mineral Lands
- Paleontological Resource Inventory, Monitoring, and Protection

Resource managers may find *Geological Monitoring* (Young and Norby 2009) useful for addressing these geologic resource management issues. The manual provides guidance for monitoring vital signs—measurable parameters of the overall condition of natural resources. Each chapter of *Geological Monitoring* covers a different geologic resource and includes detailed recommendations for resource managers, suggested methods of monitoring, and case studies. An online version of *Geological Monitoring* is available at http://go.nps.gov/geomonitoring.

Oil and Gas Development and Production

Oil and gas development and production are principal resource management concerns because the monument is situated in one of the richest and most productive oil and gas provinces in North America—the San Juan Basin (Price 2010). The monument is on the edge of the Blanco Mesaverde oil field that produces from Cretaceous sandstones at a depth of 1,300 m (4,300 ft).

Four operating, nonfederal oil and gas wells—Bobbie Herrera #1, Fee 4-A (fig. 14), Fee 9Y, and Barbara K 001 (fig. 2)—have the potential to affect monument resources. These wells were drilled through multiple producing zones, including the Upper Cretaceous Fruitland and Pictured Cliffs formations. The Fruitland Formation is a notable source of coal and coal-bed methane (see "Geologic Data" chapter). The GRI GIS data provide coal bed locations and thicknesses of the Fruitland Formation in the vicinity of the monument. In addition, the monument contains two active gathering lines.

Private mineral ownership and the potential of undeveloped oil and gas resources beneath the monument create the possibility for additional drilling inside the monument. New operations would be subject to legal and policy requirements, including Code of Federal Regulations 36, Part 9, Subpart B ("9B regulations"; see Appendix B of this report). These regulations require oil and gas operators in National Park System units to submit a plan of operations for NPS approval. The plan must detail all activities of the oil and gas development, describe how reclamation will be completed, and provide the basis for performance bonds. The National Park Service uses this information to determine the effects of the proposed operation on the environment, park management, and visitor values.

According to O'Dell (2001), well operations at the monument had caused localized and relatively minor impacts to natural resources. Vegetation and soils appear to be the most impacted natural resources. Existing and abandoned (see "Abandoned Mineral Lands" section) oil and gas operations impact approximately 2 ha (4 ac) of land within the monument (National Park Service 2010).

Past disturbances associated with wells and gathering lines have adversely affected cultural resources on the Hubbard property. The well on this property was the Moya-Hubbard #1, which was plugged and abandoned in 1977; the associated gathering line was abandoned

Figure 14. Photograph of Fee 4-A well. Oil and gas production is ongoing at Aztec Ruins National Monument. This photograph shows the Fee 4-A well in 2001. National Park Service photograph.

in place (Jeremiah Kimbell, NPS Geologic Resources Division, petroleum engineer, written communication, 4 September 2015).

Provided that operations are properly maintained and eventually reclaimed, the threat of additional damage to natural and cultural resources at the monument is minor. Monument staff works with operators to reduce the impacts of operations on monument resources and values (O'Dell 2001).

Increased activity such as new drilling, reworking old wells, or replacing gas pipelines within the monument has the potential to damage resources if sites are not properly constructed, maintained, and operated. New drilling and production operations would be subject to the protective standards of the NPS oil and gas 9B regulations, which require an operator to prevent or minimize damage to NPS resources and values. Resource protection related to the gas gathering system in the monument would be addressed through the NPS special use permit regulations at 36 CFR § § 1.6, 5.3, and 5.7 (O'Dell, 2001; Julia Brunner, NPS Geologic Resources Division, policy and regulatory specialist, personal communication, 22 March 2007).

Drilling outside the monument is occurring and is likely to continue in the future (GRI conference call, 28 May 2015). In general, potential impacts include groundwater and surface water contamination, erosion and siltation, introduction of exotic plant species, reduction of wildlife habitat, impairment of viewsheds and night skies, excessive noise, and diminished air quality. Visitor safety, visual and sound intrusions on the cultural landscape, and overall degradation of the visitor experience are specific concerns at the monument.

In the event of any future drilling and resource extraction adjacent to the monument, the National Park Service would work closely with representatives of the oil and gas industry to help insure that operations would be conducted in concert with NPS management goals and objectives and in a manner that minimizes impacts on park resources and visitor experience. If an activity outside park boundaries destroys, causes the loss of, or injures National Park System unit resources, the National Park Service has authority to seek recoveries for response costs and damages from a responsible party under "System Unit Resource Protection Act" at 54 U.S.C. §100721–100725 (formerly the Park System Resources Protection Act, 16 U.S.C. §19jj). This is a strict liability statute.

The NPS Geologic Resources Division is available to provide monument staff with policy and technical assistance regarding energy issues. The NPS Geologic Resources Division Energy and Minerals website, http://go.nps.gov/grd_energyminerals, provides additional information.

Directional Drilling and Hydraulic Fracturing

Improvements in directional drilling and hydraulic fracturing, commonly called "fracking," have renewed industry interest in the San Juan Basin, in particular for the Mancos Shale and Gallup Sandstone (National Park Service 2014; see GRI report about Chaco Culture National Historical Park by KellerLynn 2015b). In conventional vertical wells, production of oil and gas is limited by natural fractures in the targeted layers. Natural fracturing took place during the formation of the San Juan Basin during the Laramide Orogeny (see "Geologic History" chapter). Directional drilling generally involves drilling vertically to or near the top of a target formation and then turning the drill bit horizontally into the target formation for the purpose of exposing more of the production zone to the wellbore (borehole) and intersecting vertical fractures to increase production. Recent technological innovations in drilling and steering the bit to stay within the target formation have increased the success rate of this process (Just et al. 2013).

Production is further enhanced by multiple-stage hydraulic fracturing in which a liquid, typically water, is mixed with sand and chemicals and then injected at high pressure into a wellbore to create more fractures in the reservoir rock. After hydraulic pressure is removed from the well, small grains of sand or aluminum oxide, called "proppant," hold open these fractures and allow oil and gas to migrate into the wellbore (Just et al. 2013).

The potential role of this technology in the San Juan Basin cannot be overemphasized (Engler et al. 2001), and the size and scale of horizontally drilled, hydraulically fractured wells will likely dwarf anything seen in the area previously (National Park Service 2014). Effects of horizontal drilling and hydraulic fracturing may include the following:

- Water contamination related to drilling and disposal of drilling fluids;
- Reductions in streamflow and groundwater levels from operational water requirements;
- Air quality degradation from internal combustion engines on drill rigs and trucks;
- Excess dust from equipment transportation;
- Disruption of solitude and night skies from operational lights or flaring; and
- Safety concerns and impacts to wildlife associated with the necessary transportation to support drilling operations (National Park Service 2014).

All the wells in the monument are presently conventional, but in theory a current operator could frack an existing well, assuming the operator had an approved plan of operation that included hydraulic fracturing (Jeremiah Kimbell, NPS Geologic Resources Division, petroleum engineer, written communication, 4 September 2015).

Impacts from Vibrations

During the conference call, participants noted that horizontal drilling and hydraulic fracturing have the potential to impact cultural resources, including archeological structures, as a result of vibrations caused by drilling and from heavy vehicles. According to Jeremiah Kimbell (NPS Geologic Resources Division, petroleum engineer, written communication, 4 September 2015), however, the only potential vibrations that could occur are limited, localized disturbances resulting from pumps and motors associated with surface equipment used to perform fracking. Furthermore, the hydraulic fracturing process itself is relatively short, typically less than one week (written communication, 4 September 2015). Also, because all existing wells in the monument are conventional, the number of fracturing stages would be only 1–2, rather than 10–25 (typical of horizontal wells).

In Chaco Culture National Historical Park (see GRI report by KellerLynn 2015b), vibration studies established guidance for "safe distances" from archeological structures. King et al. (1985) analyzed the seismic risk to the larger archeological structures. Some of their findings may be applicable to Aztec Ruins National Monument. Based on normal blasting practices in the Chaco Canyon area, conventional rail traffic, use of road building equipment, and vehicular traffic patterns, King et al. (1985) recommended that structures be a minimum of 1.2 km (0.7 mi) from blasting, 0.5 km (0.3 mi) from railroad traffic, 45 m (150 ft) from road building, and 25 m (80 ft) from vehicular traffic. King et al. (1991) recommended that heavy vehicular traffic on a rough road be at least 30 m (100 ft) from a sensitive site. With respect to horizontal drilling and hydraulic fracturing in the vicinity of Aztec Ruins National Monument, a typical "safe distance" would be delineated by the wellsite pad (Jeremiah Kimbell, NPS Geologic Resources Division, petroleum engineer written communication, 4 September 2015).

Impacts from Injection Wells

Injection wells could be an issue for a number of reasons including high rates of casing failures, potentially leading to groundwater contamination, and permanent "noisy" facilities needed for the injection process (Jeremiah Kimbell, NPS Geologic Resources Division, petroleum engineer, written communication, 4 September 2015). In addition, injection wells have the potential to induce earthquakes. Generation of such an earthquake is highly dependent on the geophysical properties of an injection site, the amount of fluid injected, and the number of injection wells at a site. Seismic activity is not the leading cause for concern regarding injection wells.

Adjacent Development

Aztec Ruins National Monument is surrounded by the developing City of Aztec (fig. 2). According to scoping participants, one of the most threatened resources for both the city and the monument is open space. As areas of open space become increasingly scarce, developers may view the monument as "available" for use in urban functions such as new road corridors, new pipeline corridors, and new sports areas for local schools. In the vicinity of Aztec Ruins National Monument, vandalism and trespass are issues of concern related to development and increased access to the monument. Such vandalism has been a particular concern at other parks including Petroglyph National Monument near Albuquerque, New Mexico (Dave Love, New Mexico Bureau of Geology and Mineral Resources, geologist, email communication, 24 April 2007). The National Park Service has erected barbed-wire fencing along the shared boundary between the monument and a proposed subdivision to the north (GRI conference call, 28 May 2015). Impairments to the monument's viewshed are another concern related to adjacent development.

The primary area of concern for monument managers is the Mesa Escondido subdivision north of the monument (fig. 2). Development and construction at that site have impacted archeological features, in particular a stretch of prehistoric road, and their geologic contexts (Dave Love, New Mexico Bureau of Geology and Mineral Resources, geologist, email communication, 24 April 2007).

Mesa Escondido is "upslope" from the monument, so runoff is a concern. Developed land has the potential to change the timing and duration of runoff events following storms because roads concentrate water (and concentrate water faster) than natural conditions, thereby increasing peak discharge. Greater discharge equates to greater erosive power, which could affect monument resources downslope. Also, future irrigation of lawns in the subdivision could contribute to runoff onto the monument property, as well as cause unnaturally high groundwater levels (KellerLynn 2007). GRI conference call participants suggested that monument managers acquire a copy of the City of Aztec's surface water management plan, which may be useful for planning purposes and provide guidance for addressing storm-water runoff from outside sources onto monument lands.

According to the monument's foundation document (National Park Service 2015), the needs associated with adjacent development include updating the 1993 land protection plan and developing a mitigation plan with the New Mexico Historic Preservation Division. In addition, obtaining the most current LiDAR imaging of the area is needed to document and research access roads and perform a viewshed analysis. Planning needs include working with the NPS Intermountain Region Lands Office to determine the steps that the National Park Service and the land developer would take in obtaining access, securing appropriate development permits, and providing infrastructure for utilities that would probably have to cross monument lands.

Water Impacts on Monument Resources

Structural deterioration associated with water at the monument has been a problem for many decades. Chapter 12 (titled "The High Cost of Water") of Aztec Ruins National Monument: Administrative History of an Archeological Preserve (Lister and Lister 1990) contains a "long recital of the stabilization efforts at Aztec Ruins," starting in 1916 with the American Museum of Natural History and followed by the National Park Service in 1923. Summer rains, winter snows, and impacts to natural hydrologic processes, including surface runoff from adjacent lands (see "Adjacent Development" section) and subsurface drainage from irrigated fields, have led to the "high cost of water." In an effort to create a mitigation plan for protecting archeological sites at the monument, a hydrologic study began in 2005 (see Filippone et al. 2007). Filippone and Martin (2014) completed a final report that interpreted groundwater conditions at the monument and provided conclusions and management recommendations. Monument managers are referred to that report.

Irrigation of Agricultural Fields

In 2000, the National Park Service acquired agricultural fields north of the monument and stopped irrigating, which resulted in greatly decreased local recharge to the groundwater system and subsequent lowering of the water table (Filippone and Martin 2014). The maximum water table elevation after irrigation stopped was several feet lower than the maximum water-table elevation in 2005–2012 when irrigation was occurring. Now, high water levels in the vicinity are generally more than 4.5 m (15 ft) below the bottom of the Great Kiva, indicating that high water-table conditions are no longer a significant source of soil moisture at the ruins (Filippone and Martin 2014).

Farmers Ditch

Scoping participants suggested that "Farmers Ditch"—an irrigation ditch constructed in 1892 that runs through the monument (fig. 2)—may be artificially raising groundwater levels around the ruins. For many years, Farmers Ditch primarily provided water for irrigating agricultural fields in the Aztec area, but today, the ditch is also a conduit for municipal water to the City of Farmington. Water from Farmers Ditch is also used to irrigate the picnic area and heritage garden at the monument (GRI conference call, 28 May 2015). Until recently a head gate also routed irrigation water to an orchard at the monument. Irrigation of this orchard was discontinued in 2009 and the orchard was removed in 2013 (Filippone and Martin 2014).

Farmers Ditch transports water between March and November, with specific "on" and "off" dates determined by local hydrologic conditions and water supply needs of Farmington. When flowing at full capacity, the ditch conveys between 1.7 and 2.0 m^3/s (60 and 70 cfs) (Filippone and Martin 2014).

Apparently when water is flowing in Farmers Ditch, it acts as a line source to the valley-fill aquifer, raising water levels between the ditch and the Animas River, and eventually discharging to the river. Filippone and Martin (2014) noted that local groundwater conditions as influenced by the ditch could be controlled by artificially lining the ditch. On the other hand, the cottonwood trees, which "contribute cool shade and a lovely sense of place," (p. 15) may be negatively impacted if the ditch were to be lined where it crosses the monument. Filippone and Martin (2014) recommended that monument managers engage with the managers of Farmers Ditch for the purpose of communicating NPS interests. In particular, these investigators recommended that monument mangers suggest minimizing the disturbance of the low-permeability "natural" lining of the ditch during maintenance activities (cleaning and repair) as a desirable long-term management objective. Breaches to the lining can result in leaks and subsurface water movement to archeological sites.

Soil Moisture

Soil conditions near the surface at the monument vary widely within short distances (Filippone and Martin 2014). The widespread presence of interfingered sandy to clayey soils from 5–9 m (15–30 ft) thick beneath the monument restricts deep percolation of infiltrated precipitation and creates localized perched water-table conditions and increases soil moisture along the western side of the West Ruin complex.

Localized and Regional Subsidence

During the scoping meeting and site visit in 2007, participants (see Appendix A) discussed localized subsidence, which is occurring near the East Ruin, which is located on the lowest terrace (**Qt7u**). The cause of these small depressions was not apparent. Some participants suggested that discontinuing irrigation of the fields on lands acquired in 2000 north of the core ruins may have affected the groundwater levels at East Ruin, which is downslope of the previously irrigated lands, contributing to ground instability and collapse (KellerLynn 2007). In addition to water table–related subsidence, other possible causes of localized subsidence include deep-seated tectonic faulting or down warping, excessive precipitation or artificial wetting, and soil-related problems of shrinking and swelling clays or undercompacted soils (Shaw and Johnpeer 1985). Observed cracks (in November 2015), which had developed in the upper walls on opposite sides of the Great Kiva, may be a result of localized subsidence, potentially related to shrink and swell processes (Mary Gillam, independent consultant and researcher, written communication, 5 January 2016).

Acquiring an understanding of soil-engineering properties near the East Ruin is important for the preservation of cultural resources (Mary Gillam, independent consultant and researcher, written communication, 5 January 2016). Some general information is currently available. For example, the Natural Resources Conservation Service (NRCS) in collaboration with the National Park Service completed a soil survey for the monument in 2006 (National Park Service 2006). These data are publically available at NPS Integrated Resource Management Applications (IRMA), https://irma.nps.gov/DataStore/Reference/Profile/1048820, and the NRCS Web Soil Survey, http://websoilsurvey.nrcs.usda.gov/app/HomePage.htm. Fruitland sandy loam, 0%–2% slopes (soil map unit Fr) underlies the East Ruin. However, site-specific information is needed in order to address the underlying cause (or causes).

The NPS Geologic Resources Division provides assistance in evaluating and mitigating geologic hazards in National Park System units, including soil hazards and risks (see http://go.nps.gov/geohazards). Monument managers are encouraged to submit a technical assistance request to the division. GRD staff will either be able to address the request directly or serve as a liaison to other investigators, potentially including staff from the New Mexico Bureau of Geology and Mineral Resources, who have collaborated on GRI projects in the past.

In addition, minor regional subsidence occurs in association with coal-bed methane extraction in the San Juan Basin, but it is unlikely to affect the ruins (Mary Gillam, independent consultant and researcher, written communication, 5 January 2016). Since the late 1980s, coal-bed methane has been produced from coal beds, predominantly of the Fruitland Formation. The gas, which was adsorbed into the solid matrix of the coal, is extracted through the production of large volumes of water, which leads to a reduction of pore pressure within coal seams that in turn leads to the liberation of the methane, which can subsequently be produced. Findings by Katzenstein (2012) showed that enough groundwater production has taken place in the San Juan Basin to cause measurable (several cm) subsidence above the coal-bed methane–producing fields.

Piping

Piping is "erosion by percolating water in a layer of subsoil, resulting in caving and in the formation of narrow conduits, tunnels, or 'pipes' through which soluble or granular soil material is removed" (USGS "Water Basics Glossary" at http://water.usgs.gov/water-basics_glossary.html). Piping is a major management issue in anthropogenic areas such as earthen dams and raised roads. Piping also can occur in natural settings, typically when sheetwash (overland flow) erosion starts to concentrate into rill (channelized flow) erosion, entering a soil through cracks, animal burrows, fence-post holes, or excavations, and eventually moving through the subsurface to an exit point (Pete Biggam, National Park Service, soil scientist, email communication, 23 February 2007).

Scoping participants identified piping as a minor geohazard at the monument. Soil pipes have developed in an eroding bank of the "Fallon property" along the Animas River (see "Bank Erosion and Landscape Restoration" section). Piping could affect the stability of archeological sites via collapse of overlying material into a pipe.

Pipes also may have cultural importance. Ancestral Puebloans may have "enhanced" natural pipes for human use, even to the extent of excavating a kiva into a soil pipe (Pete Biggam, National Park Service, soil scientist, personal communication in KellerLynn 2007, p. 11). A cultural connection between pipes and kivas has not been definitively established, however, because excavation would have destroyed the original pipe (Aron Adams, Aztec Ruins National Monument, Chief of Cultural Resources, email communication, 27 January 2016).

Bank Erosion and Landscape Restoration

During scoping, monument staff identified erosion at an archeological site along the banks of the Animas River as a management concern. The site is part of the "Fallon property" acquired by the National Park Service in 2009. The property is along the river in a stretch with steep banks (approximately 60% slope). Elsewhere, the riparian corridor consists of sand or cobble beaches not particularly susceptible to slope movements. Before the National Park Service acquired this property, the land owner irrigated the pasture above the bank during summer months, which contributed to erosion. The pasture was heavily grazed, which denuded vegetation and compacted soil. During a moderate-intensity rainstorm, investigators observed that overland flow developed quickly, which may be a contributing factor to the rate of bank erosion (Johnson 2004). In addition, irrigation water that was allowed to slowly soak into the soil may have led to soil piping, which is evident along the bank (fig. 15).

Figure 15. Photograph of a soil pipe. Piping is occurring in an eroding bank along the Animas River at Aztec Ruins National Monument. The red mark on the ruler is at 1 foot. National Park Service photograph by Kim Johnson (taken in 2004).

Figure 16. Photograph of rip-rap along the Animas River. The steepest section of bank along the Animas River at Aztec Ruins National Monument is located along this property, which the National Park Service acquired in 2009. This photograph was taken in 2004. Since then, the National Park Service has removed the shed and fencing, but the rip-rap remains. National Park Service photograph by Kim Johnson.

The previous owner of the property added rip-rap consisting of cement slabs to protect the bank (fig. 16; Johnson 2004). The goal of the National Park Service for this property is to restore natural function and appearance while protecting archeological resources. As such, the National Park Service wants to remove the rip-rap at this site. In general, removal of debris that was used as stream-bank stabilization, including cement rip-rap and old cars, is a management goal for lands acquired within the monument's legislative boundary. Since 2009, the National Park Service has removed a shed and fencing, conducted general clean-up, and taken steps toward eradicating invasive species on the property (GRI conference call, 28 May 2015).

To further address stream-bank erosion at the property, monument managers have submitted a technical assistance request to the NPS Water Resources Division. Monument managers expect assistance after the 2016 spring runoff. This technical assistance request also includes remediation of an old lagoon site. An exotic plant management team (EPMT) will likely be involved with both projects.

Recreation and Land Use in the Animas River Corridor

The monument's foundation document (National Park Service 2015) identified the Animas River as a fundamental resource and value. The monument is situated along the banks of the river, where the waters were once used for the benefit of ancestral Puebloans. Today, people enjoy kayaking, fishing, and canoeing. The river corridor also connects the monument to the nearby city (National Park Service 2015).

The City of Aztec recently built a bridge and trail in the riparian corridor, which allows pedestrians to cross the Animas River and enter the monument. Monument managers have added buck-and-rail fencing in this area in an effort to keep recreationists on the trail and thus minimize the proliferation of social trails, which causes soil compaction and erosion. Because no park infrastructure occurs within the floodplain, flooding of the Animas River is a minor management concern (Johnson 2004).

Abandoned Mineral Lands

During the scoping process, participants identified two abandoned gas wells: Rhodes Abram #1 and Moya-Hubbard #1 (see KellerLynn 2007). These abandoned wells were plugged in 1970 and 1977, respectively.

According to the NPS Abandoned Mineral Lands (AML) database and Burghardt et al. (2014), the monument contains one (additional) plugged and abandoned gas well within the expanded boundaries of the monument—AZRU Gas Well-WE-01. The exact location of this well is unknown (Aron Adams, Aztec Ruins National Monument, Chief of Cultural Resources, written communication, 20 October 2015). The National Park Service has not yet acquired the land upon which this well is located, and no mitigation has been conducted to date.

Abandoned mineral lands can pose a variety of resource management issues such as visitor and staff safety and air, water, and soil quality. Spills or contamination from AML sites outside of the monument could also affect monument resources as evidenced by the August 2015 spill of Gold King mine waste into the Animas River. See the NPS AML website, http://go.nps.gov/aml.

Paleontological Resource Inventory, Monitoring, and Protection

All paleontological resources are nonrenewable and subject to science-informed inventory, monitoring, protection, and interpretation as outlined in the 2009 Paleontological Resources Preservation Act (see Appendix B of this report). Department of the Interior regulations associated with this act are under development. A variety of publications and online resources provide park-specific or servicewide information and guidance for paleontological resource management, for example, the NPS Fossils and

Paleontology website, http://go.nps.gov/fossils_and_paleo. Also, in *Geological Monitoring*, Santucci et al. (2009) described five methods and vital signs for monitoring in situ paleontological resources: (1) erosion (geologic factors), (2) erosion (climatic factors), (3) catastrophic geohazards, (4) hydrology/bathymetry, and (5) human access/public use.

Tweet et al. (2009) completed an inventory and monitoring report about the paleontological resources of the Southern Colorado Plateau Network, including Aztec Ruins National Monument. That report provided geologic background information and discussed potential sources of paleontological material, including the monument's bedrock and surficial deposits, monument collections, and cultural resource contexts.

In October 2015, an investigator conducted a reconnaissance level, field-based paleontological survey for the monument. Field investigations were concentrated on North Mesa, focusing on five discovered outcrops of the Nacimiento Formation and the terraces adjacent to Farmers Ditch (Phil Varela, Chaco Culture National Historical Park, paleontology technician, written communication, 5 November 2015). Because no fossils were discovered in the Nacimiento outcrops at that time, a more thorough inventory is not presently recommended. However, erosion on North Mesa could expose more bedrock and further erode already existing outcrops, thus exposing new fossil discoveries in the future.

Terrace deposits contain the most notable fossils found in the monument to date. These are Paleozoic brachiopods, crinoids, and horn corals in limestone cobbles (fig. 17). The cobbles are reworked; the source rock is most likely the Pennsylvanian (323 million–298 million years ago) Hermosa Formation of southwestern Colorado, although the Leadville Limestone (Mississippian Period, 358 million–323 million years ago) is another possibility. The recent field reconnaissance yielded five new specimens for the monument's paleontology collection, for a total of 21 catalog numbers (Phil Varela, Chaco Culture National Historical Park, paleontology technician, email communication, 15 December 2015). Before these new specimens were added, fossils identified in the monument's collections were mostly petrified wood (Tweet et al. 2009). Terrace deposits also contain pieces of reworked petrified wood of unknown origin.

Figure 17. Photographs of fossils at Aztec Ruins National Monument. Reworked limestone cobbles in the terraces at the monument contain fossils such as brachiopods (top; mostly brachiopods, but also some gastropod molds), crinoids (middle; crinoid stem segments mixed with brachiopods), and horn corals (bottom; cross section and longitudinal views of solitary rugose [horn] corals). Note the black-and-white centimeter scale. National Park Service photographs (taken in 2015) by Phil Varela (Chaco Culture National Historical Park).

Geologic History

This chapter describes the chronology of geologic events that formed the present landscape of Aztec Ruins National Monument.

Following an episode of mountain building that created the Rocky Mountains, the Animas River appeared on the landscape and began to incise episodically. Downcutting continues to the present day. Long-term channel incision was interrupted by intervals of stability or aggradation when voluminous deposits of glacial outwash accumulated on the floor of the Animas River valley. The river cut a flight of inset fluvial terraces into the valley floor, vertically eroding through each layer of outwash into underlying bedrock. Three primary terrace levels dominate the landscape of Aztec Ruins National Monument.

Laramide Orogeny

The Laramide Orogeny lasted approximately 35 million years (75 million–40 million years ago, Late Cretaceous Period to Eocene Epoch; fig. 4) and dramatically changed the landscape of western North America. This massive mountain-building event lifted up areas such as the Rocky Mountains while creating sags in Earth's crust such as the San Juan Basin.

During the Laramide Orogeny, highlands, for instance in the vicinity of the San Juan Mountains (fig. 6), shed terrestrial sediments into the subsiding San Juan Basin. Cather (2004) argued for three periods of Laramide subsidence in the San Juan Basin: (1) Late Cretaceous (approximately 80 million years ago) when the basin's oil and gas producing–rocks were deposited, (2) Paleocene Epoch when the Nacimiento Formation was deposited (64.5 million–61.0 million years ago), and (3) Eocene Epoch (55 million–50 million years ago) when the San Jose Formation was deposited. Within and in the vicinity of the monument, respectively, the Nacimiento and San Jose formations represent an overlying terrestrial package of sedimentary strata that was deposited atop downwarped Upper Cretaceous (100 million–66 million years ago) marine and coastal rocks, including the Menefee Formation and Cliff House Sandstone in Chaco Culture National Historical Park (see GRI report by KellerLynn 2015b). Upper Cretaceous marine and coastal rocks occur at depth below the monument (fig. 4).

Animas River on the Landscape

Long after the Laramide Orogeny, the Animas River began flowing from the San Juan Mountains, carving out what is now the Animas River valley. Incision of the valley began sometime between about 18 million and 3 million years ago (Miocene and Pliocene epochs), that is, well before the advance of glacial ice into the valley but after mid-Tertiary volcanism, which occurred episodically from about 35 million to 18 million years ago. Areas with active volcanoes included the San Juan volcanic field to the north of the monument and the Mogollon–Datil volcanic field to the south (see GRI report about Gila Cliff Dwellings National Monument by KellerLynn 2014 for information about the Mogollon–Datil volcanic field). Volcanic activity in the San Juan Mountains produced an apron of volcanic material that probably covered the Aztec area and may have produced its own depositional sag to accumulate sediments (Smith et al. 2002).

Glacial Record

The timing of the first glacial advance into the Animas River valley is unknown, but ancient terraces provide some clues. The oldest terrace remnants composed of glacial outwash, which possibly represent this earliest glacial stage, are found along the southern side of the river near Farmington and north of the river near Flora Vista. This material is represented by terrace gravel, unit 3, oldest (**Q3a**) of Ward (1990) and terrace 3a (**Qt3a**) of Gillam (1998a) (see GRI GIS data). The nearest remnants are 6 km (4 mi) west of the monument. Based on the height of these terrace remnants above the river, Gillam (1998b) estimated their age as roughly 800,000 years old. This estimate closely matches the findings of Rogers et al. (1992), whose study site at Hansen Bluff (210 km [130 mi] northeast of the monument) provided a long alluvial record from the San Luis Valley of Colorado. This record indicated when significant cooling first affected the San Juan Mountains.

From oldest to youngest, the best-known glacial stages in the Rocky Mountains are pre-Bull Lake, Bull Lake, and Pinedale (table 2). Knowledge about the sequence and ages of Rocky Mountain glaciations is changing as moraines at Durango, Colorado, and elsewhere are

Table 2. Terraces at Aztec Ruins National Monument

<table>
<tr><th rowspan="2">Age Estimate*</th><th colspan="3">GRI GIS Map Unit (map symbol)</th><th rowspan="2">Height above Modern Floodplain at the Monument</th><th rowspan="2">Associated Moraine/ Outwash</th><th rowspan="2">Glaciation</th></tr>
<tr><th>Gillam (1998a)</th><th>Ward (1990)</th><th>Brown and Stone (1979)</th></tr>
<tr><td>Late Pleistocene Epoch (approximately 25,000–19,000 years ago)</td><td>Terrace 7, undivided (Qt7u)</td><td>No terrace</td><td>No terrace</td><td><3 m (10 ft)</td><td>Animas City</td><td>Pinedale</td></tr>
<tr><td>Late–middle Pleistocene Epoch (approximately 160,000–140,000 years ago)</td><td>Terrace 6a (Qt6a)</td><td>Terrace gravel, unit 5 (Q5b)</td><td rowspan="2">Terrace and pediment deposits (Qtp)</td><td>30 m (98 ft)</td><td>Spring Creek</td><td>Bull Lake</td></tr>
<tr><td>Middle Pleistocene Epoch (approximately 340,000–250,000 years ago)</td><td>Terrace 5a (Qt5a)</td><td>Terrace gravel, unit 4 (Q4d)</td><td>43–46 m (141–151 ft)</td><td>Durango</td><td>Pre-Bull Lake</td></tr>
</table>

*From Gillam (1998a, 1998b; written communication, 5 January 2016); Pierce (2004); Guido et al. (2007).

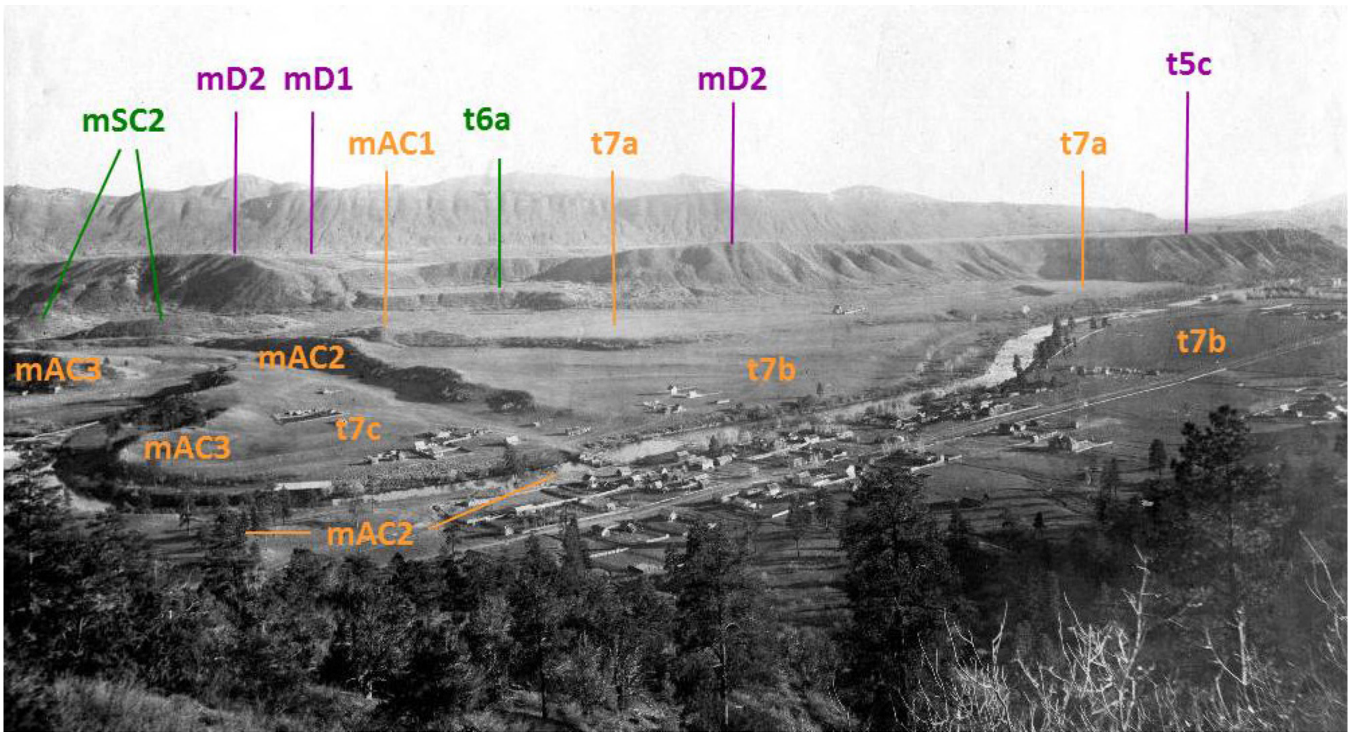

Figure 18. Photograph of the Animas River valley in 1897. The view is looking southeast over Animas City. During the Pleistocene ice ages, the Animas Glacier built a series of moraines (m)—Durango (D), Spring Creek (SC), and Animas City (AC). Meltwater streams distributed outwash that covered the valley floor. Outwash deposits, which were cut by the Animas River into terraces (t), correspond to this series of moraines (see table 2). Label colors signify major age groups: purple (pre-Bull Lake glaciation), green (Bull Lake glaciation), and yellow (Pinedale glaciation). US Geological Survey photograph by A. C. Spencer, used as plate 25-A in Atwood and Mather (1932) available at http://library.usgs.gov/photo/#/item/51dc378ce4b0f81004b7a516. Annotations provided by Mary Gillam (independent consultant and researcher, written communication, 6 March 2016).

studied and dated using more advanced techniques and multiple lines of evidence. The Wind River Range in Wyoming is the type area (reference location where these deposits were first studied) of these glaciations. Investigators have correlated glacial deposits such as moraines throughout the Rocky Mountains to that area. Very few numerical dates are available for moraines in Durango so their ages have been estimated mainly from their physical features and similarities to moraines in the Wind River Range. Local names for these moraines are from oldest to youngest: Durango, Spring Creek, and Animas City (fig. 18). Table 2 provides a correlation of terraces in the monument with moraines in Durango, outwash material downvalley of these moraines, and glacial stages.

One or more pre-Bull Lake glacial advances are the first for which moraines have been preserved in the Animas River valley (Richmond 1965). These moraines are composed of the Durango Till of Atwood and Mather (1932). Beyond these moraines, glacial meltwater deposited "Durango outwash," which forms the highest terrace at Aztec Ruins—**Q4d** of Ward (1990) and **Qt5a** of Gillam (1998a). The Animas River cut downward into this material to about 43–49 m (140–160 ft) above the present channel. Pre-Bull Lake outwash deposits can be dated by their relationship to outcrops of the Lava Creek B ash (see "Eolian Features and Processes" section); this approach suggests an age range of approximately 340,000 to 250,000 years ago (Gillam 1998b).

The Bull Lake glaciation may have been the next to leave many moraines in the Animas River valley. Glacial ice of this age is thought to have deposited Spring Creek moraines; meltwater deposited Spring Creek outwash. At Aztec Ruins, the Bull Lake glaciation is represented by terrace 6a (**Qt6a**) of Gillam (1998a) or terrace gravel, unit 5 (**Q5b**) of Ward (1990). Approximately, 160,000–140,000 years ago, the river cut into Spring Creek outwash to about 30 m (100 ft) above the level of today's floodplain, creating this terrace.

Dates from some recent investigations (Applegate 2005; Anderson and Kenney 2015; Passehl and Kenney 2015) suggest that some moraines previously identified as

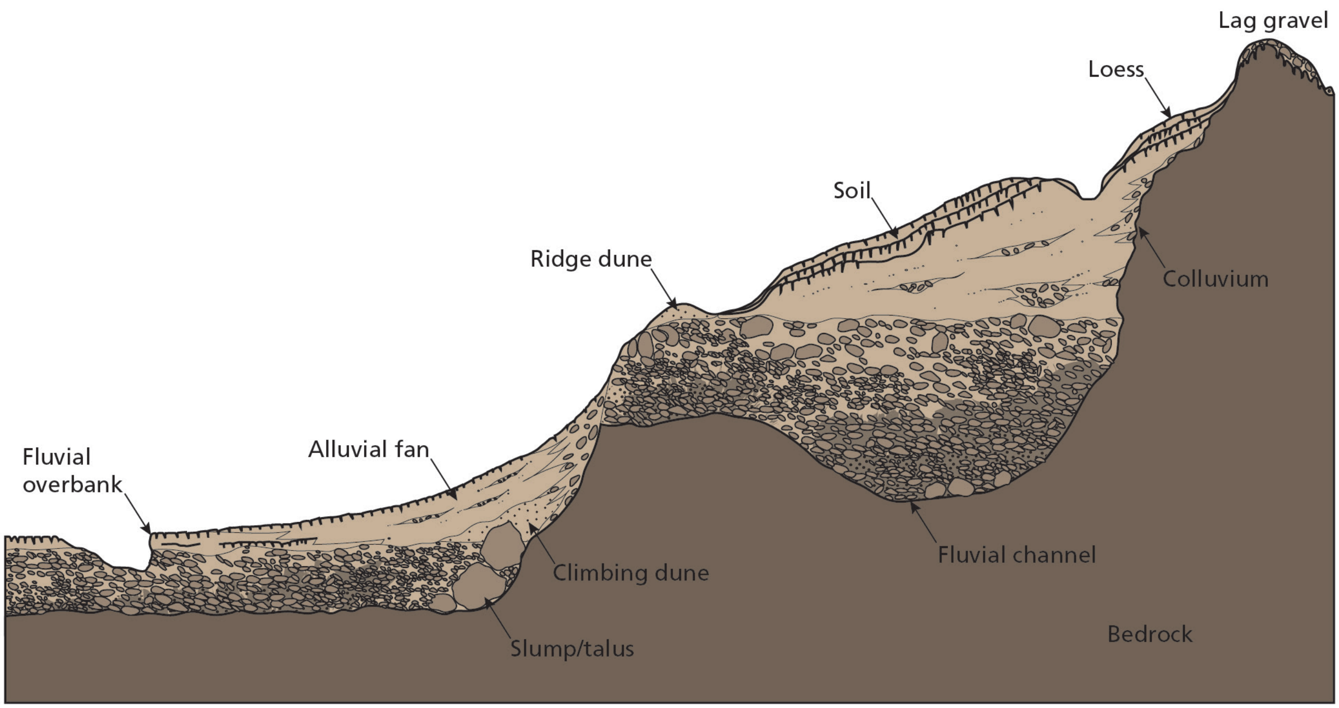

Figure 19. Schematic cross section of terraces. After a terrace is cut into outwash gravel, side streams deposit alluvial fans onto terrace benches, and wind deposits sand and silt in dunes and sheets of loess. Soil forms during periods of stability. Gravity causes colluvium to form on terrace risers and other steep slopes. Remnants of gravel, referred to as "lag," serve as evidence of past floods of glacial meltwater. To provide a sense of scale on the landscape, the alluvial fan mapped by Gillam (1998a) in the vicinity of the monument is about 1 km (0.6 mi) long. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Gillam (1998b, figure 5.7).

Durango or Spring Creek may actually correlate with an intermediate glaciation that has not been widely identified in the Rocky Mountains. This glaciation is known as early Wisconsinan in the Midwest (Mary Gillam, independent consultant and researcher, written communication, 5 January 2016).

During the next glacial period, referred to as the Pinedale glaciation (table 2), Animas City moraines and outwash were deposited. According to Gillam (1998b), the Animas River incised into Animas City outwash creating terrace 7, undivided (**Qt7u**) about 25,000 years ago. Recent findings by Guido et al. (2007) suggest that parts of this terrace could be as young as 19,000 years old. This terrace level is less than 3 m (10 ft) above the present floodplain at the monument, but elsewhere is higher, approximately 15 m (49 ft) above.

After the Animas River cut down through each outwash floodplain, creating a terrace, streams draining the valley sides deposited alluvial fans across the terrace tread, and colluvium formed on terrace risers and other steep slopes (fig. 19). With time and more valley incision, side streams began eroding the fan alluvium and eventually removed most of it from above the more resistant outwash gravel; side streams also removed some of the gravel, reducing the originally continuous terrace to discontinuous remnants (Mary Gillam, independent consultant and researcher, written communication, 5 January 2016).

All the terraces at the monument are overlain by varying amounts of modern sediment. Throughout the Animas River valley, such sediments may originate as fan alluvium, dune sand, loess, or colluvium. Thicknesses of overlying sediment are usually near zero at the river-facing edge of a terrace but increase away from the river, commonly exceeding 10 m (30 ft) and rarely reaching 45 m (150 ft) (Gillam 1998b).

Eolian Record

In the Animas River valley, buried soils within thick loess deposits, locally more than 6 m (20 ft) thick, indicate that several episodes of loess accumulation have occurred (Gillam 1998b; Scott and Moore 2007). Eolian deposition becomes significant when parts of a landscape become relatively stable, generally after fan deposition slows and in areas away from side streams. Maximum transport of windblown material coincides with availability of fine sand and silt in fluvial systems (Pazzaglia and Hawley 2004). Studies from several continents, including North America, show that most loess was deposited during glacial periods whereas soil formation occurred during interglacial periods. Glaciers are efficient producers of silt that makes up loess deposits; paleosols (old, buried soils) represent periods of landscape stability when loess deposition ceased or at least slowed significantly (Muhs et al. 2014). Loess is still accumulating in the Animas River valley today.

Ongoing Incision

The final retreat of the Animas Glacier began about 19,000 years ago and finished by about 12,000 years ago (Guido et al. 2007). By contrast, incision by the Animas River has continued to the present day. Terrace ages and early river diversions suggest that the overall incision rate (averaged across short-term cycles that produced terraces) has accelerated from late Pliocene time (fig. 4) toward the present (Gillam 1998b).

Geologic Data

This chapter summarizes the geologic data available for Aztec Ruins National Monument. Two GRI posters (in pocket) display the GIS data draped over imagery of the national monument and surrounding area. Two Map Unit Properties Tables (in pocket) summarize this report's content for each geologic map unit. Complete GIS data are available at the GRI publications website: http://go.nps.gov/gripubs.

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, these maps portray the spatial distribution and temporal relationships of rocks and unconsolidated deposits. The American Geosciences Institute website, http://www.americangeosciences.org/environment/publications/mapping, provides more information about geologic maps and their uses.

Source Maps

The GRI team digitizes paper geologic maps and converts digital geologic data to conform to the GRI GIS data model. The GRI map product includes essential elements of the source maps such as map unit descriptions, a correlation chart of units, a map legend, map notes, cross sections, figures, and references.

The GRI team used the following source maps to produce the GRI GIS data for Aztec Ruins National Monument. These sources also provided information for this report. Data from Brown and Stone (1979) covers the western side of the monument. Data from Ward (1990) covers the eastern side of the monument. Data from Gillam (1998a) covers the entire monument.

Brown, D. R., and W. J. Stone. 1979. Geologic map of Aztec quadrangle, San Juan County, New Mexico (scale 1:62,500). Hydrogeologic Sheet 1 (HS-1) in Hydrogeology of Aztec quadrangle, San Juan County, New Mexico. New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico.

Ward, A. W. 1990. Geologic map emphasizing the surficial deposits of the Farmington 30' × 60' quadrangle, New Mexico and Colorado (scale 1:100,000). Miscellaneous Investigations Series Map I-1978. US Geological Survey, Washington, DC. http://ngmdb.usgs.gov/Prodesc/proddesc_10056.htm.

Gillam, M. L. 1998a. Geomorphic map of the lower Animas River valley, San Juan County, New Mexico (scale 1:50,000). Plate 1b in Late Cenozoic geology and soils of the lower Animas River valley, Colorado and New Mexico. Dissertation. University of Colorado, Department of Geological Sciences, Boulder, Colorado.

Varying objectives for each mapping project led to mismatched contacts along the boundary between the first two maps, which passes through the middle of the monument, as well as to differing distributions and terms for unconsolidated Quaternary deposits on all three maps. In addition, contacts between units on the first two maps are approximate and locally inaccurate. Although these maps provide a geologic overview, they are not detailed enough to fully support management decisions involving geologic issues (Mary Gillam, independent consultant and researcher, written communication, 5 January 2016).

In addition, the following maps by Dames & Moore (1979a, 1979b) provided coal-bed thicknesses of the Fruitland Formation in the vicinity of the monument:

Dames & Moore. 1979a. Coal resource occurrence and coal development potential maps of the Flora Vista quadrangle, San Juan County, New Mexico (scale 1:24,000). Open-File Report OF-79-1116. US Geological Survey, Washington, DC. http://pubs.er.usgs.gov/publication/ofr791116.

Dames & Moore. 1979b. Coal resource occurrence and coal development potential maps of the southwest quarter of the Aztec 15' quadrangle, San Juan County, New Mexico (scale 1:24,000). Open-File Report OF-79-1117. US Geological Survey, Washington, DC. http://pubs.er.usgs.gov/publication/ofr791117.

GRI 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 at http://go.nps.gov/gridatamodel. 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 the monument using data model version 2.1. The GRI Geologic Maps website, http://go.nps.gov/geomaps, provides more information about GRI map products.

GRI GIS data are publically available through the NPS Integrated Resource Management Applications (IRMA) portal (https://irma.nps.gov/App/Portal/Home). Enter "GRI" as the search text and select a park from the unit list.

The following components are part of the GRI GIS data:

- A GIS readme file (azru_gis_readme.pdf) that describes the GRI data formats, naming conventions, extraction instructions, use constraints, and contact information;
- Data in ESRI geodatabase GIS format;
- Layer files with feature symbology (see tables 3, 4, and 5);
- Federal Geographic Data Committee (FGDC)–compliant metadata;
- An ancillary map information document (azru_geology.pdf) that contains information captured from source maps such as map unit descriptions, geologic unit correlation tables, legends, cross sections, and figures; and
- An ESRI map document (.mxd) that displays the digital geologic data for each of the three primary source maps (tables 3, 4, and 5).

The GRI GIS data for the monument contain three data files that provide coverage of the monument and surrounding area. These data files are identified by the following prefixes: **azte** (GRI GIS data of the Aztec quadrangle from Brown and Stone 1979; see table 3), **flvi** (GRI GIS data of the Flora Vista quadrangle from Ward 1990; see table 4), and **azrt** (GRI GIS data of Aztec Ruins National Monument and vicinity from Gillam 1998a; see table 5).

GRI Posters

Two posters of the GRI GIS data draped over a shaded relief image of the monument and surrounding area are included with this report. One of the GRI posters highlights the bedrock and surficial geology and is referred to as the "bedrock and surficial map"; the other highlights terraces and the floodplain and is referred to as the "geomorphic map." Not all GIS feature classes may be included on the GRI posters (see tables 3, 4, and 5). Selected geographic information and park features have been added to the GRI posters. Digital elevation data and added geographic information are not included in the GRI GIS data, but are available online from a variety of sources. Contact the GRI team for assistance locating these data.

Map Unit Properties Tables

Two Map Unit Properties Tables, one for each GRI poster, list the geologic time division, symbol, and a simplified description for each of the geologic map units within Aztec Ruins National Monument. Following the structure of the report, the tables summarize the geologic features and processes, resource management issues, and geologic history associated with each map unit.

Use Constraints

Graphic and written information provided in this report is not a substitute for site-specific investigations. Ground-disturbing activities should neither be permitted nor denied based upon the information provided here. Please contact the GRI team with any questions.

Minor inaccuracies may exist in the GRI GIS data and on the GRI posters with respect to the locations of geologic features relative to other geologic or geographic features. Based on the source map scale and US National Map Accuracy Standards, geologic features represented in the GRI GIS data are expected to be horizontally within the following distances of their true locations: At scale 1:24,000 (Dames & Moore 1979a, 1979b), the horizontal distance is 12 m (40 ft). At scale 1:50,000 (Gillam 1998a), the horizontal distance is 25 m (82 ft). At scale 1:62,500 (Brown and Stone 1979), the horizontal distance is 32 m (104 ft). At scale 1:100,000 (Ward 1990), the horizontal distance is 51 m (167 ft).

Table 3. GRI GIS data for Aztec Ruins National Monument (Aztec quadrangle; azte_geology.mxd; Brown and Stone 1979)

Data Layer	On GRI Poster?
Geologic Measurement Thickness (coal bed thicknesses, Fruitland Formation)	Yes
Geologic Contacts	Yes
Geologic Units	Yes

Table 4. GRI GIS data for Aztec Ruins National Monument (Flora Vista quadrangle; flvi_geology.mxd; Ward 1990)

Data Layer	On GRI Poster?
Geologic Observation Localities (Lava Creek B ash)	No
Geologic Sample Localities (radiometric ages of Qnt deposits)	No
Geologic Contacts	Yes
Geologic Units	Yes

Table 5. GRI GIS data for Aztec Ruins National Monument (terrace map; azrt_geology.mxd; Gillam 1998a)

Data Layer	On GRI Poster?
Surficial Contacts	Yes
Surficial Units	Yes

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Additional References

This chapter lists additional references, resources, and websites that may be of use to resource managers. Web addresses are valid as of June 2016. Refer to Appendix B for laws, regulations, and policies that apply to NPS geologic resources.

Geology of National Park Service Areas

- NPS Geologic Resources Division (Lakewood, Colorado) *Energy and Minerals; Active Processes and Hazards; Geologic Heritage*: http://go.nps.gov/geology
- NPS Geologic Resources Division Education Website: http://go.nps.gov/geoeducation
- NPS Geologic Resources Inventory: http://go.nps.gov/gri
- NPS Geoscientist-In-the-Parks (GIP) internship and guest scientist program: http://go.nps.gov/gip
- NPS Views program (geology-themed modules are available for Geologic Time, Paleontology, Glaciers, Caves and Karst, Coastal Geology, Volcanoes, and a variety of geologic parks): http://go.nps.gov/views
- USGS Geology of National Parks (including 3D imagery): http://3dparks.wr.usgs.gov/

NPS Resource Management Guidance and Documents

- Management Policies 2006 (Chapter 4: Natural resource management): http://www.nps.gov/policy/mp/policies.html
- 1998 National parks omnibus management act: http://www.gpo.gov/fdsys/pkg/PLAW-105publ391/pdf/PLAW-105publ391.pdf
- 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): http://go.nps.gov/geomonitoring
- NPS Technical Information Center (TIC) (Denver, Colorado; repository for technical documents): http://www.nps.gov/dsc/technicalinfocenter.htm

Climate Change Resources

- NPS Climate Change Response Program Resources: http://www.nps.gov/subjects/climatechange/resources.htm
- US Global Change Research Program: http://globalchange.gov/home
- Intergovernmental Panel on Climate Change: http://www.ipcc.ch/

Geological Surveys and Other Organizations

- New Mexico Bureau of Geology and Mineral Resources: http://geoinfo.nmt.edu/
- US Geological Survey: http://www.usgs.gov/
- Geological Society of America: http://www.geosociety.org/
- American Geophysical Union: http://sites.agu.org/
- American Geosciences Institute: http://www.americangeosciences.org/
- Association of American State Geologists: http://www.stategeologists.org/
- International Commission on Stratigraphy (ICS): http://www.stratigraphy.org/
- ICS chart/time scale: http://www.stratigraphy.org/index.php/ics-chart-timescale
- United Nations Educational, Scientific and Cultural Organization (UNESCO) world heritage sites: http://whc.unesco.org/en/list/

US Geological Survey Reference Tools

- National geologic map database (NGMDB): http://ngmdb.usgs.gov/
- Geologic names lexicon (GEOLEX; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/geolex_home.html
- Geographic names information system (GNIS; official listing of place names and geographic features): http://gnis.usgs.gov/
- GeoPDFs (download searchable PDFs of any topographic map in the United States): http://store.usgs.gov (click on "Map Locator")
- Publications warehouse (many publications available online): http://pubs.er.usgs.gov
- Tapestry of time and terrain (descriptions of physiographic provinces): http://pubs.usgs.gov/imap/i2720/

Appendix A: Scoping Participants

The following people attended the GRI scoping meeting for Aztec Ruins National Monument, held on 13 February 2007, or the follow-up report writing conference call, held on 28 May 2015. Discussions during these meetings supplied a foundation for this GRI report. The scoping summary document is available on the GRI publications website, http://go.nps.gov/gripubs.

2007 Scoping Meeting Participants

Name	Affiliation	Position
Gary Brown	Aztec Ruins National Monument	Chief of Cultural Resources
Dennis Carruth	Aztec Ruins National Monument	Superintendent
Tim Connors	NPS Geologic Resources Division	Geologist
Rich Friedman	City of Farmington	GIS Supervisor
Mary Gillam	Independent	Consultant and Researcher/Geologist
George Herring	Aztec Ruins National Monument	Interpretive Supervisor
Joe Hewitt	Bureau of Land Management	Geologist
Katie KellerLynn	Colorado State University	Research Associate/Geologist
Dave Love	New Mexico Bureau of Geology and Mineral Resources	Geologist
Terry Nichols	Aztec Ruins National Monument	Park Ranger
Lisa Norby	NPS Geologic Resources Division	Geologist
Phil Stoffer	US Geological Survey	Geologist
Heather Stanton	Colorado State University	Research Associate/Geologist

2015 Conference Call Participants

Name	Affiliation	Position
Aron Adams	Aztec Ruins National Monument	Chief of Cultural Resources
Mary Gillam	Independent	Consultant and Researcher/Geologist
Katie KellerLynn	Colorado State University	Research Associate/Geologist
Jason Kenworthy	NPS Geologic Resources Division	Geologist, GRI reports coordinator
Larry Turk	Aztec Ruins National Monument and Chaco Culture National Historical Park	Superintendent
Jim Von Haden	Aztec Ruins National Monument and Chaco Culture National Historical Park	Chief of Natural Resources

Appendix B: Geologic Resource Laws, Regulations, and Policies

The NPS Geologic Resources Division developed this table to summarize laws, regulations, and policies that specifically apply to National Park Service minerals and geologic resources. The table does not include laws of general application (e.g., Endangered Species Act, Clean Water Act, Wilderness Act, National Environmental Policy Act, or National Historic Preservation Act). The table does include the NPS Organic Act when it serves as the main authority for protection of a particular resource or when other, more specific laws are not available. Information is current as of June 2016. Contact the NPS Geologic Resources Division for detailed guidance.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Paleontology	**National Parks Omnibus Management Act of 1998, 16 USC § 5937** protects the confidentiality of the nature and specific location of paleontological resources and objects. **Paleontological Resources Preservation Act of 2009, 16 USC § 470aaa et seq.** provides for the management and protection of paleontological resources on federal lands.	**36 CFR § 2.1(a)(1)(iii)** prohibits destroying, injuring, defacing, removing, digging or disturbing paleontological specimens or parts thereof. **Prohibition in 36 CFR § 13.35** applies even in Alaska parks, where the surface collection of other geologic resources is permitted. Regulations in association with 2009 PRPA are being finalized (August 2015).	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.1** emphasizes Inventory and Monitoring, encourages scientific research, directs parks to maintain confidentiality of paleontological information, and allows parks to buy fossils only in accordance with certain criteria.
Rocks and Minerals	**NPS Organic Act, 16 USC § 1 et seq.** directs the NPS to conserve all resources in parks (including rock and mineral resources), unless otherwise authorized by law.	**36 CFR § 2.1** prohibits possessing, destroying, disturbing mineral resources… in park units. **Exception: 36 CFR § 13.35** allows some surface collection of rocks and minerals in some Alaska parks (not Klondike Gold Rush, Sitka, Denali, Glacier Bay, or Katmai) by non-disturbing methods (e.g., no pickaxes), which can be stopped by superintendent if collection causes significant adverse effects on park resources and visitor enjoyment.	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity.
Park Use of Sand and Gravel	**Materials Act of 1947, 30 USC § 601** does not authorize the NPS to dispose of mineral materials outside of park units.	None applicable.	**Section 9.1.3.3** clarifies that only the NPS or its agent can extract park-owned common variety minerals (e.g., sand and gravel), and: -only for park administrative uses; -after compliance with NEPA and other federal, state, and local laws, and a finding of non-impairment; -after finding the use is park's most reasonable alternative based on environment and economics; -parks should use existing pits and create new pits only in accordance with park-wide borrow management plan; -spoil areas must comply with Part 6 standards; and -NPS must evaluate use of external quarries. Any deviation from this policy requires a written waiver from the Secretary, Assistant Secretary, or Director.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Upland and Fluvial Processes	**Rivers and Harbors Appropriation Act of 1899, 33 USC § 403** prohibits the construction of any obstruction on the waters of the United States not authorized by congress or approved by the USACE. **Clean Water Act 33 USC § 1342** requires a permit from the USACE prior to any discharge of dredged or fill material into navigable waters (waters of the US [including streams]). **Executive Order 11988** requires federal agencies to avoid adverse impacts to floodplains. (see also **D.O. 77-2**) **Executive Order 11990** requires plans for potentially affected wetlands (including riparian wetlands). (see also D.O. 77-1)	None applicable.	**Section 4.1** requires NPS to manage natural resources to preserve fundamental physical and biological processes, as well as individual species, features, and plant and animal communities; maintain all components and processes of naturally evolving park ecosystems. **Section 4.1.5** directs the NPS to re-establish natural functions and processes in human-disturbed components of natural systems in parks, unless directed otherwise by Congress. **Section 4.4.2.4** directs the NPS to allow natural recovery of landscapes disturbed by natural phenomena, unless manipulation of the landscape is necessary to protect park development or human safety. **Section 4.6.4** directs the NPS to (1) manage for the preservation of floodplain values; [and] (2) minimize potentially hazardous conditions associated with flooding. **Section 4.6.6** directs the NPS to manage watersheds as complete hydrologic systems and minimize human-caused disturbance to the natural upland processes that deliver water, sediment, and woody debris to streams. **Section 4.8.1** directs the NPS to allow natural geologic processes to proceed unimpeded. Geologic processes…include… erosion and sedimentation…processes. **Section 4.8.2** directs the NPS to protect geologic features from the unacceptable impacts of human activity while allowing natural processes to continue.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Mining Claims	**Mining in the Parks Act of 1976, 16 USC § 1901 et seq**. authorizes NPS to regulate all activities resulting from exercise of mineral rights, on patented and unpatented mining claims in all areas of the System, in order to preserve and manage those areas. **General Mining Law of 1872, 30 USC § 21 et seq.** allows US citizens to locate mining claims on Federal lands. Imposes administrative and economic validity requirements for "unpatented" claims (the right to extract Federally-owned locatable minerals). Imposes additional requirements for the processing of "patenting" claims (claimant owns surface and subsurface). Use of patented mining claims may be limited in Wild and Scenic Rivers and OLYM, GLBA, CORO, ORPI, and DEVA. **Surface Uses Resources Act of 1955, 30 USC § 612** restricts surface use of unpatented mining claims to mineral activities.	**36 CFR § 5.14** prohibits prospecting, mining, and the location of mining claims under the general mining laws in park areas except as authorized by law. **36 CFR Part 6** regulates solid waste disposal sites in park units. **36 CFR Part 9, Subpart A** requires the owners/operators of mining claims to demonstrate bona fide title to mining claim; submit a plan of operations to NPS describing where, when, and how; prepare/submit a reclamation plan; and submit a bond to cover reclamation and potential liability.	**Section 6.4.9** requires NPS to seek to remove or extinguish valid mining claims in wilderness through authorized processes, including purchasing valid rights. Where rights are left outstanding, NPS policy is to manage mineral-related activities in NPS wilderness in accordance with the regulations at 36 CFR Parts 6 and 9A. **Section 8.7.1** prohibits location of new mining claims in parks; requires validity examination prior to operations on unpatented claims; and confines operations to claim boundaries.
Nonfederal Oil and Gas	**NPS Organic Act, 16 USC § 1 et seq.** authorizes the NPS to promulgate regulations to protect park resources and values (from, for example, the exercise of mining and mineral rights).	**36 CFR Part 6** regulates solid waste disposal sites in park units. **36 CFR Part 9, Subpart B** requires the owners/operators of nonfederally owned oil and gas rights to -demonstrate bona fide title to mineral rights; -submit a plan of operations to NPS describing where, when, how they intend to conduct operations; -prepare/submit a reclamation plan; and -submit a bond to cover reclamation and potential liability.	**Section 8.7.3** requires operators to comply with 9B regulations.
Nonfederal minerals other than oil and gas	**NPS Organic Act, 16 USC §§ 1 and 3** **Surface Mining Control and Reclamation Act of 1977, 30 USC § 1201 et. seq.** prohibits surface coal mining operations on any lands within the boundaries of a NPS unit, subject to valid existing rights.	**NPS regulations at 36 CFR Parts 1, 5, and 6** require the owners/operators of other types of mineral rights to obtain a special use permit from the NPS as a § 5.3 business operation, and § 5.7 – Construction of buildings or other facilities, and to comply with the solid waste regulations at Part 6. **SMCRA Regulations at 30 CFR Chapter VII** govern surface mining operations on Federal lands and Indian lands by requiring permits, bonding, insurance, reclamation, and employee protection. Part 7 of the regulations states that National Park System lands are unsuitable for surface mining.	**Section 8.7.3** states that operators exercising rights in a park unit must comply with 36 CFR Parts 1 and 5.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Federal Mineral Leasing (Oil and Gas, Salable Minerals, and Non-locatable Minerals)	**The Mineral Leasing Act, 30 USC § 181 et seq., and the Mineral Leasing Act for Acquired Lands, 30 USC § 351 et seq**. do not authorize the BLM to lease federally owned minerals in NPS units. Exceptions: Native American Lands Within NPS Boundaries Under the **Indian Allottee Leasing Act of 1909, (25 USC § 396)**, and the **Indian Leasing Act of 1938 (25 USC §§ 396a, 398 and 399)** and **Indian Mineral Development Act of 1982 (25 USC §§ 2101-2108)**, all minerals are subject to lease and apply to Native American trust lands within NPS units. **Federal Coal Leasing Amendments Act of 1975, 30 USC § 201** does not authorize the BLM to issue leases for coal mining on any area of the national park system.	**36 CFR § 5.14** states prospecting, mining, and…leasing under the mineral leasing laws [is] prohibited in park areas except as authorized by law. BLM regulations at 4**3 CFR Parts 3100, 3400, and 3500** govern Federal mineral leasing. Regulations re: Native American Lands within NPS Units: **25 CFR Part 211** governs leasing of tribal lands for mineral development. **25 CFR Part 212** governs leasing of allotted lands for mineral development. **25 CFR Part 216** governs surface exploration, mining, and reclamation of lands during mineral development. **25 CFR Part 224** governs tribal energy resource agreements. **25 CFR Part 225** governs mineral agreements for the development of Indian-owned minerals entered into pursuant to the **Indian Mineral Development Act of 1982, Pub. L. No. 97-382, 96 Stat. 1938 (codified at 25 USC §§ 2101-2108)**. **30 CFR §§ 1202.100-1202.101** governs royalties on oil produced from Indian leases. **30 CFR §§ 1202.550-1202.558** governs royalties on gas production from Indian leases. **30 CFR §§ 1206.50-1206.62 and §§ 1206.170-1206.176** governs product valuation for mineral resources produced from Indian oil and gas leases. **30 CFR § 1206.450** governs the valuation coal from Indian Tribal and Allotted leases. **43 CFR Part 3160** governs onshore oil and gas operations, which are overseen by the BLM.	**Section 8.7.2** states that all NPS units are closed to new federal mineral leasing except Glen Canyon, Lake Mead and Whiskeytown-Shasta-Trinity NRAs.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Soils	**Soil and Water Resources Conservation Act, 16 USC §§ 2011–2009** provides for the collection and analysis of soil and related resource data and the appraisal of the status, condition, and trends for these resources. **Farmland Protection Policy Act, 7 USC § 4201 et. seq**. requires NPS to identify and take into account the adverse effects of Federal programs on the preservation of farmland; consider alternative actions, and assure that such Federal programs are compatible with State, unit of local government, and private programs and policies to protect farmland. NPS actions are subject to the FPPA if they may irreversibly convert farmland (directly or indirectly) to nonagricultural use and are completed by a Federal agency or with assistance from a Federal agency. Applicable projects require coordination with the Department of Agriculture's Natural Resources Conservation Service (NRCS).	**7 CFR Parts 610 and 611** are the US Department of Agriculture regulations for the Natural Resources Conservation Service. Part 610 governs the NRCS technical assistance program, soil erosion predictions, and the conservation of private grazing land. Part 611 governs soil surveys and cartographic operations. The NRCS works with the NPS through cooperative arrangements.	**Section 4.8.2.4** requires NPS to -prevent unnatural erosion, removal, and contamination; -conduct soil surveys; -minimize unavoidable excavation; and -develop/follow written prescriptions (instructions).

NPS 319/133454, July 2016

National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science
1201 Oak Ridge Drive, Suite 150
Fort Collins, Colorado 80525

www.nature.nps.gov

Geologic Resources Inventory

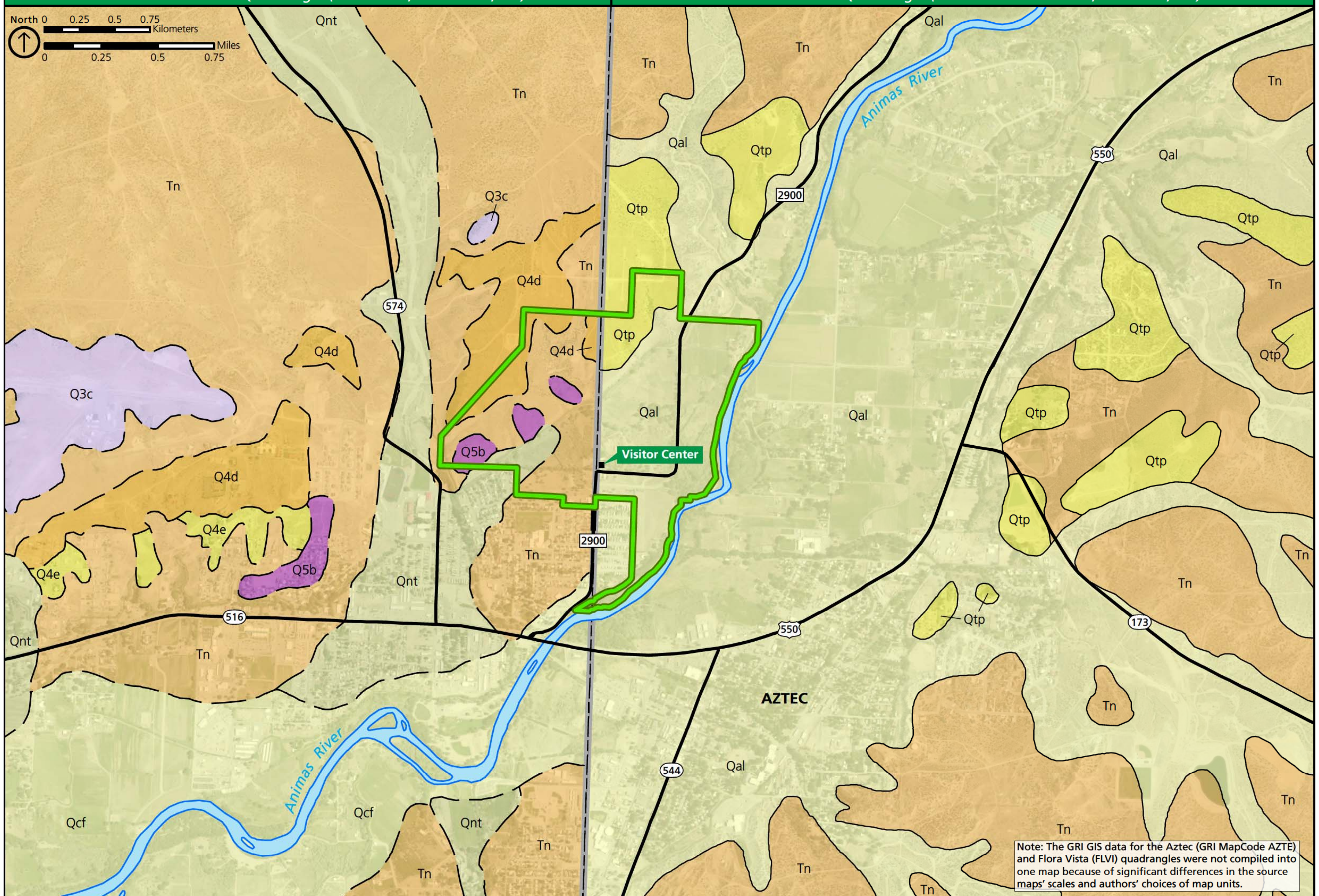
National Park Service
U.S. Department of the Interior

Geology of Aztec Ruins National Monument, New Mexico

Bedrock and Surficial Map

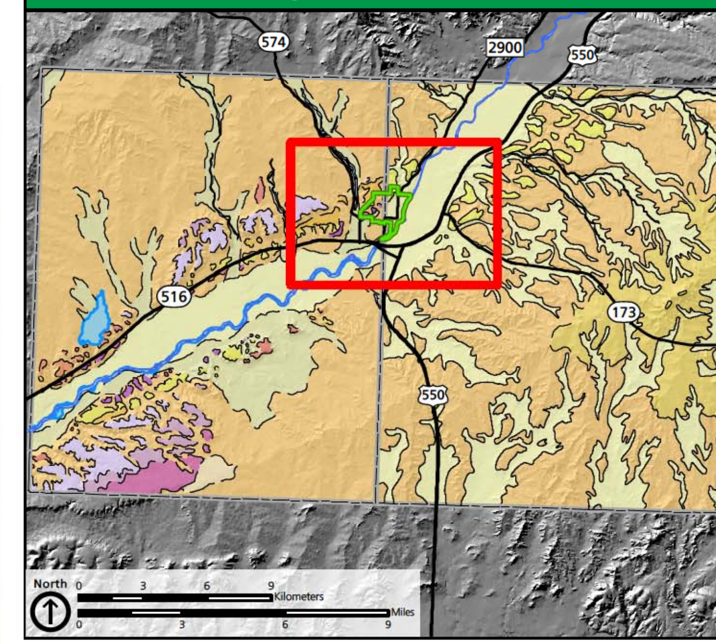
Portion of Flora Vista Quadrangle (Ward 1990; scale 1:100,000)

Portion of Aztec Quadrangle (Brown and Stone 1979; scale 1:62,500)



Note: The GRI GIS data for the Aztec (GRI MapCode AZTE) and Flora Vista (FLVI) quadrangles were not compiled into one map because of significant differences in the source maps' scales and authors' choices of map units.

Full Extent of Digital Data, Area of Detail in Red



NPS Boundary

Infrastructure
- Structures
- Roads

Geologic Contacts
- known or certain
- approximate
- quadrangle boundary

Geologic Units
- Qal Alluvium
- Qcf Channel and floodplain alluvium
- Qnt Naha and Tsegi Alluviums, undifferentiated
- Qes Eolian sand
- Qtp Terrace and pediment deposits
- Q5b Terrace gravel, unit 5, lowest terrace
- Q4e Terrace gravel, unit 4, youngest
- Q4d Terrace gravel, unit 4, intermediate
- Q4c Terrace gravel, unit 4, intermediate
- Q4a Terrace gravel, unit 4, oldest
- Q3c Terrace gravel, unit 3, youngest
- Q3b Terrace gravel, unit 3, intermediate
- Q3a Terrace gravel, unit 3, oldest
- Tsj San Jose Formation
- Tn Nacimiento Formation
- Water

This map displays geologic map data compiled by the National Park Service Geologic Resources Inventory. It is not a substitute for site-specific investigations.

Source Maps
Brown and Stone (1979): New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico.
Ward (1990): US Geological Survey, Washington, DC.
See "Geologic Data" chapter of report for full citations.

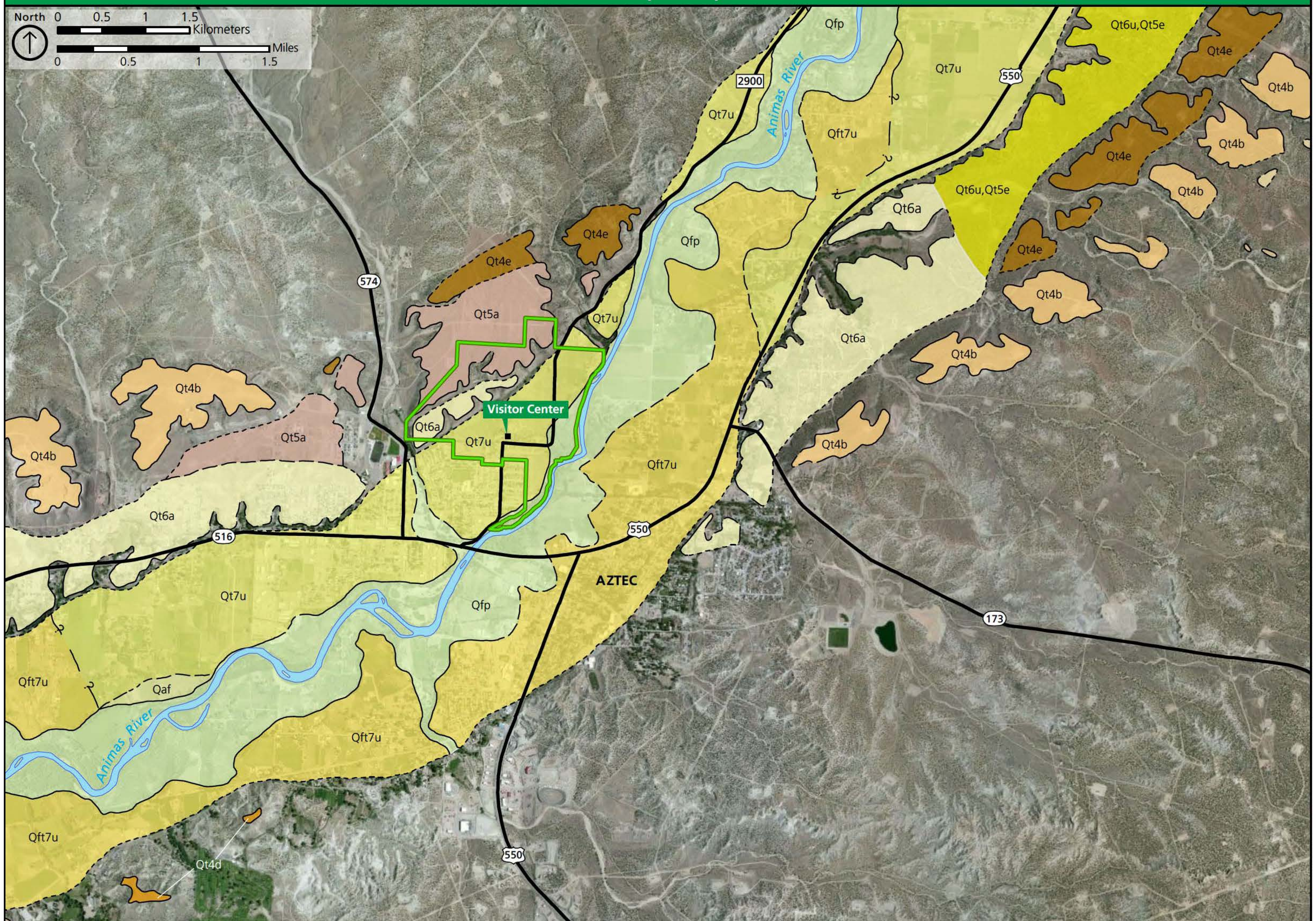
Source Scales 1:62,500 and 1:100,000
According to US National Map accuracy standards, features are expected to be within the following distances of their true locations:
32 m (104 ft) for scale 1:62,500
51 m (167 ft) for scale 1:100,000.

Poster Layout
Georgia Hybels
(Colorado State University)
Poster Date
May 2016
GRI Data Date
March 2015
Source Map Dates
1979 and 1990

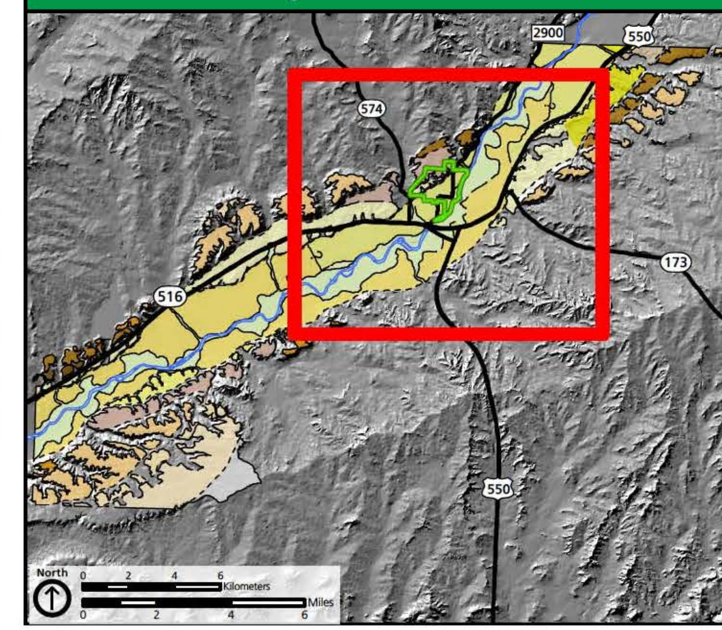
All Geologic Resources Inventory geologic map data and publications are available at http://go.nps.gov/gripubs.

Geology of Aztec Ruins National Monument, New Mexico

Geomorphic Map



Full Extent of Digital Data, Area of Detail in Red



NPS Boundary

Infrastructure
- Structures
- Roads

Surficial Contacts
- known or certain
- approximate
- concealed
- approximate and queried
- concealed and queried
- map boundary

Surficial Units
- Qfp Modern floodplain

Animas City Moraines
- Qft7u Terrace 7 and alluvial fans, undivided
- Qt7u Terrace 7 undivided

Spring Creek Moraines
- Qt6u Terrace 6 undivided
- Qt6u, Qt5e Terrace 6 and Terrace 5e, undivided
- Qt6b Terrace 6b
- Qt6a Terrace 6a

Durango Moraines
- Qt5eu Terrace 5e
- Qt5a Terrace 5a

Terraces that project above Durango Moraines
- Qt4ex Terrace 4ex
- Qt4e Terrace 4e
- Qt4d Terrace 4d
- Qt4c Terrace 4c
- Qt4b Terrace 4b

Other Surficial Units
- Qaf Alluvial fans
- Qt3a Terrace 3a
- Qt3b Terrace 3b
- Qp Pediment
- QTtaf Stream terrace or incised alluvial fan
- Tt1u Terrace 1 undivided
- Water

This map displays geologic map data compiled by the National Park Service Geologic Resources Inventory. It is not a substitute for site-specific investigations.

Source Map
Gillam, M. L. 1998a. Geomorphic map of the lower Animas River valley, San Juan County, New Mexico (scale 1:50,000). Plate 1b in Late Cenozoic geology and soils of the lower Animas River valley, Colorado and New Mexico. Dissertation. University of Colorado, Department of Geological Sciences.

Source Scale 1:50,000
According to US National Map accuracy standards, features are expected to be within 25 m (82 ft) of their true location.

Poster Layout
Georgia Hybels
(Colorado State University)
Poster Date
May 2016
GRI Data Date
March 2015
Source Map Date
1998

All Geologic Resources Inventory geologic map data and publications are available at http://go.nps.gov/gripubs.

Bedrock and Surficial Map Unit Properties Table: Aztec Ruins National Monument

Table shows units mapped by Brown and Stone (1979) on the eastern side of monument and Ward (1990) on the western side of monument. Colors in Map Unit column correspond to the bedrock and surficial map poster (in pocket). Bold text refers to sections in the GRI report.

Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
QUATERNARY (Holocene)	Naha and Tsegi Alluviums, undifferentiated (Qnt) Ward (1990)	Well-stratified, yellowish gray and grayish brown silt and sand. Mapped where Naha and Tsegi Alluviums are indistinguishable, but probably consists of mostly Tsegi Alluvium. In places, **Qnt** buries outwash deposited by the Animas River.	**Alluvium**—**Qnt** is alluvium of Hack (1941) with the type area in Arizona. Correlation to New Mexico is uncertain. Mapped as a "finger" of Estes Arroyo in the monument.	**Abandoned Mineral Lands**—abandoned gas well occurs within the expanded boundaries of the monument. Associated map unit unknown.	**Glacial Record**—correlates to terrace **Qt7u** of Gillam (1998a), approximately 25,000–19,000 years old. **Ongoing Incision**—dissected by modern arroyos.
QUATERNARY (Holocene and Late Pleistocene)	Alluvium (Qal) Brown and Stone (1979)	Valley-fill deposits consisting of gravel, sand, silt, and clay in the modern floodplain, lowest outwash terraces, and overlying alluvial fans.	**Alluvium**—**Qal** covers most of the eastern half of the monument.	**Localized and Regional Subsidence**—small depressions have developed in the vicinity of East Ruin, which is situated on **Qal** of Brown and Stone (1979). **Piping**—minor geohazard at the monument. Soil pipes have developed in an eroding bank of the Fallon property along the Animas River. Could affect the stability of archeological sites via subsidence. Pipes may have cultural importance as the beginning of an excavated kiva. **Bank Erosion and Landscape Restoration**—the NPS goal is to restore natural function and appearance while protecting cultural resources along the banks of the Animas River. **Recreation and Land Use in the Animas River Corridor**—no park infrastructure was built on the floodplain, so flooding is not a significant issue. **Abandoned Mineral Lands**—abandoned gas well occurs within the expanded boundaries of the monument. Map unit unknown.	**Animas River on the Landscape**—**Qal** records aggradation by the Animas River or its tributaries. **Ongoing Incision**—**Qal** represents continuing deposition along rivers and streams.
QUATERNARY (Pleistocene)	Terrace and pediment deposits (Qtp) Brown and Stone (1979)	Veneers of gravel and sand along valley sides and on mesa tops, mainly in terraces and alluvial fans.	**Terraces**—**Qtp** is described as including both terrace and pediment alluvium. However pediments (gravel-covered erosional slopes) are absent or rare in the map area (Mary Gillam, independent consultant and researcher, written communication, 5 January 2016).	**Oil and Gas Development and Production**—well operations (e.g., Bobbie Herrera #1) account for localized and relatively minor impacts to natural resources, including denuded vegetation and eroded and compacted soil on terrace surfaces. **Abandoned Mineral Lands**—abandoned gas well occurs within the expanded boundaries of the monument. Associated map unit unknown. **Paleontological Resource Inventory, Monitoring, and Protection**—terraces contain reworked Paleozoic invertebrate fossils in limestone cobbles.	**Animas River on the Landscape**—formed as the Animas River was incising its channel and valley sides were retreating.
QUATERNARY (Pleistocene)	Terrace gravel, unit 5, lowest (Q5b) Ward (1990)	Terrace gravel consisting of glacial outwash and fan alluvium. Unit 5 has moderately developed soils that typically have stage II (Gile et al. 1966) carbonate. Lowest and youngest terrace that Ward did not include in other map units.	**Terraces**—**Q5b** consists mostly of glacial outwash from the Animas Glacier. Stepping up from the modern floodplain (represented by **Qal**), terraces are past floodplains that mark former courses of the Animas River. Unit 5 includes subunits **Q5b** and **Q5a**, which represent the lowest and highest terraces of this group respectively.	**Abandoned Mineral Lands**—abandoned gas well occurs within the expanded boundaries of the monument. Associated map unit unknown. **Paleontological Resource Inventory, Monitoring, and Protection**—terraces contain reworked Paleozoic invertebrate fossils in limestone cobbles.	**Animas River on the Landscape**—**Q5b** documents river incision and represents a former Animas River floodplain. **Glacial Record**—equivalent to terrace **Qt6a** of Gillam (1998a), approximately 160,000–140,000 years old.

Table shows units mapped by Brown and Stone (1979) on the eastern side of monument and Ward (1990) on the western side of monument. Colors in Map Unit column correspond to the bedrock and surficial map poster (in pocket). Bold text refers to sections in the GRI report.

Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
QUATERNARY (Pleistocene)	Terrace gravel, unit 4, intermediate (Q4d) Ward (1990)	Terrace gravel consisting of glacial outwash and fan alluvium. Unit 4 has moderately developed soils that typically have stage III and locally stage IV (Gile et al. 1966) carbonate. Includes five subunits, from youngest to oldest Q4e, **Q4d**, Q4c, Q4b, and Q4a.	**Terraces**—**Q4d** consists of glacial outwash from the Animas Glacier. Stepping up from the modern floodplain, terraces are past floodplains that mark former courses of the Animas River. **Q4d** is an intermediate level terrace of Group 4, as mapped by Ward (1990). It is the highest and oldest in the monument.	**Oil and Gas Development and Production**—well operations (e.g., Bobbie Herrera #1) account for localized and relatively minor impacts to natural resources, including denuded vegetation and eroded and compacted soil on terrace surfaces. **Adjacent Development**—potential impacts include loss of archeological resources, runoff-related erosion, and visual impairments. **Abandoned Mineral Lands**—abandoned gas well occurs within the expanded boundaries of the monument. Associated map unit unknown. **Paleontological Resource Inventory, Monitoring, and Protection**—terraces contain reworked Paleozoic invertebrate fossils in limestone cobbles.	**Animas River on the Landscape**—incision of the Animas River valley began between about 18 million and 3 million years ago (Miocene and Pliocene epochs). **Q4d** documents river incision and represents a former Animas River floodplain. **Glacial Record**—equivalent to terrace **Qt5a** of Gillam (1998a), approximately 340,000–250,000 years old.
Rocks or unconsolidated deposits from the Eocene through Pliocene epochs are not mapped within Aztec Ruins National Monument.					
PALEOGENE (Paleocene)	Nacimiento Formation (Tn) Brown and Stone (1979) Ward (1990)	Gray, green, and purple claystone, shale, and siltstone; gray and yellow, coarse conglomeratic cross-bedded and massive sandstone. Most areas that Ward mapped as **Tn** within the monument are covered by thin outwash alluvium and colluvium.	**Nacimiento Formation**—bedrock of the monument. Exposed in drainages on North Mesa. **Building Stone and Lithic Resources**—ancestral Puebloans used **Tn** in construction. The distinctive "greenstone" bed was incorporated as a decorative band.	**Oil and Gas Development and Production**—well operations (e.g., Bobbie Herrera #1, Fee 9Y, and Fee 4-A) account for localized and relatively minor impacts to natural resources, including denuded vegetation and eroded and compacted soil on terrace surfaces. **Adjacent Development**—potential impacts include loss of archeological resources, runoff-related erosion, and visual impairments. **Localized and Regional Subsidence—**small depressions have developed in the vicinity of East Ruin, which is situated on **Tn** of Ward (1990)**.** **Abandoned Mineral Lands**—abandoned gas well occurs within the expanded boundaries of the monument. Associated map unit unknown. **Paleontological Resource Inventory, Monitoring, and Protection**—elsewhere, **Tn** yields vertebrate fossils important for interpreting the beginning of the "Age of Mammals." Also yields plant fossils, including petrified wood, and invertebrate fossils.	**Laramide Orogeny**—deposited during the mountain-building event that created the Rocky Mountains. **Tn** consists of sediments shed from uplifts into a subsiding basin.

Terraces Map Unit Properties Table: Aztec Ruins National Monument

Table shows units mapped by Gillam (1998a) within Aztec Ruins National Monument. Colors in Map Unit column correspond to the geomorphic map poster (in pocket). Bold text refers to sections in report.

Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
QUATERNARY (Holocene)	Modern floodplain (Qfp)	Modern floodplain, including active alluvial fans graded to the floodplain.	**Terraces**—three primary terraces levels (**Qt7u**, **Qt6a**, and **Qt5a**) step up from the modern floodplain (**Qfp**). **Alluvium**—**Qfp** is composed of post-glacial alluvium.	**Oil and Gas Development and Production**—well operations account for localized and relatively minor impacts to natural resources, including denuded vegetation and eroded and compacted soil on terrace surfaces. **Adjacent Development**—potential impacts include loss of archeological resources, runoff-related erosion, and visual impairments. **Localized and Regional Subsidence**—small depressions have developed in the vicinity of East Ruin, which is situated on **Qt7u.** **Piping**—primarily in **Qfp** and **Qt7u**, piping is a minor geohazard at the monument. Soil pipes have developed in an eroding bank of the Animas River. Could affect the stability of archeological sites via subsidence. Pipes may have cultural importance as the beginning of an excavated kiva. **Bank Erosion and Landscape Restoration**—the NPS goal is to restore natural function and appearance while protecting cultural resources along the banks of the Animas River. **Recreation and Land Use in the Animas River Corridor**—no park infrastructure was built on the floodplain (**Qfp**), so flooding is not a significant issue. A public trail along the river (**Qfp** and **Qt7u**) connects downtown Aztec to the monument; buck-and-rail fencing is meant to keep recreationists on the trail. **Abandoned Mineral Lands**—abandoned gas well occurs within the expanded boundaries of the monument. Associated map unit unknown. **Paleontological Resource Inventory, Monitoring, and Protection**—terraces contain reworked Paleozoic invertebrate fossils in limestone cobbles.	**Animas River on the Landscape** and **Ongoing Incision**—incision and aggradation of the modern floodplain by the Animas River is ongoing. **Glacial Record**—**Qfp** developed after the final retreat (about 12,000 years ago) of the Animas Glacier.
QUATERNARY (Late Pleistocene)	Terrace 7, undivided (Qt7u)	Less than 3 m (10 ft) above the present floodplain at the monument, but elsewhere is higher (approximately 15 m [49 ft] above). Terraces graded to the Animas City moraines in Durango, Colorado. Elsewhere, divided into three levels (Qt7a, Qt7b, and Qt7c).	**Building Stone and Lithic Resources**—ancestral Puebloans used terrace materials such as boulders and cobbles for foundations and silt to make mortar and plaster. **Terraces**—this terrace level was not mapped by either Brown and Stone (1979) or Ward (1990).		**Animas River on the Landscape**—lowest and youngest terrace at the monument. **Glacial Record**—**Qt7u** developed approximately 25,000–19,000 years ago during the Pinedale glaciation.
QUATERNARY (Late middle Pleistocene)	Terrace 6a (Qt6a)	27–34 m (89–112 ft) high (above the modern floodplain). **Qt6a** grades to the Spring Creek moraines in Durango, Colorado.	**Building Stone and Lithic Resources**—ancestral Puebloans used terrace materials such as boulders and cobbles for foundations and silt to make mortar and plaster. **Terraces**—**Qt6a** is composed of glacial outwash from the Animas Glacier. It is the intermediate and middle-aged terrace level at the monument.		**Animas River on the Landscape**—represents the "middle-aged" floodplain cut by the Animas River at the monument. **Glacial Record**—**Qt6a** developed approximately 160,000–140,000 years ago during the Bull Lake glaciation.
QUATERNARY (Middle Pleistocene)	Terrace 5a (Qt5a)	43–46 m (141–151 ft) high (above the modern floodplain). Graded to the Durango moraines in Durango, Colorado.	**Building Stone and Lithic Resources**—ancestral Puebloans used terrace materials such as boulders and cobbles for foundations and silt to make mortar and plaster. **Terraces**—**Qt5a** is composed of glacial outwash from the Animas Glacier. It is the highest and oldest terrace level within the monument.		**Animas River on the Landscape**—the river began to incise its channel following the Laramide Orogeny but before the pre–Bull Lake glaciation. **Qt5a** was the first terrace to be cut by the Animas River at Aztec Ruins. **Glacial Record**—**Qt5a** developed approximately 340,000–250,000 years ago during the pre-Bull Lake glaciation.