National Park Service
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Natural Resource Stewardship and Science

Chaco Culture National Historical Park

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2015/1045

ON THE COVER: Photograph of Pueblo Bonito in Chaco Culture National Historical Park. Pueblo Bonito is a massive stone building, referred to as a "great house," in Chaco Canyon. The Chacoan cultural complex, which encompassed these great houses, covered much of the present-day Southwest, including the San Juan Basin in northwestern New Mexico. National Park Service photograph.

THIS PAGE: Photograph of Casa Rinconada in Chaco Culture National Historical Park. The blocks of Cliff House Sandstone used in construction were once part of a barrier island off the west coast of the Western Interior Seaway. The seaway inundated New Mexico about 96 million years ago. This time-lapse photograph shows star trails. The park's natural nighttime darkness, commitment to reducing light pollution, and ongoing public outreach have led to its certification as an International Dark Sky Park by the International Dark-Sky Association. National Park Service photograph.

Chaco Culture National Historical Park

Geologic Resources Inventory Report

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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 GRI. This report synthesizes discussions from a scoping meeting for Chaco Culture National Historical Park (New Mexico) on 14 February 2007 and follow-up conference calls on 13 February 2014 and 15 April 2014, which were held by the Geologic Resources Division to identify geologic resources of significance 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.

Chaco Culture National Historical Park encompasses 13,744 ha (33,960 ac) in four park units—the main Chaco Canyon unit and three smaller outliers (Kin Bineola, Pueblo Pintado, and Kin Ya'a). The park's main geomorphic feature is Chaco Canyon, which contains 13 primary prehistoric sites and hundreds of smaller ones. A major Chacoan building phase produced multistoried great houses and large kivas (underground or partly underground chambers) between 850 to 1150 CE (common era).

Most of the Chacoan great houses were built along the northern side of Chaco Canyon, under vertical cliffs of towering Cliff House Sandstone. This sandstone and the other bedrock units in the park were deposited during the Late Cretaceous Period between about 100 million and 70 million years ago when a vast sea, called the "Western Interior Seaway," inundated the central part of North America, splitting the continent into two land masses. The site of Chaco Culture National Historical Park was on the western shoreline of this seaway.

The ancestral Chaco River cut down though Upper Cretaceous bedrock, exposing former deposits of the Western Interior Seaway in the walls of Chaco Canyon. The exact timing of incision of Chaco Canyon is unknown but estimated to have initiated less than 2 million years ago. At least seven preserved Pleistocene gravel deposits, three of which are in the park, reflect an erosional episode related to changes in the grade of the Chaco River or the San Juan River.

Once the canyon was incised, more 30 m (100 ft) of alluvium (silt, sand, and gravel in stream channels), eolian (windblown) sand, and slope-wash material (clay, silt, and rock fragments distributed by overland flow) began to fill it. These sediments serve as a record of past events, but dynamic sedimentation continues to the present.

Throughout its history, the floor of Chaco Canyon has alternated between being deeply gullied by arroyo channels, as it is today, and having no arroyo. Integrated analysis using both geologic and archeologic methods (i.e., geoarcheology) shows that ancient occupants of the canyon experienced these changes.

This GRI report was written for resource managers to support science-informed decision making at Chaco Culture National Historical Park. It may also be useful for interpretation. The report was prepared using available geologic information, and the NPS Geologic Resources Division (GRD) did not conduct any new fieldwork in association with this report. Chapters of the report discuss distinctive geologic features and processes within the park, highlight geologic issues facing resource managers, describe the geologic history leading to the present-day landscape, and provide information about the GRI geographical information system (GIS) data. A poster (in pocket) illustrates these data. In addition, the Map Unit Properties Table (in pocket) summarizes report content for each map unit within Chaco Culture National Historical Park.

Geologic features and processes at Chaco Culture National Historical Park include the following:

- **Upper Cretaceous Rocks and Fossils**. The Western Interior Seaway inundated the area about 96 million years ago, and advanced and retreated for 30 million years, depositing sediments in marine, coastal, and continental settings. The shoreline migrated as a result of changes in sea level, sedimentation, and subsidence of the ocean basin. The five primary bedrock units at Chaco Culture National Historical Park—Crevasse Canyon Formation, Menefee Formation, Cliff House Sandstone, Lewis Shale, and Pictured Cliffs Sandstone—record these changes and the life-forms that lived in these ancient environments.

- **Quaternary Fossils**. Chaco Culture National Historical Park is a prolific source of packrat (*Neotoma* spp.) middens, which contain collections of plant material, food waste, coprolites (fossil dung), and bones from the last 2.6 million years (Pleistocene and Holocene epochs). Additionally, Pleistocene gravels may yield ice-age vertebrate fossils.
- **Chaco Canyon**. Chaco Canyon cuts through the main unit of Chaco Culture National Historical Park. The canyon is 32 km (20 mi) long. The asymmetry of the north and south sides, sheer walls of Cliff House Sandstone, and an alluvial floor currently cut by an arroyo are distinctive features of the canyon.
- **Chaco Arroyo**. Multiple episodes of arroyo cutting and filling are recorded in Chaco Canyon. Chaco Arroyo is the most recent. Historical observations indicate that an intermittent channel or succession of pools had developed by 1849, and incision of Chaco Arroyo began before 1877. Photographs and channel measurements beginning in 1896 show an incising arroyo with little vegetation and a flat bottom until the early 1930s. The active inner channel developed after 1934.
- **Dynamic Sedimentation and Arroyo Development**. About 11 m (36 ft) of alluvial fill, as well as slope-wash and eolian deposits, are exposed in the walls of Chaco Arroyo. Arroyos existed on at least seven separate occasions throughout the development of Chaco Canyon.
- **Alluvial Fill**. As shown on source maps and in the GRI GIS data, the floor of Chaco Canyon is covered by Naha alluvium (map unit **Qn**) and undivided Naha and Tsegi Alluviums (**Qnt**), which were originally described by Hack (1941) in "Navajo Country" of Arizona and later used in Chaco Canyon. Hall (1977, 2010) and other investigators showed that the alluvial fill exposed on the floor of Chaco Canyon and in the walls of Chaco Arroyo has a distinctive stratigraphy, as indicated by color, grain size, and sedimentary structures, as well as the presence of archeological sites of different ages. Hall (1977, 2010) dated and divided the alluvial fill of Chaco Canyon into four units, using nomenclature from local geographic features: (1) pre-Gallo (undated), (2) Gallo (6,700–2,800 years BP), (3) Chaco (2,100–1,000 years BP), and (4) Bonito (800–100 years BP).
- **Sheetwash Alluvium and Slope-Wash Deposits**. Part of the sedimentary fill of Chaco Canyon consists of sheetwash alluvium and slope-wash deposits, which also covers mesa tops. These units were deposited via overland flow, which is not concentrated in a channel and moves downslope as a thin, continuous sheet of water.
- **Eolian Features**. Investigators have mapped and described eolian features, such as sand dunes and sand sheets, throughout Chaco Culture National Historical Park. These windblown deposits occur on cliff tops and at the mouth of Chaco Canyon, as well as in tributary canyons. The idea that a sand dune dammed Chaco Wash and created "Lake Chaco" has become part of the scientific and popular literature about the park. Geomorphic and stratigraphic evidence does not support the occurrence of such a lake, however.
- **Tinajas and Charcos**. In the 1920s, Kirk Bryan—the well-known geoarcheologist whose work in Chaco Canyon led the way for decades of research—was one of the first scientists to study tinajas (potholes) in the US Southwest. He also studied charcos (mud holes) on the alluvial floor of Chaco Canyon. These features are valuable geologic (and ecologic) resources at Chaco Culture National Historical Park, providing an ephemeral but significant source of surface water and habitat for wildlife and microorganisms. A thorough inventory of these features has not been conducted at the park.
- **Badlands**. Badlands are a distinctive and scenic feature of natural landscapes in the western United States. The badlands topography at Chaco Culture National Historical Park develops in areas of the Menefee Formation, in particular the Juans Lake Beds of Miller (1984) (**Kmfaj**). Results of an ongoing paleontological inventory in the park indicate that badlands topography, especially in the Juans Lake Beds, is highly fossiliferous.
- **Cave Shelters**. In Chaco Culture National Historical Park, cave shelters form along the shale-sandstone contact between the Menefee Formation and Cliff House Sandstone. These shelters provided temporary and permanent living areas for prehistoric peoples, and are noteworthy for the resources they contain, including packrat (*Neotoma* spp.) middens and some of the earliest datable, cultural material such as corn and basketry. As a result of investigation of packrat middens,

the location of most cave shelters in the park are known, and could be plotted in the park's GIS for use in management.

Geologic resource management issues identified during the 2007 GRI scoping meeting and 2014 follow-up conference calls include the following:

- **Oil and Gas Development**. Perhaps the most pressing issue for park managers is the development of oil and gas resources in the San Juan Basin. Improvements in horizontal drilling and hydraulic fracturing have spurred renewed industry interest in the Mancos Shale and Gallup Sandstone. The location of Chaco Culture National Historical Park near the center of this highly productive basin makes it vulnerable to oil and gas exploration and development on federal (Bureau of Land Management) lands, tribal lands, and allotments held by individual tribal members. Oil and gas exploration and development could impact the park's cultural resources, paleontological resources, air quality, visual resources, night skies, natural and cultural soundscapes, water resources, and wilderness characteristics.
- **Coal Resources and Mining**. The Crevasse Canyon Formation, Menefee Formation, and Kirtland Shale–Fruitland Formation are known for coal in the San Juan Basin. The Gibson Coal Member of the Crevasse Canyon Formation (**Kcg**) in the vicinity of the Kin Ya'a unit of the park, and the Allison Member coal zone of the Menefee Formation (**Kmfa**), which crops out on West Mesa and along the Chaco River west of the confluence of Chaco and Escavada washes, contain coal resources. Although coal mining could occur on any of the eight allotments within the administrative boundaries of the park, participants at the scoping meeting thought this was unlikely. If an owner chose to pursue his or her right, however, park managers, with the assistance of the NPS Geologic Resources Division, would work with an owner to ensure that NPS resources and values were not adversely impacted.
- **Uranium Production**. Uranium has been produced from the 156 million–147 million-year-old (Jurassic Period) Morrison Formation in the Grants uranium district, which encompasses Chaco Culture National Historical Park. At present, no uranium production is occurring, but the district has the potential to become an important future global source of uranium, adding to its historical significance.
- **Abandoned Mineral Lands**. The National Park Service mined sand and gravel at Chaco Culture National Historical Park for administrative uses until the late 1980s. Three abandoned coal mines are known to occur within the Chaco Canyon unit of the park. The Kin Ya'a unit contains 73 drill sites from past uranium exploration. The New Mexico Mines Database documents nine sites with past activity associated with uranium exploration in the vicinity of the Chaco Canyon and Kin Ya'a units. These sites and features have not yet been recorded in the NPS servicewide Abandoned Mineral Lands (AML) database.
- **Disturbed Lands Restoration**. Past disturbances at Chaco Culture National Historical Park include a legacy of grazing during the late 1800s and early 1900s. In 1947, the National Park Service fenced the park area to exclude grazing, which has resulted in the return of native grasses, shrubs, and wildlife. Grazing is still allowed and could occur on allotments within the administrative boundary of the park, however. Disturbances associated with work by the Civilian Conservation Corps (CCC) in the 1930s include berms constructed on the floor of Chaco Canyon for erosion control and a CCC camp in Marcia's Rincon. From the 1950s to the early 1990s, the National Park Service disposed of solid waste in trenches on the eastern side of South Gap. Except for arsenic, all contaminants tested were below a standard safety threshold, and arsenic was lower than background mean concentrations for New Mexico. Park managers are looking for funding options to remove the site. An earth dam (**Qaf1**), surrounding a flowing well, occurs in the Kin Ya'a unit of the park. Earth dams also occur in the Kin Bineola unit. In some places, these earth dams have totally altered normal drainage and sediment deposition along the Kim-me-ni-oli Wash. The National Park Service has no plans to remove these dams at present.
- **Rockfall**. The stratigraphic arrangement of more resistant sandstone (Cliff House Sandstone) over more rapidly eroding mudstone (Menefee Formation) at Chaco Culture National Historical Park creates rockfall hazards. The park housing area and Gallo Campground, which are at the base of highly jointed cliffs of sandstone, are of greatest concern because they are frequently occupied by

people. As a result of a technical assistance request by park managers in 2013, GRD staff provided rockfall-monitoring guidance and a risk assessment of these areas.

- **Paleontological Resource Inventory and Monitoring**. An inventory of the Upper Cretaceous rocks at Chaco Culture National Historical Park, which started in 2005 and is ongoing, revealed abundant and widespread paleontological resources, primarily in the Menefee Formation and Cliff House Sandstone. In 2009, investigators provided an inventory and monitoring report for paleontological resources in the Southern Colorado Plateau Network, including Chaco Culture National Historical Park. In 2014, NPS representatives from Chaco Culture National Historical Park and the Geologic Resources Division met with representatives of 28 American Indian tribes to discuss fossils. Discussions illuminated the cultural significance of these resources at the park and provided impetus for park planning. Also in 2014, a meeting with professional paleontologists took place in order to develop a strategy for future paleontological research and resource management at the park.
- **Piping**. Piping is a type of subsurface erosion that forms conduits, tunnels, or "pipes" through which soluble or granular soil material is removed. Piping is a management concern at Chaco Culture National Historical Park because it infringes on and endangers archeological sites and threatens roads. Piping can occur in "fill soils" used in reburial (a conservation strategy) of archeological sites such as Chetro Ketl in the park. Piping also creates bat habitat.
- **Seismicity**. Earth movements ("seismicity") may be caused by earthquakes (movement along a fault), landslides, blasting, drilling, road building, or vehicular traffic. The primary concern at Chaco Culture National Historical Park is that ground shaking could damage archeological structures. It also may induce rockfalls. A seismic and vibration-hazard investigation at the park provided guidelines for construction and traffic on park roads. Activities associated with coal mining are considered too far away to cause damage, but oil and gas activities adjacent to the park could cause mild shaking. The probability of a moderate earthquake (>magnitude 5.0) shaking the Chaco Canyon unit over the next 100 years is between 0.04 and 0.10 (4% to 10% "chance"). The probability increases to the east toward Los Alamos and Santa Fe.
- **Eolian Processes**. Historically, eolian processes have buried archeological sites at Chaco Culture National Historical Park with windblown silt and sand. Winds can cause walls of archeological structures to sway, initiating seismic vibrations. The bracing of walls, particularly using modern materials, generally increases the natural frequencies of these structures, which can make them more susceptible to wind-induced vibrations. Eolian processes cause dust storms, impairing visibility. Before the park road was rerouted to its present location, eolian processes transported sand across the road, which required regular maintenance. The removal of sediment, between a cliff face and loose rock, by eolian processes may aid rockfall hazards.
- **Efflorescence**. Efflorescence—also called "salt weathering"—appears as a whitish, fluffy, or crystalline powder on stone surfaces. Scoping participants suggested that efflorescence may accelerate the deterioration of stone and mortar in structures at Chaco Culture National Historical Park and accelerate the deterioration of roof surfaces in natural cave shelters. Not all salt behaviors result in deterioration, however, and efflorescence may cause only minor surface damage. Park managers use the presence of efflorescence as an indicator of water penetration, drainage problems, and stone deterioration. Also, efflorescence is evidence that replacement mortars used in preservation are less permeable than the original fabric, thus indicating the need to reevaluate mortar mixes.

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.

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Geologic Setting and Significance

This chapter describes the regional geologic setting of Chaco Culture National Historical Park and summarizes connections among geologic resources, other park resources, and park stories.

Originally proclaimed as Chaco Canyon National Monument in 1907 to preserve sites of the prehistoric Chacoan culture, the monument was expanded and designated Chaco Culture National Historical Park in 1980. The park now encompasses 13,740 ha (33,960 ac) and consists of four units—the main Chaco Canyon unit (plate 1, in pocket) and three smaller outliers: Kin Bineola, which is west of the main unit, Pueblo Pintado to the east, and Kin Ya'a to the south (see poster, in pocket). The park is both nationally and internationally significant. It is listed in the National Register of Historic Places and is part of a World Heritage Site that includes Aztec Ruins National Monument in the National Park System and five smaller Chacoan sites managed by the Bureau of Land Management.

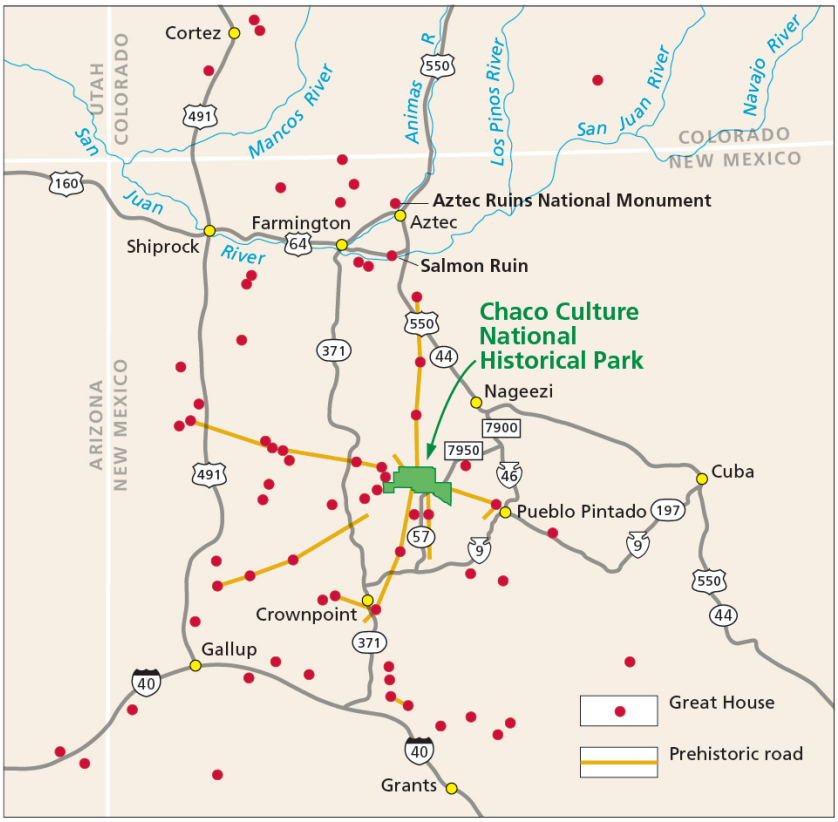

Figure 1. Regional map showing the location of Chaco Culture National Historical Park (detail map is plate 1, in pocket), great houses, and prehistoric roads. By 1050 CE, Chaco had become the ceremonial, administrative, and economic center of the San Juan Basin. Its sphere of influence was extensive. Dozens of great houses in Chaco Canyon were connected by roads to more than 150 great houses throughout the region. National Park Service graphic.

Chaco Canyon was a major center of trade, political activity, and spiritual ceremonies in a vast cultural complex that dominated the region in the mid-ninth to early 13th centuries (fig. 1). Planned in stages, this ancient cultural complex was unlike anything constructed before or since. It is remarkable for its monumental public buildings and distinctive multistory "great houses," which demonstrate a sophisticated understanding of astronomical phenomena. The Chacoan great houses, including those in Chaco Canyon and the ones at Aztec Ruins National Monument to the north, were linked by an elaborate system of carefully engineered and constructed roads (UNESCO 2014; fig. 1).

The Chacoan cultural complex covered much of the present-day Southwest, including the San Juan Basin of New Mexico and Colorado (National Park Service 2006). The San Juan Basin developed during three phases of tectonic subsidence at the end of the Laramide Orogeny—the mountain-building event that created the Rocky Mountains (Cather 2003). At that time, additional, mostly continental and coastal, sediments accumulated atop sediments previously deposited in the Western Interior Seaway. These "previously deposited" sediments comprise the cliffs and mesa tops of the park and record sea level rise and fall between 100 million and 70 million years ago (i.e., during the Late Cretaceous Period; fig. 2). At that time, the park was situated on the western shoreline of the Western Interior Seaway, which bisected the North American continent and stretched from the Arctic Ocean to the Gulf of Mexico (fig. 3). As sea water

Eon	Era	Period	Epoch	MYA	Life Forms	North American Events
Phanerozoic	Cenozoic (CZ)	Quaternary (Q)	Holocene (H)	0.01	Age of Mammals: Extinction of large mammals and birds; Modern humans	Ice age glaciations; glacial outburst floods; Cascade volcanoes (W)
			Pleistocene (PE)	2.6		
		Tertiary (T): Neogene (N)	Pliocene (PL)	5.3	Spread of grassy ecosystems	Linking of North and South America (Isthmus of Panama); Columbia River Basalt eruptions (NW); Basin and Range extension (W)
			Miocene (MI)	23.0		
		Tertiary (T): Paleogene (PG)	Oligocene (OL)	33.9		
			Eocene (E)	56.0		Laramide Orogeny ends (W)
			Paleocene (EP)	66.0	Early primates; Mass extinction	
	Mesozoic (MZ)	Cretaceous (K)		145.0	Age of Reptiles: Placental mammals; Early flowering plants	Laramide Orogeny (W); Western Interior Seaway (W); Sevier Orogeny (W)
		Jurassic (J)		201.3	Dinosaurs diverse and abundant	Nevadan Orogeny (W); Elko Orogeny (W)
		Triassic (TR)		252.2	Mass extinction; First dinosaurs; first mammals; Flying reptiles; Mass extinction	Breakup of Pangaea begins; Sonoma Orogeny (W)
	Paleozoic (PZ)	Permian (P)		298.9	Age of Amphibians: Coal-forming swamps; Sharks abundant; First reptiles	Supercontinent Pangaea intact; Ouachita Orogeny (S); Alleghany (Appalachian) Orogeny (E); Ancestral Rocky Mountains (W)
		Pennsylvanian (PN)		323.2		
		Mississippian (M)		358.9	Mass extinction; Fishes: First amphibians; First forests (evergreens)	Antler Orogeny (W); Acadian Orogeny (E-NE)
		Devonian (D)		419.2		
		Silurian (S)		443.8	First land plants; Mass extinction; Marine Invertebrates: Primitive fish; Trilobite maximum	Taconic Orogeny (E-NE)
		Ordovician (O)		485.4	Rise of corals	Extensive oceans cover most of proto-North America (Laurentia)
		Cambrian (C)		541.0	Early shelled organisms	
Proterozoic	Precambrian (PC, X, Y, Z)			2500	Complex multicelled organisms; Simple multicelled organisms	Supercontinent rifted apart; Formation of early supercontinent; Grenville Orogeny (E); First iron deposits; Abundant carbonate rocks
Archean				4000	Early bacteria and algae (stromatolites)	Oldest known Earth rocks
Hadean				4600	Origin of life; Formation of the Earth	Formation of Earth's crust

Figure 2 (facing page). 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 GIS abbreviations for each time division are in parentheses. Compass directions in parentheses indicate the regional locations of events. Boundary ages are millions of years ago (MYA). Upper Cretaceous rocks and Pleistocene deposits and unconsolidated deposits document the geologic story at Chaco Culture National Historical Park, which includes inundation by the Western Interior Seaway during the Cretaceous Period (K; fig. 3), creation of the San Juan Basin as a result of tectonic forces during the Laramide Orogeny in the Cretaceous (K) and Paleogene (PG) periods, development of Chaco Canyon during the Quaternary Period (Q), and dynamic sedimentation and deposition of alluvium during the Pleistocene (PE) and Holocene (H) epochs. National Park Service graphic using dates from the International Commission on Stratigraphy (http://www.stratigraphy.org/index.php/ics-chart-timescale; accessed 27 August 2015).

repeatedly advanced and retreated, sediments were deposited in variety of marine and coastal environments such as barrier islands, lagoons, tidal inlets, stream deltas, estuaries, and swamps. Changes in sea level, sediment supply, and subsidence caused multiple northeast–southwest shifts in shoreline position (Love 2010).

Encompassing more than 67,000 km^2 (26,000 mi^2), the San Juan Basin is the dominant structural and physical feature in northwestern New Mexico. It is a nearly circular depression containing a thick sequence of sedimentary rocks, ranging in age from Pennsylvanian to Pliocene (300 million to 2 million years ago; fig. 2). These sedimentary units are underlain by Precambrian (1.7 billion to 1.4 billion years ago) crystalline rocks (Price 2010). The sedimentary layers of the San Juan Basin form a bull's eye in map view, and resemble nested mixing bowls in cross section (fig. 4). As is the case of structural basins, the youngest strata are exposed near the center of the basin, where the thickest accumulations of sediments occur. Aztec Ruins National Monument sits on these younger sediments (see GRI report by KellerLynn in review). Progressively older strata are exposed toward the edges of the basin, where Precambrian rocks were uplifted and crop out in mountain ranges such as the Nacimiento and Zuni mountains in New Mexico and the San Juan Mountains in Colorado. Chaco

Figure 3. 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. Base paleogeographic map by Ron Blakey (Colorado Plateau Geosystems, Inc.), available at http://cpgeosystems.com/index.html (accessed 7 July 2014).

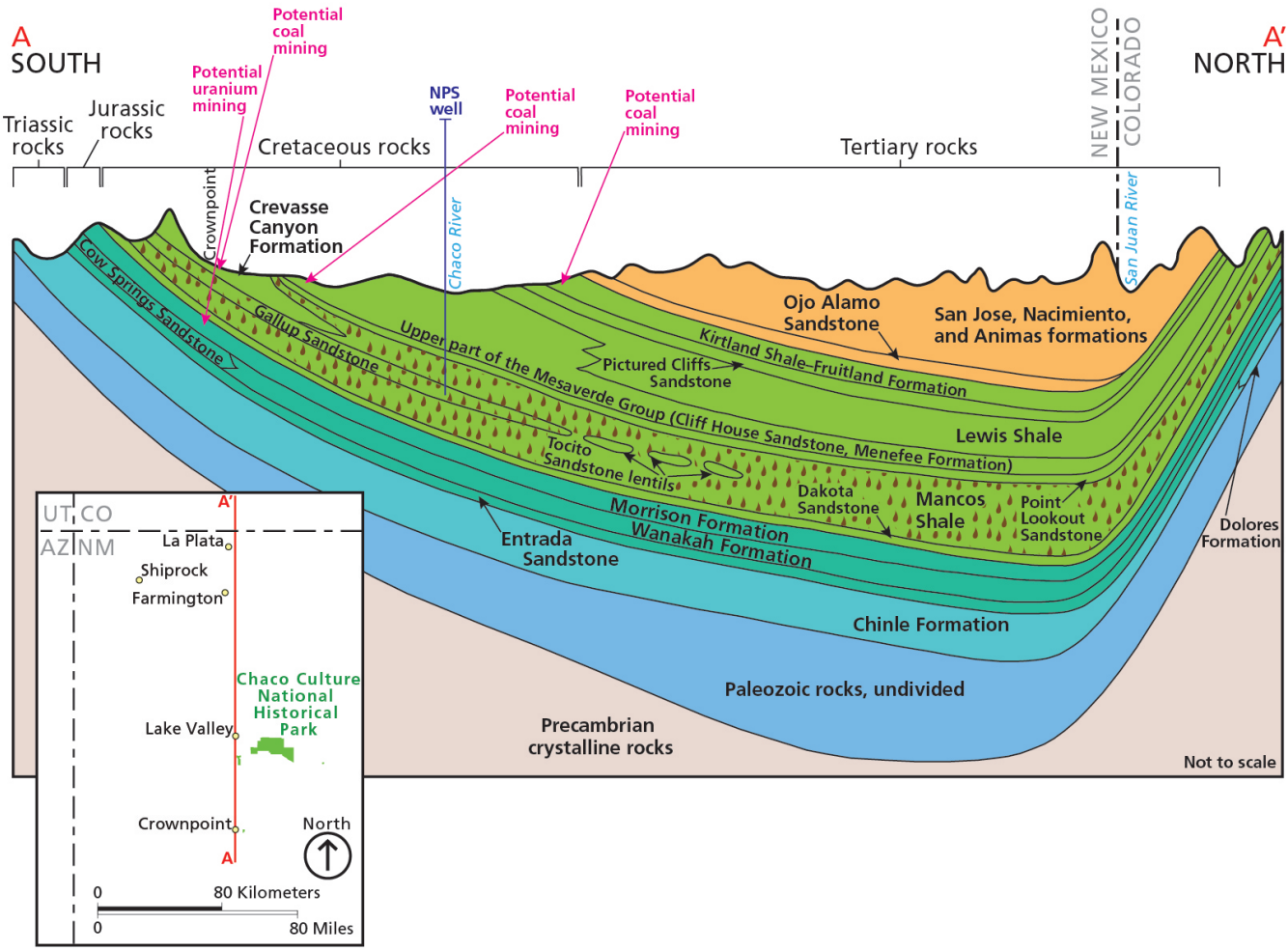

Figure 4. Cross section of the San Juan Basin. Before subsidence during the Laramide Orogeny, the San Juan Basin occupied a small area on the western edge of the Western Interior Seaway where sediments were deposited in marine, coastal, and continental settings and include the Crevasse Canyon Formation, Cliff House Sandstone, Menefee Formation, Lewis Shale, and Pictured Cliffs Sandstone in Chaco Culture National Historical Park. Late in the Cretaceous Period, the basin began to subside and thousands of feet of additional terrestrial sediment accumulated (shown as Tertiary rocks in orange). The thickest accumulation of sediments is close to the center of the basin. This figure shows the locations of the park's drinking-water well and coal and uranium mining areas in the vicinity of the park. The Gallup Sandstone and Mancos Shale are the current target formation for oil and gas production, as illustrated by the brown droplets on the figure. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Brister and Hoffman (2002, figure 3) and Martin (2005, figure 9).

Culture National Historical Park is about 72 km (45 mi) southwest of the center of the basin where folded sedimentary layers of Upper Cretaceous rocks crop out at the surface (fig. 4).

In Chaco Culture National Historical Park, the Chaco River and its tributaries have incised deeply into Upper Cretaceous bedrock, producing excellent three-dimensional exposures (Donselaar 1989). Above the mouth of the canyon, which is marked by the confluence of the Chaco and Escavada washes, the river is referred to as "Chaco Wash." Below the mouth of the canyon, Chaco Wash joins Escavada Wash, and the "Chaco River" moves out of its presently entrenched channel and becomes a broad meandering alluvial stream between 200 and 450 m (660 and 1,480 ft) wide (Love 1977; Simon, Li & Associates, Inc. 1982a). The river then continues southwest, west, and north to join the San Juan River at Shiprock, New Mexico.

Throughout most of the year, the Chaco River's sandy bed is dry, but its considerable length and the violence

of its floods dignify the name "river" (Bryan 1954). It is more than 220 km (140 mi) long and drains an 11,500-km^2- (4,400-mi^2-) area of semiarid lands.

At the headwaters on the Continental Divide, 40 km (25 mi) east of the park, the river is not entrenched. The dominant landforms in the upper catchment basin are gently sloping erosional surfaces called pediments. These are capped by Quaternary sediments, including alluvium and eolian deposits, and dissected by badlands composed of Fruitland Formation (**Kf**; see poster in pocket) and Kirtland Shale (**Kk**). The Kirtland Shale and Fruitland Formation crop out northeast of the Chaco Canyon unit of the park and represent post–Western Interior Seaway swamp, river, lake, and floodplain deposits laid down landward and on top of the Pictured Cliff Sandstone (**Kpc**; Fassett 1974). Tributaries draining the badlands flow into the ephemeral Chaco Wash (Simon, Li & Associates, Inc. 1982a).

The dominant landforms in the lower catchment basin are canyons, in particular Chaco Canyon, but also tributary side canyons such as Mockingbird and Clys canyons on the north, and South Gap on the south. Gallo Wash joins Chaco Wash from the north; Fajada Wash joins Chaco Wash from the south. Commonly, Chaco Wash and Fajada Wash do not flow at the same time, and local runoff that reaches the main canyon from the sides tends to precede the floods from the headwaters. As a result, discharge does not increase through the canyon, and sediments brought into the canyon from the headwaters or from the local canyon sides are not immediately transported out of the canyon, downstream to the San Juan River (Love 1977).

Other features in the lower catchment basin include Fajada Butte, Chacra Mesa, and other mesas and buttes along the course of the river. These were created by erosion. Depositional features include talus slopes (**Qc**) and sheetwash alluvium (**Qsw**) below cliff faces, and alluvial fans (**Qf**) that spread onto the floor of Chaco Canyon from the mouths of tributary canyons. Additionally, sand dunes are common on the tops of mesas and in some tributary canyons.

The attraction of Chaco Canyon for researchers started more than 150 years ago and continues to this day. Geoarcheologists apply geological concepts and methods to archeological problems and vice versa. Studies at Chaco Canyon incorporated some of the earliest applications of tree-ring dating and biogeochemistry, palynology, physical and chemical anthropology, remote sensing, archeological stratigraphy, and millennial-scale environmental reconstructions using packrat (*Neotoma* spp.) middens.

The history of geoarcheology at Chaco Canyon includes the following:

- 1849—James Hervey Simpson and Richard H. Kern described Chaco Canyon and its sites and speculated about environmental changes during occupation of the great houses and other structures. Simpson (1850) documented the Washington Expedition—a military reconnaissance that surveyed the "Navajo Country" and reported on the ancestral Puebloan and Navajo cultural sites now associated with Chaco Culture National Historical Park.
- 1877—William Henry Jackson drew Pueblo del Arroyo and methodically described the filled-in gully at this site. He also found and described prehistoric human remains, including a cranium.
- 1878—Walter James Hoffman, the physician who examined the prehistoric cranium collected by Jackson in 1877, was the first to speculate about environmental degradation as a result of human activities.
- 1903—Richard E. Dodge made one of the first attempts to correlate geologic data with the results of archeological work, in a study entitled "An Interesting Landslide of Chaco Cañon, New Mexico" (Dodge 1903).
- 1920s—Kirk Bryan spent parts of the summers of 1924 and 1925 in Chaco Canyon developing an alluvial chronology and geomorphic models for interpreting behavior of ephemeral streams in the semiarid Southwest. He also provided interpretations about the paleochannel now known as the "Bonito channel." His work was published posthumously in 1954.
- 1950s and 1960—Sponsored by the National Geographic Society, Neil Judd systematically studied and excavated Pueblo Bonito and Pueblo del Arroyo. He applied geologic data in his analyses and interpretations (see Judd 1954, 1959, 1964).
- 1960s—Yi-Fu Tuan reviewed and summarized previous ideas concerning arroyo behavior in New Mexico (e.g., Tuan 1966). He pointed out the paucity of critical data for determining the timing of inception of Chaco Arroyo and the timing of cut-

and-fill sequences of buried channels, such as the Bonito channel. His critical review was published in 1966.

- 1970s and 1980s—In 1969, the National Park Service and the University of New Mexico instituted a long-term interdisciplinary research program, called the Chaco Project. This effort attracted researchers from a variety of fields. The resulting publications between 1970 and 1980 were 20 times more voluminous than those generated over the previous 100 years (Greening 1995).
- 2010s—As part of the Chaco Project, Steven H. Hall and David W. Love studied and mapped exposures of Chaco Canyon alluvium, including charcoal and pollen, and extended interpretations of environmental changes over several thousand years. More recent studies include new interpretations of alluvial and paleovegetation records from the canyon by Hall (2010) and analysis and applications of geomorphology, hydrology, and alluvial stratigraphy in lower Chaco Canyon by Love et al. (2011).

A thorough bibliography is listed at the Chaco Research Archive (http://www.chacoarchive.org/cra/chaco-resources/bibliography/; accessed 27 August 2015).

Geologic Features and Processes

This chapter describes noteworthy geologic features and processes in Chaco Culture National Historical Park.

During the 2007 scoping meeting and 2014 conference calls, participants (see Appendix A) identified the following geologic features and processes:

- Upper Cretaceous Rocks and Fossils
- Quaternary Fossils
- Chaco Canyon
- Chaco Arroyo
- Dynamic Sedimentation and Arroyo Development
- Alluvial Fill
- Sheetwash Alluvium and Slope-Wash Deposits
- Eolian Features
- Tinajas and Charcos
- Badlands
- Cave Shelters

Figure 5. Photograph of Fajada Butte. Fajada Butte is an impressive landmark in Chaco Canyon. This view is from the Fajada Butte Overlook. The name Fajada means "striped, belted, or banded" in Spanish and describes the black coal seams and other sedimentary layers that run across the butte. Within Chaco Canyon, investigators have subdivided and named the various beds of Cliff House Sandstone ("Kch" units; see Map Unit Properties Table and poster, in pocket). The Menefee Formation ("Kmf" units) intertongues with these beds. US Geological Survey photograph available at http://3dparks.wr.usgs.gov/chcu/html2/chaco044.htm (accessed 6 May 2014).

Upper Cretaceous Rocks and Fossils

The majority of strata exposed in Chaco Culture National Historical Park belong to a suite of rocks known as the Mesaverde Group for exposures in Mesa Verde National Park (see GRI report for Mesa Verde National Park by Graham 2006). The Mesaverde Group was deposited during the Late Cretaceous Period (100 million–66 million years ago). Conforming to standard use in geologic writing, this report uses "Late" in describing geologic time and "Upper" in describing the position of rocks. Collier (1919) divided the Mesaverde Group into three formations (from oldest to youngest): Point Lookout Sandstone (not exposed in Chaco Culture National Historical Park), Menefee Formation, and Cliff House Sandstone. In the process of naming, Collier (1919) joined the two words, "Mesa Verde" to become "Mesaverde." Attempts to return the spelling to its two-word origins have not succeeded (Fasset et al. 2010). The oldest rock unit in Chaco Culture National Historical Park is the Upper Cretaceous Crevasse Canyon Formation, which was added to the Mesaverde Group in 1954 (Allen and Balk 1954). This bedrock (map units **Kcg** and **Kcda**) appears in the Kin Ya'a unit of the park only (see poster, in pocket).

The Menefee Formation and Cliff House Sandstone are the most prevalent rock units in Chaco Canyon. The Menefee Formation is part of West, South, and Chacra mesas, as well as Fajada Butte, where the contact between the underlying Menefee Formation and overlying Cliff House Sandstone is readily visible (fig. 5). The Menefee Formation is the primary bedrock unit in the Kin Bineola unit of the park (see poster, in pocket). The Cliff House Sandstone makes up the walls on both sides of Chaco Canyon, but forms particularly impressive cliffs on the northern side. It also caps the West, South, and Chacra mesas on the southern side of Chaco Canyon and underlies the southwestern corner of the Pueblo Pintado unit.

The towering cliffs of Cliff House Sandstone provided people of the Chaco Culture with ample building stone (National Park Service 2006). Most of the rock used at the height of Chacoan construction was quarried from a layer of dense, dark Cliff House Sandstone that capped the canyon cliffs. Once quarried, stone blocks were probably dropped to the floor of Chaco Canyon where

they were shaped and dressed (put the finishing touches on the stone) (Strutin 1994).

Stone for later buildings (early 12th century) was probably quarried from the softer sandstone near the base of the cliffs (Strutin 1994). Some archeologists believe that by the last quarter of the 11th century, the dense stone used in classic Chacoan buildings had been almost completely stripped from the rim of the cliffs. This resource shortage may have caused changes in the style of later buildings, though new architectural ideas and approaches were being adapted at Chaco and other regions at the time (Strutin 1994).

Ironstone concretions, which occur in the Menefee Formation and Cliff House Sandstone, were used to decorate floors in kivas and may have possessed a particular Chacoan "value" or source of power. Coal seams in the Crevasse Canyon and Menefee formations are clearly visible throughout the park and were probably used by Indian inhabitants prior to exploration by European Americans (Nickelson 1988).

In addition to the Cliff House Sandstone and Menefee Formation, two other rock units occur in the park but are not part of the Mesaverde Group—Lewis Shale and Pictured Cliffs Sandstone. These too are Late Cretaceous in age but younger than the Mesaverde Group. Lewis Shale covers the eastern part and northeastern corner of the Pueblo Pintado and Chaco Canyon units of the park, respectively. The Pictured Cliffs Sandstone crops out in the northeastern corner of the Chaco Canyon unit.

The bedrock at Chaco Culture National Historical Park was deposited following inundation by the Western Interior Seaway across the North American continent. Seawater began to cover the land area that is now New Mexico about 96 million years ago. The seaway was oriented northwest–southeast, and the park was on the western shoreline (fig. 3). As the shoreline migrated back and forth for 30 million years,

Table 1. Upper Cretaceous stratigraphy of the San Juan Basin

Upper Cretaceous Rocks (Map Unit Symbol)			Event	Environmental Setting	Energy Resources
Kirtland Shale (Kk)			Post–Western Interior Seaway	Swamp, river, lake, and floodplain	Coal
Fruitland Formation (primarily shale) (Kf)			Post–Western Interior Seaway	Swamp, river, lake, and floodplain	Coal, coal-bed methane
Western Interior Seaway	Pictured Cliffs Sandstone (Kpc)		Final retreat of seaway from San Juan Basin area	Coastal delta front, beach, and stream channel	Oil, gas
	Lewis Shale (Kl)		Marine deposition between a major transgressive (advance)–regressive (retreat) cycle	Offshore marine (deep water)	Gas
	Mesaverde Group	Cliff House Sandstone (Kch, Kchu, Kchwu Kchwl, Kchm, Kchi, and Kchl)	Marine transgression	Barrier island	Oil, gas
		Menefee Formation (primarily shale) (Kmf, Kmft Kmfa, Kmfaj, and Kmfal)	Continental deposition between a major marine regressive–transgressive cycle	Lowland swamp, lagoon, and stream channel	Coal, coal-bed methane, gas
		Point Lookout Sandstone	Marine regression/retreat	Nearshore marine (littoral/intertidal zone)	Oil, gas
		Crevasse Canyon Formation (primarily shale) (Kcg and Kcda)	Marine regression	Lagoon, estuary, and beach	Coal
	Gallup Sandstone		Marine transgression	Offshore marine to coastal (shoreface)	Oil, gas
	Mancos Shale		Marine transgression	Offshore marine	Oil
	Dakota Sandstone		Initial advance of the Western Interior Seaway into New Mexico	Stream channel and floodplain grading into offshore marine	Oil, gas

Notes: Blue-shaded units occur within Chaco Culture National Historical Park. These rocks are between 100 million and 66 million years old (fig. 6).
Source: Brister and Hoffman (2002).

and sandstone, shale, mudstone, coal, and limestone formed in continental, coastal, and marine settings (table 1). When sea level rose, a marine transgression took place, causing retreat of the western shoreline toward the southwest. When sea level fell, a marine regression took place, causing the western shoreline to advance toward the northeast (table 1). During the existence of the Western Interior Seaway, as many as five major transgression–regression episodes and many minor ones took place (Molenaar 1977). These cycles are recorded by the rock formations of the San Juan Basin of New Mexico and Colorado (figs. 4 and 6). Not all of these formations occur in Chaco Culture National Historical Park (table 1).

Sea level rise during the Late Cretaceous Period was primarily the result of changes in the rate of sediment delivery into the subsiding ocean basin (Fassett et al. 1990), rather than melting of continental ice caps like today. At least 2,000 m (6,500 ft) of sediment was deposited in the San Juan Basin while sea level was rising and/or the area was subsiding (Molenaar 1977).

Characteristic of their marine history, Upper Cretaceous rocks are known to be fossiliferous (Siemers and King 1974). The remains of organisms (organic matter) deposited along with sediment would later be converted to hydrocarbons as the basin subsided during the Laramide Orogeny (approximately 75 million–40 million years ago), and more sediment accumulated atop these Cretaceous strata (fig. 4). Oil and gas was ultimately developed in the Upper Cretaceous rocks as a result of increasing burial depth that caused increased temperature. By the end of the Laramide Orogeny, these rocks had reached a maximum depth of burial. Following the orogeny, regional heating of deeply

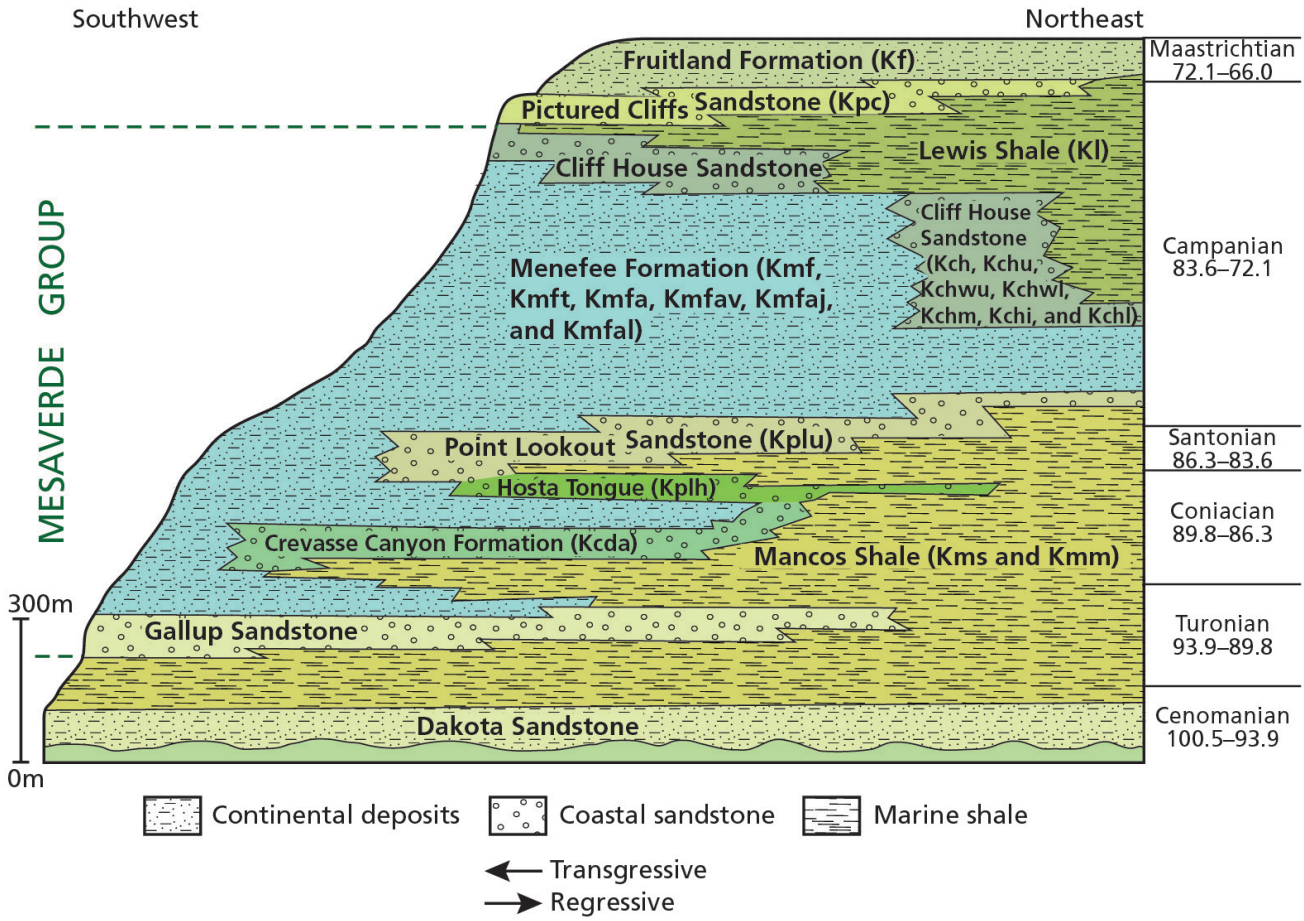

Figure 6. Graphic representation of San Juan Basin stratigraphy. The stratigraphic record at Chaco Culture National Historical Park includes the Crevasse Canyon Formation, Menefee Formation, Cliff House Sandstone, Lewis Shale, and Pictured Cliffs Sandstone, which were deposited during the Late Cretaceous Period (100 million–66 million years ago). The scale on the right breaks the Late Cretaceous Period into stages. The map unit symbols are from the GRI GIS data. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Donselaar (1989, figure 2).

buried organic matter resulted in the generation of hydrocarbons.

The following discussion highlights the rocks and fossils that were deposited in the Western Interior Seaway in what is now Chaco Culture National Historical Park. Tweet et al. (2009) provided a detailed list of fossils documented from rocks that occur in the park. Varela (2013a, 2013b) presented preliminary results of an ongoing field-based inventory of paleontological resources within the park (see "Paleontological Resource Inventory and Monitoring" section).

Crevasse Canyon Formation

The oldest bedrock at Chaco Culture National Historical Park is the Crevasse Canyon Formation, which marks a marine regression (retreat) after deposition of the marine Mancos Shale (table 1). The Crevasse Canyon Formation crops out in the Kin Ya'a unit of the park, where Robertson (1986, 1992) mapped the Gibson Coal (map unit Kcg) and Dalton Sandstone (**Kcda**) members. The Gibson Coal Member, which overlies the Dalton Sandstone Member, is composed of carbonaceous shale, siltstone, and claystone, as well as sandstone. It was deposited in estuarine, fluvial-channel, distributary-channel, and floodplain-splay settings. The unit locally intertongues (grades laterally into) tidal-channel and marine-beach and bar deposits (Robertson 1986, 1992). Some beds are bioturbated, indicating animal activity (Robertson 1986). The Gibson Coal Member has yielded pollen, spores, coal (Tschudy 1976), plant debris, petrified wood, leaf impressions (Kirk and Zech 1977), and a few fragments of dinosaurs (Lucas et al. 2000), including a partial lower jaw from a duckbilled dinosaur (Williamson 2000).

The Dalton Sandstone was deposited during a marine regression (Kirk and Zech 1977). As the shoreline migrated seaward, a succession of settings—lagoon, tidal or estuarine channel, and shore or beach—developed (Robertson 1986, 1992). A variety of life-forms inhabited these paleoenvironments. Abundant plant life lived in lagoons. Some plant fossils retained probable root structures. Animals burrowed into lagoonal sediments, leaving trace fossils. Sediments in tidal or estuarine channels also are bioturbated (churned up by organisms) and contain trace fossils such as *Ophiomorpha* (burrows presumably made by marine crustaceans), *Thalassinoides* (cylindrical, horizontal branched burrows), and *Skolithos* (tubelike, vertical burrows). Foreshore sediments contain fish teeth, broken shell fragments, and a few fossil burrows. Upper shoreface sediments locally contain *Skolithos*, *Ophiomorpha*, and *Thalassinoides* burrows. Lower shoreface sediments contain a few trace fossils such as *Ophiomorpha* and *Skolithos* (Robertson 1992). The Dalton Sandstone has yielded internal casts of ammonites (steinkerns), coprolites of cartilaginous fish, and body fossils of turtles, mosasaurs, crocodilians, dinosaurs, and cartilaginous and bony fish (Johnson and Lucas 2003).

Menefee Formation

The dark shale of the Menefee Formation forms slopes at the base of the steep northern walls of Chaco Canyon. Locally as much as 50 m (160 ft) of the uppermost part of the Menefee Formation is exposed (Siemers and King 1974). On the southern side of the canyon, the regional dip of the rocks to the north and east brings the shale to the surface, where erosion has produced irregular ledges rather than continuous cliffs (Bryan 1928). The Menefee Formation also forms badlands (fig. 7).

The Menefee Formation crops out in the Chaco Canyon and Kin Bineola units of the park. The main formation (**Kmf**) and tongues (**Kmft**) occur in the

Figure 7. Photograph of badlands. Areas of badlands topography occur in Chaco Culture National Historical Park, including near Kin Klizhin, shown here. They form from the Menefee Formation (shale). National Park Service photograph available at http://www.nps.gov/chcu/photosmultimedia/photogallery.htm (accessed 17 April 2014).

Chaco Canyon unit. Tongues extend and thin into the Cliff House Sandstone northward from the main body of the Menefee Formation. Investigators mapped the Allison Member (**Kmfa**), the lower part of the Allison Member (**Kmfal**), and Juans Lake Beds of the Allison Member (**Kmfaj**) in the Kin Bineola unit (see Map Unit Properties Table, in pocket).

With respect to its origin in the Western Interior Seaway, the Menefee Formation lies between the Point Lookout Sandstone (not mapped in the park; see table 1), which was deposited during a marine regression to the northeast, and the Cliff House Sandstone (**Kch**), which was deposited during a marine transgression to the southwest (Fassett 1974).

The Menefee Formation preserves abundant evidence of its origins as lowland swamps, streams, and lagoons, which became coal seams, sandstone ledges, and mudstone with abundant plant and animal fossils. The Juans Lake Beds (mudstone; **Kmfaj**) are particularly fossiliferous, especially in badlands terrain at the park (Varela 2013b; see "Badlands" section). Typical fossils are petrified wood, including several in situ stumps, some of which are still upright (fig. 8). Investigators found rare fossilized in-filled termite burrows in the

Figure 8. Photograph of fossil tree stump. Petrified wood occurs in the Menefee Formation at Chaco Culture National Historical Park. Investigators discovered several preserved in situ stumps, some of which are still upright. Compass atop stump for scale. National Park Service photograph (Chaco Culture National Historical Park, CHCU 109791, Coll 0200/007-#116738) by Tom Lyttle (taken in 2006).

Figure 9. Photograph of ceratopsian (?) fossil. One of the vertebrate fossils discovered during the paleontological inventory at Chaco Culture National Historical Park is a possible ceratopsian vertebra in the Menefee Formation. Ceratopsians were herbivorous, beaked dinosaurs that thrived during the Cretaceous Period. Ancestral forms lived earlier, in the Jurassic Period (see fig. 2). National Park Service photograph (Chaco Culture National Historical Park, CHCU 109791, Coll 0200/007-#109333) by Phil Varela (taken in 2011).

Figure 10. Photograph of side-neck turtle fossil. *Testudines palomeusidea* lived during the Late Cretaceous Period. Investigators found this specimen in the Menefee Formation during the paleontological resource inventory. Paintbrush for scale. National Park Service photograph (Chaco Culture National Historical Park) by Tom Lyttle (taken in 2007).

wood and casts of palm leaves and bark impressions (Varela 2013b). During the paleontological resource inventory, investigators documented fragmentary dinosaur bones, including hadrosaur and theropod, and a possible ceratopsian vertebra (fig. 9). Additionally, investigators found a carapace of a rare, extinct pelomedusid (side-necked turtle) (fig. 10), as well as other fragmentary turtle specimens such as a trionychid turtle (fig. 11). A pelomedusid turtle specimen, which is the first of its kind known from the Menefee Formation (Tom Lyttle, Chaco Culture National Historical Park, volunteer, personal communication in Tweet et al. 2009, p. 66), was prepared by curators at Petrified Forest National Park and is now housed at the Hibben Center at the University of New Mexico in Albuquerque (Phil Varela, Chaco Culture National Historical Park, paleontology technician, written communication, 31 October 2014). The Menefee Formation also yielded possible crocodilian remains, including limb elements, scute fragments, and a possible skull/snout element (fig. 12).

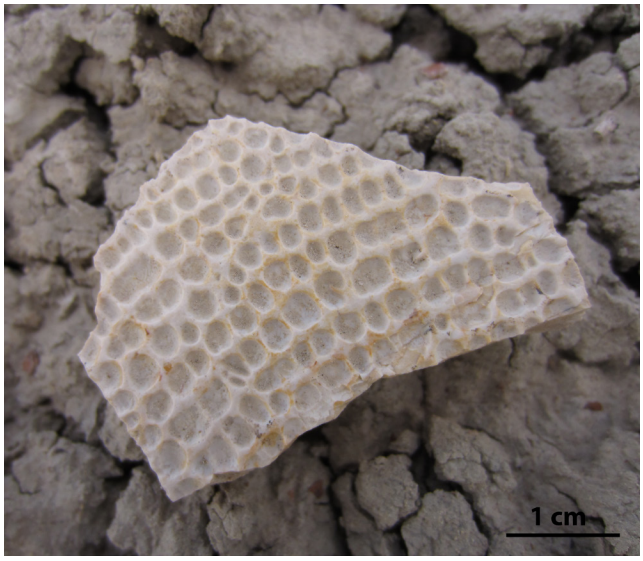

Figure 11. Photograph of turtle remains. Trionychid turtles lived in coastal lowland swamps, streams, and lagoons where the Menefee Formation was deposited. National Park Service photograph (Chaco Culture National Historical Park, CHCU 109791, Coll 0200/007-#109950) by Phil Varela (taken in 2012).

Figure 12. Photograph of crocodile fossil. During the paleontological resource inventory, investigators found this possible skull/snout element of an Upper Cretaceous crocodilian specimen in the Menefee Formation. Other fragmentary evidence includes several limb and scute fragments. National Park Service photograph (Chaco Culture National Historical Park, CHCU 109791, Coll 0200/007-#112183) by Phil Varela (taken in 2012).

Concretions

In addition to fossils, large calcareous (calcium carbonate [$CaCO_3$]–rich) concretions characterize the Juans Lake Beds of the Allison Member (**Kmfaj**) (fig. 13). Calcareous, as well as siderite (iron carbonate [$FeCO_3$]–rich), concretions are hard masses of

Figure 13. Photograph of Menefee Formation concretions. The Juans Lake Beds of the Menefee Formation are characterized by large calcareous concretions (hard masses of cemented sandstone) and small ironstone (siderite) concretions. As groundwater flowed through sedimentary strata, concretions formed within previously deposited layers. Concretionary "cement" makes the concretions harder and more resistant to weathering than the host stratum. The outcrop is approximately 5 m (15 ft) high. National Park Service photograph (Chaco Culture National Historical Park).

cemented sandstone. Concretions are typically oval or round, though irregular shapes occur. They form as a result of the precipitation of mineral cements within the spaces between sediment grains. Commonly concretions form around some kind of nucleus such as organic matter (leaf) or fossil fragment (piece of shell), which enhances chemical reactions, altering local chemistry to precipitate iron or calcite in a uniform (spherical) manner (Chan and Parry 2002).

As groundwater flows through sedimentary strata, concretions form within previously deposited layers, usually early in the burial history of the sediment before the rest of the sediment is hardened into rock. Concretionary "cement" makes the concretions harder and more resistant to weathering than the host stratum, thus preserving these early sedimentary structures (Mozley 1995). Concretions may preserve features of the original sediment such as sedimentary layering, burrows, or fossils. For this reason, fossil collectors are attracted to concretions, breaking them open in their search for plant and animal remains.

The presence of calcareous concretions distinguishes the Juans Lake Beds (**Kmfaj**) from the lower part of Allison Member (**Kmfal**), which it overlies. The Juans Lake Beds also contain small ironstone (siderite) concretions scattered along individual horizons or coalescing into thin beds. The base of the Juans Lake Beds is defined as the lowest occurrence of calcareous concretions. No calcareous concretions and few siderite concretions occur in the lower part of Allison Member.

Cliff House Sandstone

The Cliff House Sandstone overlies the Menefee Formation and forms vertical cliffs and intervening slopes within Chaco Canyon and its tributaries (see Map Unit Properties Table, in pocket). Cross-bedding (fig. 14), laminations, fossils including burrows, and cross-canyon changes within the sandstone show that these alternating cliffs and slopes are the vertically stacked remnants of barrier islands (fig. 15). The Menefee Formation represents shoreward lagoons, and the Lewis Shale represents offshore marine mud (fig. 16). The barrier islands built upward and prograded seaward as sediment accumulated (David W. Love, New Mexico Bureau of Geology and Mineral Resources, geologist, written communication, 15 May 2007).

Figure 14. Photograph of cross-bedding in Cliff House Sandstone. Packages of cross-bedding suggest deposition in water, in this case along the western shoreline of the Western Interior Seaway. National Park Service photograph available at http://www.nps.gov/chcu/photosmultimedia/photogallery.htm (accessed 17 April 2014).

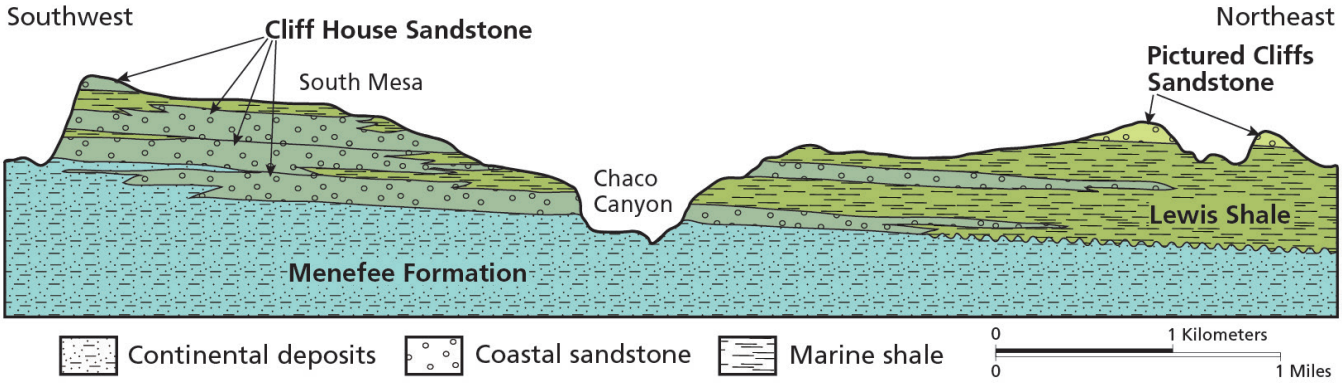

Figure 15. Cross section of Chaco Canyon. This generalized southwest–northeast cross section shows the bedrock across Chaco Canyon. Note the levels of Cliff House Sandstone, which represent past barrier-island complexes. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Love (2010, page 69).

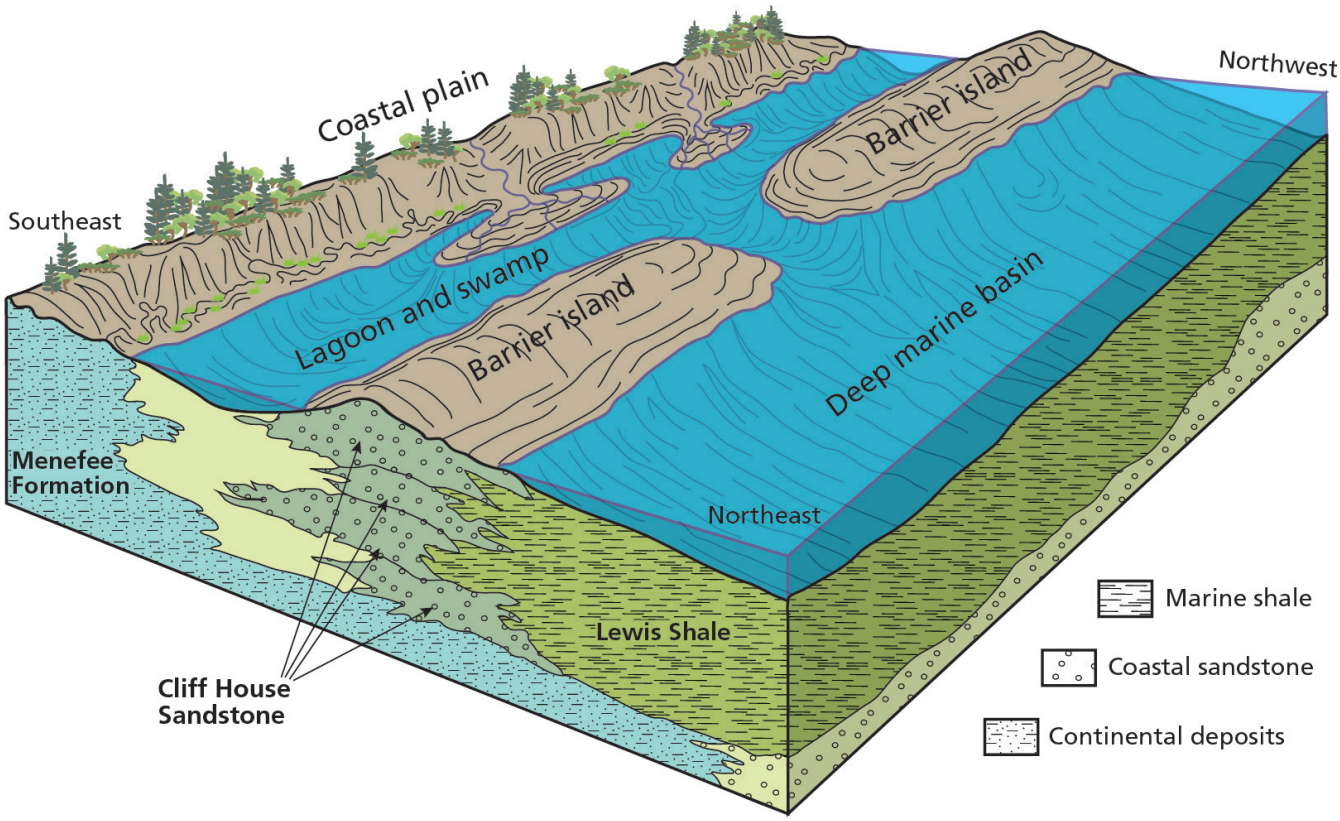

Figure 16. Schematic diagram of barrier-island complex. Upper Cretaceous rocks in Chaco Culture National Historical Park record deep marine water (Lewis Shale); barrier islands (Cliff House Sandstone); and lagoon, swamp, and coastal plain settings (Menefee Formation) along the western shoreline of the Western Interior Seaway. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Love (2010, page 71).

Island position shifted back and forth during sediment accumulation so that cliffs now vary in height and record different depositional environments across the canyon and adjacent mesas (Love 2010). Each barrier-island sand deposit is about 5 km (3 mi) wide and as much as 20 m (70 ft) thick.

By analyzing the outcrops of Cliff House Sandstone in Chaco Culture National Historical Park, Donselaar (1989) was able to reconstruct the development of the western shoreline of the Western Interior Seaway. Donselaar (1989) identified notable examples of tidal-channel deposits in Gallo Canyon. These deposits show

Figure 17. Photograph of tidal "bundles" in Cliff House Sandstone. Tidal channels exposed in Gallo Canyon record lunar/tidal cycles in a barrier-island system of the Western Interior Seaway. This 10-m- (32-ft-) thick package of sandstone shows an ebb-tidal delta and tidal channel sequence with a sharp, flat base resting on the distal part of the ebb-tidal delta, which consists of interbedded sandy shale and very fine-grained, parallel laminated sand. These "bundles" of sand once moved with flooding (landward) and ebbing (seaward) of tides. New Mexico Bureau of Geology and Mineral Resources photograph by David W. Love, as discussed and annotated in Donselaar (1989).

Figure 18. Photograph of storm deposit. Sometimes referred to as "invertebrate hash," deposits of shell fragments record storm events in the Western Interior Seaway, shown here in the Cliff House Sandstone. New Mexico Bureau of Geology and Mineral Resources photograph by David W. Love.

where seawater alternately flooded landward across a barrier island with the rising tide and ebbed seaward with the falling tide, depositing flood-tidal and ebb-tidal deltas, respectively. This coastal process is preserved in the rock record as lunar "bundles" of sand (fig. 17). In addition, Donselaar (1989) documented many fine-scale features of barrier islands such as hummocky cross stratification in beach deposits and storm deposits composed of concentrated shell fragments (fig. 18). Paleontologists commonly refer to these storm deposits as "invertebrate hash" horizons.

Cliff House Sandstone preserves past sea life such as bivalves (fig. 19), gastropods (fig. 20), and rare ammonite casts (*Placenticeras* sp. [fig. 21] and *Baculites* sp.), which are associated with invertebrate hash horizons (i.e., storm deposits). Because of their sheer numbers, shrimp (*Callianasa*) burrows are noteworthy in the sandstone; the fossil burrows themselves are called *Ophiomorpha nodosa* (figs. 22 and 23). Fossil wood is less common in the Cliff House Sandstone than the Menefee Formation, but several in situ logs protrude from cliffs (fig. 24).

Figure 19. Photograph of bivalve fossil. Bivalve fossils are exposed on ledges that cap the lower and upper sandstones of the Cliff House Sandstone. National Park Service photograph (Chaco Culture National Historical Park, CHCU 109791, Coll 0200/007-#116295) by Tom Lyttle (taken in 2006).

Figure 20. Photograph of gastropod fossil. Indicative of life in the Western Interior Seaway, gastropods are preserved in the Cliff House Sandstone at Chaco Culture National Historical Park. National Park Service photograph (Chaco Culture National Historical Park, CHCU 109791, Coll 0200/007-#116292) by Tom Lyttle (taken in 2006).

Figure 21. Photograph of ammonite cast. *Placenticeras* sp. from the lower sandstone of the Cliff House Sandstone was a rare find during the paleontological resource inventory at Chaco Culture National Historical Park. Ammonites are an extinct group of marine mollusks related to living octopus and squid. National Park Service photograph (Chaco Culture National Historical Park, CHCU 109791, Coll 0200/007-#116499) by Phil Varela (taken in 2011).

Although vertebrate fossils are not abundant in the Cliff House Sandstone, the lower sandstone (**Kchl**) contains shark teeth (fig. 25). Significant horizons of shark teeth, fish vertebrae, and fragmentary bone material occur in the upper sandstone (**Kchu**). Particularly notable vertebrate fossils from the Cliff House Sandstone include a fragment of a mosasaur dentary (jaw) (fig. 26) and a plesiosaur humerus (fig. 27). During the paleontological resource inventory, investigators also found fragmentary bone material throughout the sandstone. Other specimens of interest are a possible plesiosaur vertebra and a single tyrannosaurid tooth fragment found among many shark teeth (Varela 2013b).

Concretions

Like the Menefee Formation, the Cliff House Sandstone contains concretions (fig. 28). Study of concretions provides a means for understanding diagenetic (post-depositional) processes and events,

Figure 22. Photograph of fossil burrows and bioturbation. Animal activity burrowed and churned up barrier-island sand, creating interesting features in the Cliff House Sandstone. For example, fossil shrimp (*Callianasa*) created trace fossil burrows (*Ophiomorpha*), which are abundant in the sandstone in the park. National Park Service photograph (Chaco Culture National Historical Park, CHCU 109791, Coll 0200/007-#116300) by Tom Lyttle (taken in 2006).

Figure 23. Photograph of fossil burrows. These *Skolithos* (vertical) burrows are trace fossils in the Cliff House Sandstone. National Park Service photograph available at http://www.nps.gov/chcu/photosmultimedia/photogallery.htm (accessed 17 April 2014).

Figure 24. Photograph of petrified log. Petrified wood is common in the Menefee Formation, but the Cliff House Sandstone (shown here) also contains Upper Cretaceous tree specimens. National Park Service photograph (Chaco Culture National Historical Park, CHCU 109791, Coll 0200/007-#116325) by Tom Lyttle (taken in 2008).

Figure 25. Photograph of shark teeth fossils. Although vertebrate fossils are uncommon in the Cliff House Sandstone, shark teeth occur in horizons in the lower sandstone. National Park Service photograph available at http://www.nps.gov/chcu/photosmultimedia/photogallery.htm (accessed 17 April 2014).

Figure 26. Photograph of mosasaur fossil. During the paleontological resource inventory at Chaco Culture National Historical Park, investigators documented a fragment of a mosasaur dentary (jaw) from the lower sandstone of the Cliff House Sandstone. Mosasaurs are an extinct marine reptile. With the extinction of ichthyosaurs and decline of plesiosaurs at the end of the Cretaceous Period, mosasaurs became the dominant marine predators. National Park Service photograph from Varela (2013b, figure 8).

Figure 27. Photograph of plesiosaur fossil. Notable vertebrate fossils from the Cliff House Sandstone include a plesiosaur humerus from the upper sandstone. Plesiosaurs were large, marine reptiles that swam in the Western Interior Seaway. National Park Service photograph (Chaco Culture National Historical Park, CHCU 109791, Coll 0200/007-#109583) by Phil Varela (taken in 2012).

including the timing, flow direction, and geochemistry of groundwater over long time scales (McBride et al. 2003). Many of the spheroidal concretions likely formed in a deltaic groundwater system where reduced iron was able to mobilize for relatively early diagenetic precipitation of cements in the concretions. Based on the complex relationships and internal structure of some of the concretions, multiple episodes of iron mobility and precipitation occurred (Roberts and Chan 2010).

Figure 28. Photograph of concretion. Concretions are typically round, possibly forming around a nucleus of organic matter or other material that enhanced chemical reactions and precipitation. This concretion formed in the Cliff House Sandstone at Chaco Culture National Historical Park. National Park Service photograph (taken in 2009).

Figure 29. Photograph of iron-cemented burrows. Ancient burrows made by shrimplike organisms were later cemented by iron oxides, including hematite. Organic matter related to the burrowing organisms provided a locally reducing environment that mobilized the iron. The width of an individual burrow is an estimated 5 cm (2 in) across. National Park Service photograph available at http://www.nps.gov/chcu/photosmultimedia/photogallery.htm (accessed 17 April 2014).

Hematite-Cemented Trace Fossils

Hematite-cemented trace fossils such as *Ophiomorpha* are a distinctive feature of Cliff House Sandstone (fig. 29). The organic matter in the fecal pellets of the burrowing organisms may have provided the right mixture of reducing and oxidizing waters to precipitate the iron. Some of the concentrated iron in the burrows may actually be iron that was disseminated and

distributed in the original shoreline sands (Chan and Parry 2002). The cemented trace fossils are intriguing because of the preferential iron-oxide cementation in the burrows and the implication that organics from the original burrow helped enhance iron cementation (Roberts and Chan 2010).

Honeycomb Weathering

Honeycomb weathering—also known as tafoni, stone lattice, stone lace, fretting, or alveolar weathering (Grisez 1960; Mustoe 1982; Neuendorf et al. 2005)—is another interesting feature of the Cliff House Sandstone. This irregular surface phenomenon consists of numerous small pits a few millimeters or centimeters wide and deep that coalesce to create a network resembling honeycomb (fig. 30). Honeycomb weathering occurs in a variety of rock types and a range of built and natural settings. It shapes ocean cliffs, deserts rocks, and Arctic landscapes (Rodriguez-Navarro et al. 1999). Honeycomb weathering may also help alter rocks on other planets, such as Mars (Rodriguez-Navarro 1998).

Charles Darwin (1839) made the first documented observation of honeycomb weathering on the voyage of the HMS *Beagle*, and Kirk Bryan made the first documented observations in Chaco Canyon (Bryan 1928). Despite long-standing interest of this geomorphic "curiosity," however, the origin of honeycomb weathering is poorly understood. Suggested mechanisms include wind erosion (Futterer 1899), mechanical disintegration induced by expansive chemical changes and associated agents of removal of debris (e.g., wind) (Blackwelder 1929), freeze-thaw (Cailleux 1953), thermal changes (Klaer 1956), erosion of large clasts (Schattner 1961), variation in moisture content in clay-rich rocks (Dragovich 1969), salt weathering (Evans 1970; Bradley et al. 1978; Mustoe 1982), chemical weathering (Gill et al. 1981; Mottershead and Pye 1994), erosion of the core stone or "core softening" (Conca and Rossman 1985), and a dynamic balance between salt weathering and the protective effects of endolithic (growing within rock) microbes (Mustoe 2010). In many cases, identifying and isolating a single mechanism responsible for the development of honeycomb has been difficult (Martini 1978). Moreover, a dearth of laboratory experiments that test the many hypotheses for the development of honeycomb weathering has added to the ambiguity of its genesis (Rodriguez-Navarro et al. 1999).

Figure 30. Photograph of honeycomb weathering. In the 1920s, Kirk Bryan made the first documented observations of honeycomb weathering in the Cliff House Sandstone of Chaco Canyon. This surface-weathering feature appears in all types of rocks and climates but is particularly notable in arid and semiarid environments. National Park Service photograph (taken in 2014).

Researchers at the Getty Conservation Institute in Los Angeles, California, were the first to experimentally reproduce honeycomb weathering (Rodriguez-Navarro et al. 1999). They showed that heterogeneous wind flow over a homogeneous limestone surface is important in the development of honeycomb weathering. Wind promotes evaporative salt growth between grains on a stone surface (see "Efflorescence" section), resulting in the development of small, randomly distributed cavities. A reduction in air pressure within the cavities resulted in increased wind speed and rapid evaporation. A high evaporation rate and evaporative cooling of the saline solution in the cavity led to more rapid and greater granular disintegration than in the surrounding areas. Apparently, local supersaturation and subsequent buildup of salt crystallization pressure ultimately resulted in the formation of this weathering pattern.

These findings demonstrated the close relationship between salts, wind, and honeycomb weathering, and offered new ways to understand the genesis of this interesting and sometimes harmful (to building stone) feature. Better understanding of honeycomb weathering has important implications for geomorphology and environmental geology, as well as stone conservation (Goudie and Viles 1997).

Lewis Shale

The Lewis Shale (**Kl**; fig. 31)—which consists of thin-bedded siltstone, sandy shale, and shale, with some sandstone beds, as well as sandy concretionary limestone—represents marine deposition in deeper water, farther offshore during an advance of the Western Interior Seaway to the southwest. The Lewis Shale reached its maximum thickness of 745 m (2,400 ft) on the northeastern side of the San Juan Basin (Molenaar 1983). It is only about 30 m (100 ft) thick in the Chaco area. North of Chaco Canyon, the Lewis Shale forms a broad, soil-covered slope. On the mesas south of the canyon, the Lewis Shale and the upper few meters of the Cliff House Sandstone have been removed by erosion (Siemers and King 1974).

Limestone beds in the Lewis Shale in the park are fossiliferous (Mytton and Schneider 1987). Trace fossils, a tooth, bone, and shell fragments are known from the Pueblo Pintado unit (Tweet et al. 2009). Plant material including petrified wood has been found on Lewis Shale surfaces at the park, but may have eroded from the overlying Pictured Cliff Sandstone (Tom Lyttle, Chaco Culture National Historical Park, volunteer, personal communication in Tweet et al. 2009, p. 69).

Pictured Cliffs Sandstone

Pictured Cliffs Sandstone (**Kpc**) is present in the main Chaco Canyon unit of the park where it forms low bluffs and has a total thickness of about 18 m (60 ft).

Figure 31. Photograph of Lewis Shale. Lewis Shale was deposited in deep, marine waters during an advance of the Western Interior Seaway. National Park Service photograph available at http://www.nps.gov/chcu/photosmultimedia/photogallery.htm (accessed 17 April 2014).

The coastally deposited sandstone represents the final retreat of the Western Interior Seaway from the San Juan Basin area. The sea retreated to the northeast and deposited delta front, beach barrier, and distributary channel sediments (Erpenbeck and Flores 1979; Flores 1979; Dam et al. 1990). Fossils are not common in the Pictured Cliffs Sandstone at the park, except for the trace fossil *Ophiomorpha* (Mytton and Schneider 1987).

Mostly north of the park, this massively bedded unit is resistant to erosion and forms sandstone cliffs. The unit was named in 1875 during the Hayden Survey for the exposures of sandstone in cliffs along the San Juan River in northwestern New Mexico (Holmes 1877). The Pictured Cliffs rise stratigraphically some 380 m (1,250 ft) across the San Juan Basin (Fassett and Hinds 1971).

Quaternary Fossils

Tweet et al. (2012, p. 359) identified Chaco Culture National Historical Park as "a prolific source of [packrat (*Neotoma* spp.)] middens," which contain collections of plant material, food waste, coprolites (fossil dung), bones, and other biological materials. The majority of the middens at the park are younger than 5,550 radiocarbon years before present (BP, where "present" is 1950 CE) (Betancourt and Van Devender 1981). The oldest dated middens are 10,600 ± 200 years BP and 10,500 ± 250 years BP (Betancourt and Van Devender 1981). Middens are an important tool for the reconstruction of late Pleistocene and Holocene paleoecology and climate in western North America because they document evidence of the builder's foraging range. Commonly, they are well preserved in arid, protected settings, such as alcoves and rock shelters (see "Cave Shelters" section).

A database maintained by the US Geological Survey (USGS) and National Oceanographic and Atmospheric Administration (NOAA) records 55 middens from nine sites at Chaco Culture National Historical Park. Betancourt (1990) identified more than 300 middens in Chaco Canyon that contain needles of the now much less abundant Colorado pinyon (*Pinus edulis*). These midden sites are at elevations of 1,860 to 2,020 m (6,100 to 6,630 ft) between Chacra Mesa and the mouth of Chaco Canyon.

Studies of packrat middens at the park led to the discovery of an extinct species of rabbitbrush (*Chrysothamnus pulchelloides*) by Anderson (1980).

The type material came from a midden in Mockingbird Canyon radiocarbon dated at 1,910 ± 90 years BP. This species records the only known Holocene plant extinction in the Southwest; its extinction may be related to human activities (Anderson 1980).

In addition to park rat middens and Upper Cretaceous rocks, scoping participants noted that Pleistocene gravels are known to yield vertebrate fossils (KellerLynn 2007). None have been found in the park, to date, however.

Chaco Canyon

Chaco Canyon is the primary geomorphic feature at Chaco Culture National Historical Park. It is 32 km (20 mi) long, 500 to 1,000 m (1,600 to 3,200 ft) wide, and traverses the main unit of the park from the southeast to the northwest. The canyon has incised into Upper Cretaceous rocks by as much as 180 m (590 ft) (Love 1983). The floor is covered by alluvium (see "Alluvial Fill" section).

A striking feature of the canyon is the asymmetry of its walls (King et al. 1985). Because the bedrock dips gently (2°–3°) northeastward, the elevation on the south side of the canyon is higher than the north side. Moreover, the canyon walls on the south side are sloped. Fanlike deposits of broken, eroded rock spill onto the canyon floor from crumbling walls (fig. 32). The south side also is more deeply dissected by tributary canyons than the north side.

Small villages, some predating the great houses but most concurrent with them, lie at the base of the southern slopes and are now buried by centuries of sheetwash alluvium (**Qsw**) and eolian (windblown) sand (**Qes**) (Strutin 1994). By contrast, the Chacoans built great houses, including the immense D-shaped Pueblo Bonito (see front cover), under the sheer, buff-colored cliffs on the north side of the canyon.

Chaco Arroyo

The alluvial-covered floor of Chaco Canyon is presently cut by Chaco Arroyo, which in turn is cut by an active inner channel (fig. 33). Throughout its history, the floor of Chaco Canyon has experienced repeated cut-and-fill cycles (see "Alluvial Fill" section), alternating between deeply gullied with arroyo channels, as it is currently, and having no gullies (Love 2010). With respect to the most recent cycle, Simpson (1850) reported observing that an intermittent channel or succession of pools had developed by 1849. Incision apparently began

Figure 32. Photograph of Chetro Ketl. The northern and southern sides of Chaco Canyon are distinctly different. Fans of debris on the southern side of canyon, as shown in the background, spill onto the canyon floor from crumbling walls. Cliffs of vertical sandstone mark the northern walls of the canyon. National Park Service photograph available at http://www.nps.gov/chcu/photosmultimedia/photogallery.htm (accessed 17 April 2014).

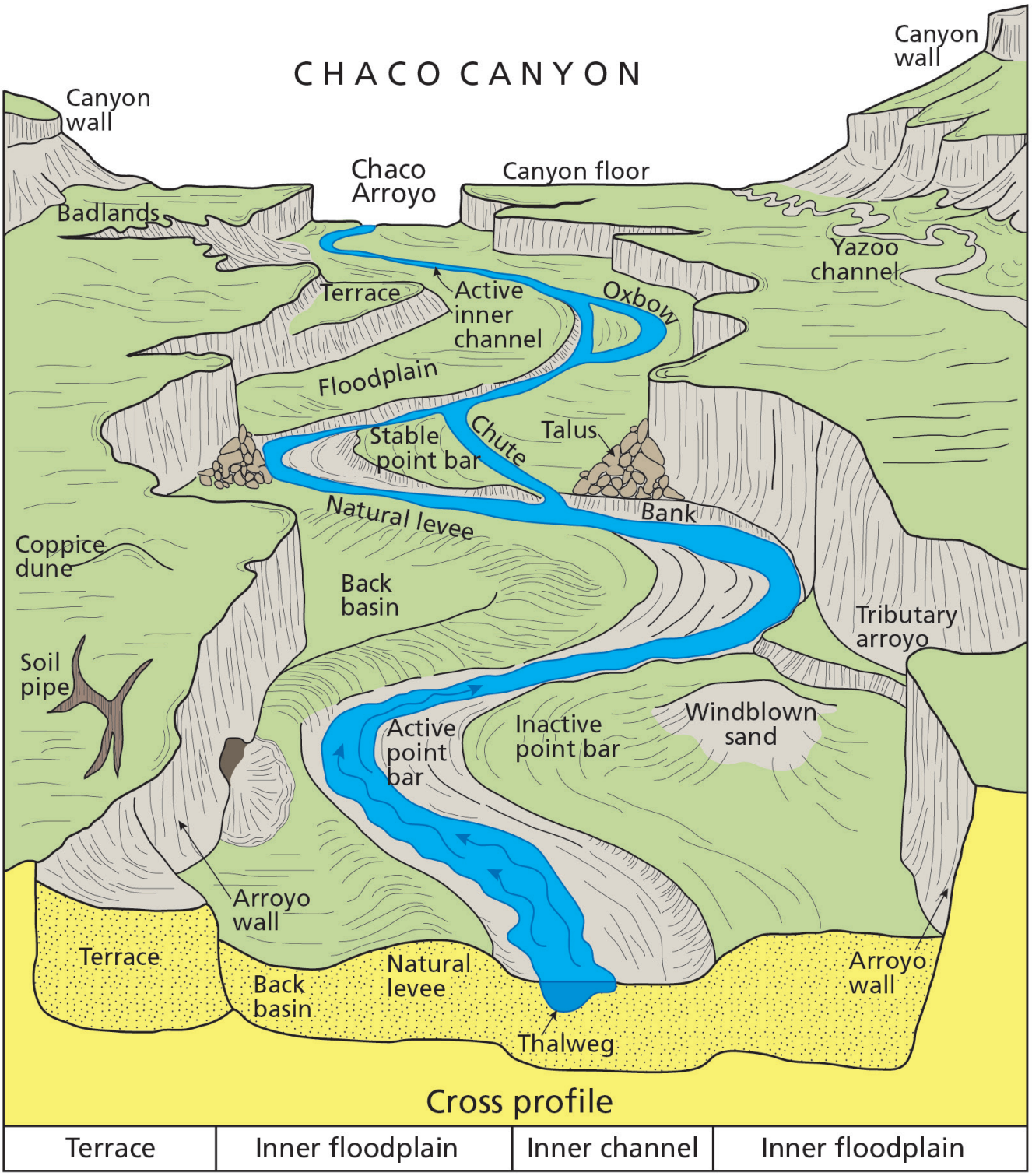

Figure 33. Schematic diagram of geomorphic features of Chaco Canyon. Chaco Canyon is the primary landscape feature in Chaco Culture National Historical Park. Chaco Arroyo cut into the canyon floor before 1877. The active inner channel cut into the floor of Chaco Arroyo after 1934. The lowest point of the active inner channel is the thalweg. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Love (1980, figure 17).

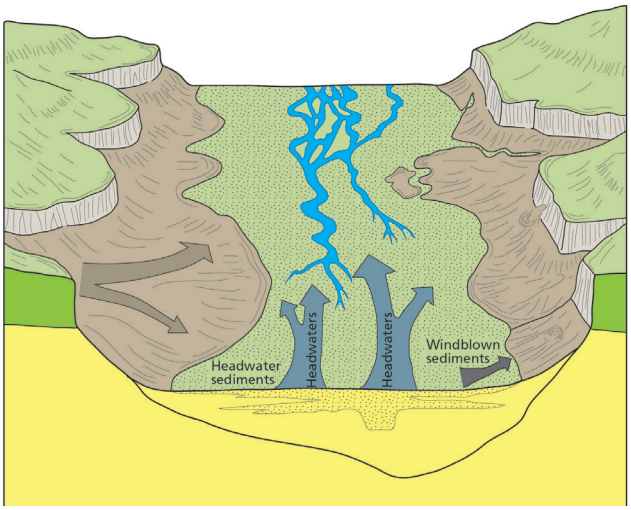

Figure 34. Schematic diagram of Chaco Canyon without an arroyo. Without an entrenched channel (arroyo), sediments from the headwaters (gray arrows) spread across the canyon floor (light stipple) during a flood and interfinger with locally derived sediments (brown deposits) along the canyon margins. Headwater sediments also may be transported by overland flow or in a single shallow channel or numerous shallow braided channels. Some sediment from the headwaters may be windblown onto the canyon margins (black arrow on right). Side channels may be flooded (brown arrows). Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Love (1977, figure 10).

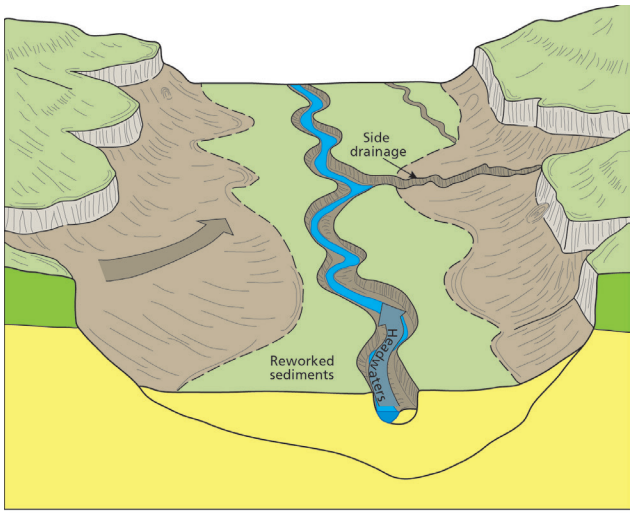

Figure 35. Schematic diagram of Chaco Canyon with an arroyo. When sediments from the headwaters are confined to an arroyo, sediments from the canyon margins (brown arrow) and reworked sediments on the canyon floor dominate deposition. Local side drainages also may be confined to channels. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after from Love (1977, figure 9).

before 1877 when Jackson (1878) reported a channel more than 4 m (13 ft) deep. Photographs and channel measurements beginning in 1896 describe an incising arroyo with little vegetation and a flat bottom until the early 1930s (Love 1980). The active inner channel developed after 1934 (see "Geologic History" chapter).

The walls of Chaco Arroyo are between 3 and 11 m (10 and 36 ft) high and exhibit various stages of erosion, from freshly broken vertical walls to eroded, badlands-like slopes. The floor of the arroyo averages 65 m (200 ft) wide (Love 1977). The walls of the active inner channel are between 1 and 3 m (3 and 10 ft) high, and the width of the channel is between 3 and 10 m (10 and 30 ft) across. Ephemeral waters in Chaco Wash flow within the active inner channel and sometimes onto the floor (floodplain) of Chaco Arroyo during floods (fig. 33).

Geomorphic features in Chaco Arroyo include, from roughly top to bottom, windblown sand, natural levees, oxbows, active and inactive point bars, and the thalweg (lowest point of the active inner channel) (Love 1980).

Additionally, a terrace or bench of alluvium is 1.5 to 3 m (5 to 10 ft) below the top of the arroyo's walls (fig. 33).

Dynamic Sedimentation and Arroyo Development

Chaco Canyon has 30 m (100 ft) of alluvial fill; 11 m (36 ft) of this fill is exposed in the walls of Chaco Arroyo (Love 1983). Color, clay mineralogy, and sedimentary structures distinguish these sediments as eolian, side canyon, arroyo channel, or bank deposits (Love 1977). The fill consists of both locally derived and headwater derived sediments (Siemers and King 1974). Locally derived Cliff House Sandstone sediments are "sandy" yellowish kaolinite (clay), whereas sediments derived from upstream areas in the Menefee Formation are "clayey" brownish gray or grayish brown montmorillonite (clay) (Love 1977; Hall 2010).

Love (1977) proposed that when no arroyo is present, sediments from the headwaters dominate the sedimentary record, spreading across the canyon floor and interfingering with locally derived deposits along the canyon margins (fig. 34). When an arroyo is present, local sediments dominate the sedimentary record because headwater sediments are confined to an arroyo (fig. 35).

Alluvial Fill

As shown on the source maps and in the GRI GIS data, the floor of Chaco Canyon is covered by undifferentiated Naha and Tsegi Alluviums (**Qnt**) or Naha Alluvium (**Qn**) (see poster, in pocket). The terms "Naha" and "Tsegi" come from work by Hack (1941) in Arizona's "Navajo Country." Hack's system of alluvium, in ascending order (oldest to youngest), is Jeddito, Tsegi, and Naha. According to Hack (1941), the Jeddito Alluvium contains proboscidian remains, 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). Investigators in the Chaco Canyon area, including Weide et al. (1980), Scott et al. (1984), and Mytton and Schneider (1987), used this nomenclature introduced by Hack (1941).

By contrast, Miller et al. (1991) used less formal names, which according to that study, seemed easier to understand and better fit the surficial geology in La Vida Mission quadrangle, including the Kin Bineola unit of the park. Some parts of the areas mapped as soil cover (**Qsl** and **Qss**) and as alluvium (**Qal**) in La Vida Mission quadrangle may include surficial deposits of the type designated as Naha by other investigators.

In the Kin Ya'a unit of the park, Robertson (1986, 1992) mapped two alluvial deposits of different ages. The older unit—unit 2 (**Qa2**)—was deposited during the Holocene Epoch before the latest cycle of arroyo cutting. Robertson (1986, 1992) cited Bryan (1954) for the timing of arroyo cutting, beginning about 1850. The younger unit—unit 1 (**Qa1**)—is upper Holocene in age. Robertson (1986, 1992) noted that this unit has been incised by recent arroyos, starting about 1850 (Bryan 1954).

The youngest unit of alluvium (**Qal**) occurs in the Chaco Canyon and Kin Bineola units of the park. It was mapped by Weide et al. (1980), Scott et al. (1984), Mytton and Schneider (1987), and Miller (1991) and consists of stream-deposited clay, silt, sand, and gravel along major drainages. This unit fills the lowest channels cut into the floodplains of ephemeral streams, including Chaco Wash.

Hall (1990, 2010) questioned the use of Hack's terminology in Chaco Canyon because the timing of deposition of these alluviums is unclear, and a correlation between the type localities in Arizona and Chaco Canyon in New Mexico has not been established. During geologic mapping at Chaco Canyon in the 1980s, investigators chose to use and apply Hack's terminology rather than Chaco-specific work by Bryan (1954), Hall (1977), and Love (1977), which showed that the exposed alluvial fill is neither uniformly the same over the canyon floor as indicated by color, grain size, and sedimentary structures, nor the same age, as indicated by the presence of archeological sites of different ages. Hall (1977, 2010) found that at any one place on the canyon floor, alluvium could be one of four types: (1) pre-Gallo (not dated, but estimated at late Pleistocene or early Holocene age), (2) Gallo (6,700–2,800 years BP), (3) Chaco (2,100–1,000 years BP), or (4) Bonito (800–100 years BP) (see "Geologic History" chapter).

Sheetwash Alluvium and Slope-Wash Deposits

Overland flow is runoff that moves over the land surface, ultimately on its way to a stream channel. In contrast to streamflow, overland flow is not concentrated in a channel, but moves downslope as a thin, continuous sheet of water.

Source maps included two map units of overland flow: sheetwash alluvium (**Qsw**) in the Chaco Canyon unit of the park, and slope-wash deposits (**Qswd**) in the Kin Bineola unit of the park. Scott et al. (1984) and Mytton and Schneider (1987) mapped sheetwash alluvium (**Qsw**) on the tops of mesas north and south of Chaco Canyon and along the canyon's margins. This material accumulated when rain fell and moved fine sediments downslope where they grade into stream-deposited alluvium. Most of this material originated from the underlying Menefee Formation, but was deposited during the Holocene Epoch, and is still accumulating. Some small areas of gravel with a sheetwash origin along Fajada Wash are older (Pleistocene Epoch). These deposits correlate with the Jeddito Alluvium of Hack (1941), which is exposed in a gravel pit 0.8 km (0.5 mi) southwest of park headquarters, and may be equivalent to the "Fajada gravel" of Hall (1977, 2010) (see "Geologic History" chapter).

Miller et al. (1991) mapped slope-wash deposits (**Qswd**) in the Kin Bineola unit of the park. Many large and small areas in the La Vida Mission quadrangle, where Kin Bineola is located, consist of gently sloping, almost smooth surfaces that have been formed by

Figure 36. Photograph of broken concretions. The formation of concretions takes place underground, but where exposed at the surface can become broken into fragments. This debris is from the Menefee Formation south of Chaco Culture National Historical Park. Photograph by David W. Love (New Mexico Bureau of Geology and Mineral Resources).

"sheetflood" erosion. Sheetfloods usually occur before runoff is sufficient to promote channel flow, or after a period of sudden and heavy rainfall (Neuendorf et al. 2005). Slope-wash deposits developed most readily where mudstone of the Menefee Formation weathered to form an easily eroded mantle. Some of the slope-wash surfaces consist of mud left behind by a flood, but some are paved with sand or rock fragments from nearby weathered beds of sandstone in the Menefee Formation. Still others have a veneer of angular chips of ironstone derived from the disintegration of ironstone concretions (fig. 36), which occur in the Juans Lake Beds (**Kmfaj**). Margins of the slope-wash areas are commonly irregular and interfinger with stabilized eolian sand or soil (Miller et al. 1991).

Eolian Features

Eolian processes refer to windblown erosion, transportation, and deposition of sediments (Lancaster 2009). The broad, continuous channel of Escavada Wash–Chaco River, at the mouth of Chaco Canyon, is a source of abundant loose sand available for eolian transport (Love et al. 2011). Exposed bedrock, such as the Cliff House and Pictured Cliffs sandstones, is another source of eolian material (Weide et al. 1980; Scott et al. 1984). Southwest–northeast-prevailing winds have eroded and transported sand from channels of major washes and sandstone bedrock to create eolian features since the Pleistocene Epoch (Weide et al. 1980).

Three types of eolian deposits occur in the GRI GIS data for Chaco Culture National Historical Park. These deposits range in age from Pleistocene to Holocene. From oldest to youngest they are (1) older eolian deposits (**Qoe**), (2) eolian sand (**Qes**), and (3) alluvium and eolian deposits (**Qae**) (see Map Unit Properties Table, in pocket).

In the Chaco Canyon unit of the park, investigators mapped eolian sand (**Qes**) on mesa tops, at the mouth of Chaco Canyon, in Weritos Rincon (southern side of Chaco Canyon), and surrounding Tsin Kletsin. Much of the surface of the Kin Ya'a unit is covered by older eolian deposits (**Qoe**) of Holocene and Pleistocene age. A mixture of alluvium and eolian deposits (**Qae**) covers parts of the Kin Bineola unit. Investigators did not map any eolian units at the Pueblo Pintado unit, but deposits occur nearby.

In addition, *Soil Survey of Chaco Culture National Historical Park, New Mexico* (Zschetzsche and Clark 2004) mapped eolian soils in the park. In the Chaco area, eolian soils can be very deep and located in large dune fields or they can occur as a shallow mantle over bedrock-controlled surfaces. The Razito series is found on dunes.

Sand dunes at Chaco Culture National Historical Park include the following types:

- Barchan—crescent-shaped dunes perpendicular to the direction of the prevailing winds, composed of younger eolian sand (**Qes**) in the Chaco Canyon unit (Scott et al. 1984).
- Climbing—dunes formed by the piling-up of sand against a cliff, composed of younger eolian sand (**Qes**) in the Chaco Canyon unit (Scott et al. 1984).
- Coppice—small dunes forming on the lee side of vegetation, mostly above the cliffs in Chaco Canyon and along mesa tops (Love 1980).
- Parabolic—U-shaped dunes with arms pointing upwind, associated with large alluvial fans at the mouths of tributary canyons (Love 1980).
- Transverse—elongated, asymmetrical dunes perpendicular to the direction of prevailing winds. According to Zschetzsche and Clark (2004), most dunes in the Chaco area are relatively small, mostly stable transverse dunes; vegetation that restricts their activity has been established. Transverse dunes are associated with the Chaco River and Escavada

Wash near the mouth of Chaco Canyon; these dunes are up to 4 m (13 ft) high (Love 1980).

- Seif (meaning "sword")—elongated dunes parallel to the prevailing winds. Robertson (1992) mapped large-scale seif dunes (Qoesd; see GRI GIS data), some combined with barchan dunes, near Kin Ya'a, but not within the park. Seif dunes rise 1–6 m (3–20 ft) above older eolian deposits.

Zschetzsche and Clark (2004) noted that dunes may be a component of most of the other landforms. Dunes also occur within tributary canyons; for example, the dune in Weritos Rincon is more than 30 m (100 ft) high and 500 m (1,640 ft) long (Love 1980). Scoping participants mentioned this dune, as well as large dunes in the vicinity of Pueblo Pintado (KellerLynn 2007).

The general locations of the eolian deposits in and around the park remain consistent. Their forms change over time, however, as does the amount of stabilizing vegetation. Love et al. (2011) compared 1935 and 2009 aerial photographs of the mouth of Chaco Canyon that showed that active oblique transverse dunes in 1935 had shifted north and east and became blowouts (eroded hollows in a preexisting dune) and parabolic dunes with long, partially stabilized arms. In addition, thick accumulations of eolian sand along the lower cliffs on the northeastern side of the Chaco Canyon had shifted slightly east, and blowouts exposed lower cliffs that had been buried by eolian sand in 1935.

"Lake Chaco"

The idea that a sand dune dammed Chaco Wash and created a lake at the mouth of the canyon is part of the scientific and popular literature about Chaco Culture National Historical Park (see Force et al. 2002 and Force 2004). Creation of so-called "Lake Chaco" is proposed to have taken place on several occasions and has been associated with a prehistoric wall, which apparently Chacoan people built to actively manage the "dune dam." Scoping participants were skeptical of this idea, particularly because the existence of a lake had not been verified; also, the age of the dune had not been established (see KellerLynn 2007).

Since the 2007 scoping meeting, Love et al. (2011) published findings that provided several lines of evidence that nullify the hypothesis that a sand dune dammed Chaco Wash during Pueblo II occupation (900–1150 CE). Lines of evidence include the dynamic geomorphology of the sand dunes at the confluence of Chaco and Escavada washes and the floor of Chaco Arroyo, the shape of the bedrock outcrops at the confluence that influences wind currents and dune locations, the hydrology of Chaco Wash, and detailed stratigraphic mapping and analysis of the locality where lake beds were thought to exist. Descriptive details of the modern geomorphology and dynamic nature of the confluence of Chaco and Escavada washes and the sand dunes near the mouth of Chaco Canyon indicate that the dunes could not have formed a resistant dam for the discharges of Chaco Wash. Based on observed geomorphology and stratigraphy, Love et al. (2011) saw no evidence, actual or theoretical, of lacustrine depositional environments in lower Chaco Canyon.

Tinajas and Charcos

In 2007, GRI scoping participants identified tinajas as a potentially valuable geologic (and ecologic) resource in need of study at Chaco Culture National Historical Park. Participants suggested that these natural potholes may have been and may continue to be a significant source of surface water within the park, providing seasonal habitat for wildlife and microorganisms. Kirk Bryan (see "Geologic Setting and Significance" chapter) was one of the first scientists to study tinajas in the US Southwest. Bryan referred to these features as "rock tanks," though noted the name "tinajas," meaning bowl or jar in Spanish. Bryan (1920, p. 188) recognized the importance of these features in arid regions, where small water supplies made possible "a journey which otherwise could not be undertaken." Bryan saw these features as "an interesting geologic problem" and noted that regional physiography controlled their distribution. He also observed that the bases of these depressions are covered by "an effective seal composed of the slime from decayed organic matter and dust" (Bryan 1923, p. 301).

A primary characteristic of tinajas is that they form in bedrock, which in the Colorado Plateau region is usually characterized by flat, exposed surfaces of porous sandstone (Chan et al. 2005, 2006). Another characteristic of tinajas is that they form naturally, although their origin continues to be a scientific enigma. Early attempts to explain their formation included unequal weathering of rock surfaces by glaciers, streams, dissolution, and even sea urchins (Elston 1917, 1918; Bryan 1920; Ross 1923; Alexander 1932). Recent investigations indicate that the formation of tinajas may be linked to biology. Organisms adapt and

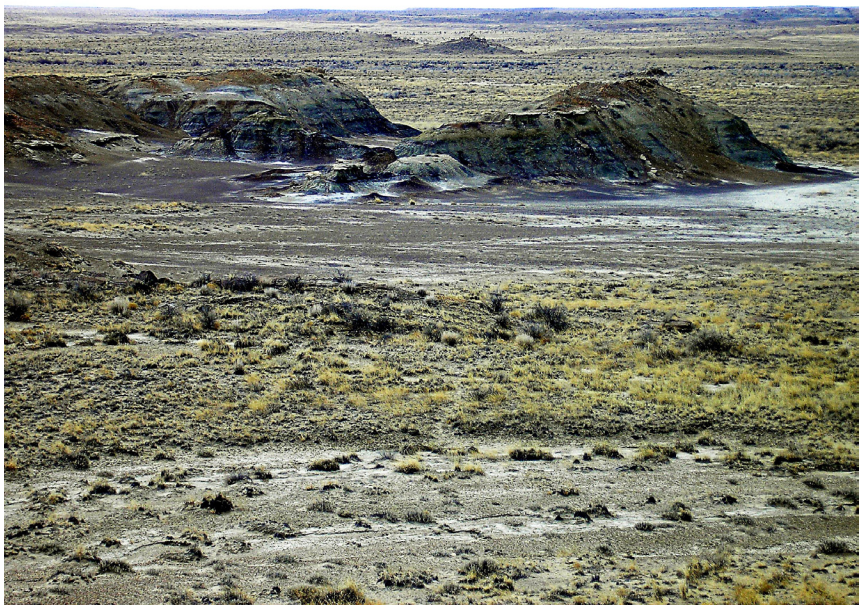

Figure 37. Photograph of Menefee badlands. Once identified by negative attributes—difficult for travel and unsuitable for farming—visitors today view and enjoy badlands as a distinctive feature of the natural landscape. Badlands are a characteristic of the Menefee Formation in Chaco Culture National Historical Park. National Park Service photograph available at http://www.nps.gov/chcu/photosmultimedia/photogallery.htm (accessed 17 April 2014).

flourish within tinajas despite extreme seasonal and daily fluctuations in moisture, temperature, and pH (Chan et al. 2001). Many species become dormant when these features dry, and must endure intense heat, UV radiation, desiccation, and freezing, but flourish again upon rehydration. These life-forms appear as a black biofilm within tinajas, which may dissolve the cement between sandstone grains, causing enlargement, as well as sealing the tinajas, enabling them to retain water longer than the surrounding sandstone (Chan et al. 2001).

Most tinajas are passive water sources, as opposed to active water sources such as springs. They require recharge by direct precipitation (Brown and Johnson 1983). Factors that affect the presence or longevity of water in a tinaja include the amount of protection or shade, the size of the adjacent bedrock catchment area, the amount of sediment infilling, and the permeability of the bedrock (Brown and Johnson 1983; Pate and Filippone 2006).

Charcos, meaning pond or small lake in Spanish, are another surface water feature at Chaco Culture National Historical Park. They are mud holes or watering holes that form in depressions in an alluvial plain or ephemeral stream bed, filling with water after rains or floods. Surface water collects in such pools at the confluence of the Chaco and Escavada washes (Mathien 2005). Bryan (1920, 1954) studied these features in Chaco Canyon and observed that they were a water supply during the growing season and, although limited, probably provided favorable conditions for farming in the canyon.

Badlands

The term "badlands" was first applied to an area in South Dakota by early French fur traders who found the lands difficult for traveling ("mauvaises terres du traverser") (see the GRI report about Badlands National Park by Graham 2008). Other connotations of "badlands" imply areas of sparse vegetation, not suitable for agriculture. Badlands in the western United States today, however, are commonly viewed as "charming features of the natural landscape" (Love 2002, p. 26). These features are abundant in northwestern New Mexico, forming 30%–40% of the area (Love 2002). Some of the most extensive badlands occur in coal-bearing rocks such as the Menefee Formation, which is mapped throughout the park, and the Fruitland-Kirtland formations, which occur in the Chaco River headwaters east of the park. Badlands are notable in the southwestern part of the park, south of West Mesa (fig. 37).

Cave Shelters

In Chaco Culture National Historical Park, cavelike features form as a result of differential weathering along the shale-sandstone contact between the Menefee Formation and Cliff House Sandstone (fig. 38). Usually referred to as "shelters," these features are notable for the resources they contain, such as packrat (*Neotoma* spp.) middens (see "Quaternary Fossils" section).

As a result of the investigation of packrat middens, the locations of many cave shelters in the park are known, and could possibly be plotted in the park's GIS (Dabney Ford, Chaco Culture National Historical Park, chief, Cultural Resources, conference call, 15 April 2014). An estimated 100 to 150 of these features occur in the park. In addition, an estimated 100 or so shelters were built under or attached to large talus boulders, and are essentially detached cliff shelters (Dabney Ford, Chaco Culture National Historical Park, chief, Cultural Resources, email correspondence, 13 August 2014). A thorough cave inventory of these features has not been conducted.

Cave shelters provided temporary and permanent living areas for prehistoric peoples. Excavations in some of the larger cave shelters at the park have provided significant information on older cultures that date back to pre-Clovis times, 11,000 years ago and older (Dale Pate, NPS Geologic Resources Division, National Cave and Karst Program, coordinator, written communication, 22 May 2014). Cave shelters preserve some of the earliest datable cultural material such as corn and basketry, which elsewhere readily biodegrade (KellerLynn 2007).

Figure 38. Photograph of cave shelter. Cave shelters, which prehistoric people used as temporary and permanent dwellings, such as the Gallo cliff dwelling shown here, form along the contact between the Menefee Formation (shale) and Cliff House Sandstone. This opening is 70 m (230 ft) wide, 8 m (26 ft) deep, and 5 m (15 ft) high at its highest point. National Park Service photograph (taken in 2006).

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 Chaco Culture National Historical Park. The NPS Geologic Resources Division provides technical and policy assistance for these issues.

During the 2007 scoping meeting (see KellerLynn 2007) and 2014 conference calls, participants (see Appendix A) identified the following geologic resource management issues:

- Oil and Gas Development
- Coal Resources and Mining
- Uranium Production
- Abandoned Mineral Lands
- Disturbed Lands Restoration
- Rockfall
- Paleontological Resource Inventory and Monitoring
- Piping
- Seismicity
- Eolian Processes
- Efflorescence

Resource managers may find *Geological Monitoring* (Young and Norby 2009) useful for addressing some of these geologic resource management issues. The manual provides guidance for monitoring vital signs—measurable parameters of the overall condition of natural resources. Each chapter covers a different geologic resource and includes detailed recommendations for resource managers and suggested methods of monitoring. An online version of *Geological Monitoring* is available at http://go.nps.gov/geomonitoring (accessed 27 August 2015).

As this report was in final review, the foundation document was completed for Chaco Culture National Historical Park (National Park Service 2015). The foundation document lists the following as "fundamental" resources or values:

- Core canyon communities and associated architectural features (great houses, great kivas, earthen mounds, community/habitation sites, prehistoric roads, stairways, shrines, signaling stations, rock art, and water control features)
- Chaco regional system (cultural landscape)
- Museum collections
- Ongoing cultural connections
- Unique visitor experience

Fundamental resources or values warrant primary consideration during planning and management processes because they are essential to achieving the purpose of the park and maintaining its significance.

Paleontological resources (fossils) are considered "important" resources or values. Important resources are not fundamental to the purpose of the park and may be unrelated to its significance, but are important to consider in planning processes. Geologic features and processes and some of the resource management issues described in this chapter affect these values and resources highlighted in the foundation document.

Oil and Gas Development

Oil and gas development and associated impacts are a potential threat to four of the five fundamental values (the fifth being museum collections) identified in the park's foundation document (National Park Service 2015). Oil and gas development is therefore a "key issue" for park managers and additional information on threats posed by hydraulic fracturing ("fracking") is a medium priority data need (National Park Service 2015).

At present, the Mancos Shale (oil) and Gallup Sandstone (oil and gas) are the primary targets for oil and gas development in the San Juan Basin. Improvements in horizontal drilling and hydraulic fracturing, commonly called "fracking," have spurred renewed industry interest in these rocks (National Park Service 2014b). 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 2014b).

In conventional vertical wells, production of oil and gas in the Mancos Shale and Gallup Sandstone is limited by natural fracturing, which was induced as a result of deformation that occurred during basin formation. Horizontal drilling can enhance production by first drilling vertically to or near the top of the target formation and then turning the drill bit horizontally into the target formation. This maneuver intersects a series of vertical fractures, exposing more of the production zone to the well bore. 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 fracking of the rock to concentrate pressures and increase subsequent fracture length (Just et al. 2013). Fracturing rock in this way is accomplished using a technique in which a liquid, typically water, is mixed with sand and chemicals, and then injected at high pressure into a well bore to create artificial fractures, along which gas and oil can migrate. After hydraulic pressure is removed from the well, small grains of sand or aluminum oxide, called "proppant," hold these fractures open.

Fracking of the Gallup Sandstone is a particular concern for park managers because the park's drinking water well is developed in this sandstone. The risk is related to potential contamination from the introduction of fracking fluids in the production well development process (Stephen Monroe, NPS Southern Colorado Plateau Network, hydrologist, written communication, 30 October 2014). If large-scale development of natural gas from the Mancos Shale were occurring close to the park, it could be cause for concern about the potential for contamination of the fresh groundwater resource in the Gallup Sandstone (Larry Martin, NPS Water Resources Division, hydrogeologist, email communication, 5 September 2014).

Other 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;
- Impacts to cultural resources, including archeological structures, as a result of vibrations from transportation and drilling (see "Seismicity" section); and
- Safety concerns and impacts to wildlife associated with the necessary transportation to support drilling operations (National Park Service 2013, 2014b).

A concern of park managers at Chaco Culture National Historical Park is the uncertainty of how many wells will be drilled. Estimates depend on current technology, as well as interest and investment by oil and gas companies. For example, Engler et al. (2001) discussed reasonable foreseeable development in the New Mexico portion of the San Juan Basin and predicted the completion of 16,615 wells over a 20-year period (2002–2022). These investigators estimated a significant reduction (25%) in this number (to 12,461) as a result of opportunities for commingling (producing oil and gas from two or more reservoirs at different depths) and dual completion (a single well that produces from two separate formations at the same time), equating to a rate of 623 wells completed per year. In actuality, 1,519 wells were completed in the San Juan Basin with an average of 190 wells per year between January 2006 and December 2013 (Ron Broadhead, New Mexico Bureau of Geology and Mineral Resources, principal senior petroleum geologist, email communication, 2 May 2014). Thus the actual outcome at that time was noticeably lower than those anticipated by Engler et al. (2001) because that report was prepared before the advent of horizontal drilling and was based on the assumption that all wells would be conventional vertical wells, which are less costly. A substantial increase in the number of completed wells (greater than 190) is anticipated based on the interest and investment of the three most involved companies—Encana Corporation, WPX Energy, and Logos Resources, LLC. If these companies can define the most productive parts of the play, and if production is substantial enough, then drilling will probably increase year-to-year over the next few years (Ron Broadhead, New Mexico Bureau of Geology and Mineral Resources, principal senior petroleum geologist, email communication, 2 May 2014).

The New Mexico Oil Conservation Division provides data and statistics about wells drilled in the state,

including a weekly activity report on intentions to drill at https://wwwapps.emnrd.state.nm.us/ocd/ocdpermitting//Reporting/Activity/WeeklyActivity.aspx (accessed 24 August 2015). This information may help park managers anticipate future activity near the park's boundary. This website provides the county and land type (federal, state, or private) of each well.

Another concern for park managers is the location of future drilling activities and wells. The majority (82%) of adjacent land to Chaco Culture National Historical Park is tribally owned by the Navajo Nation or is Navajo allotted lands, some of which are available for leasing (fig. 39). In addition, eight allotments occur within the administrative boundaries of the park. Allotments are not held by the tribal government but have been given to individual tribal members by the federal government. Most allotees inherited the land from their parents, grandparents, or great-grandparents. The incentive for allotees to develop their mineral rights is potentially high. Many allotment owners in northwestern New

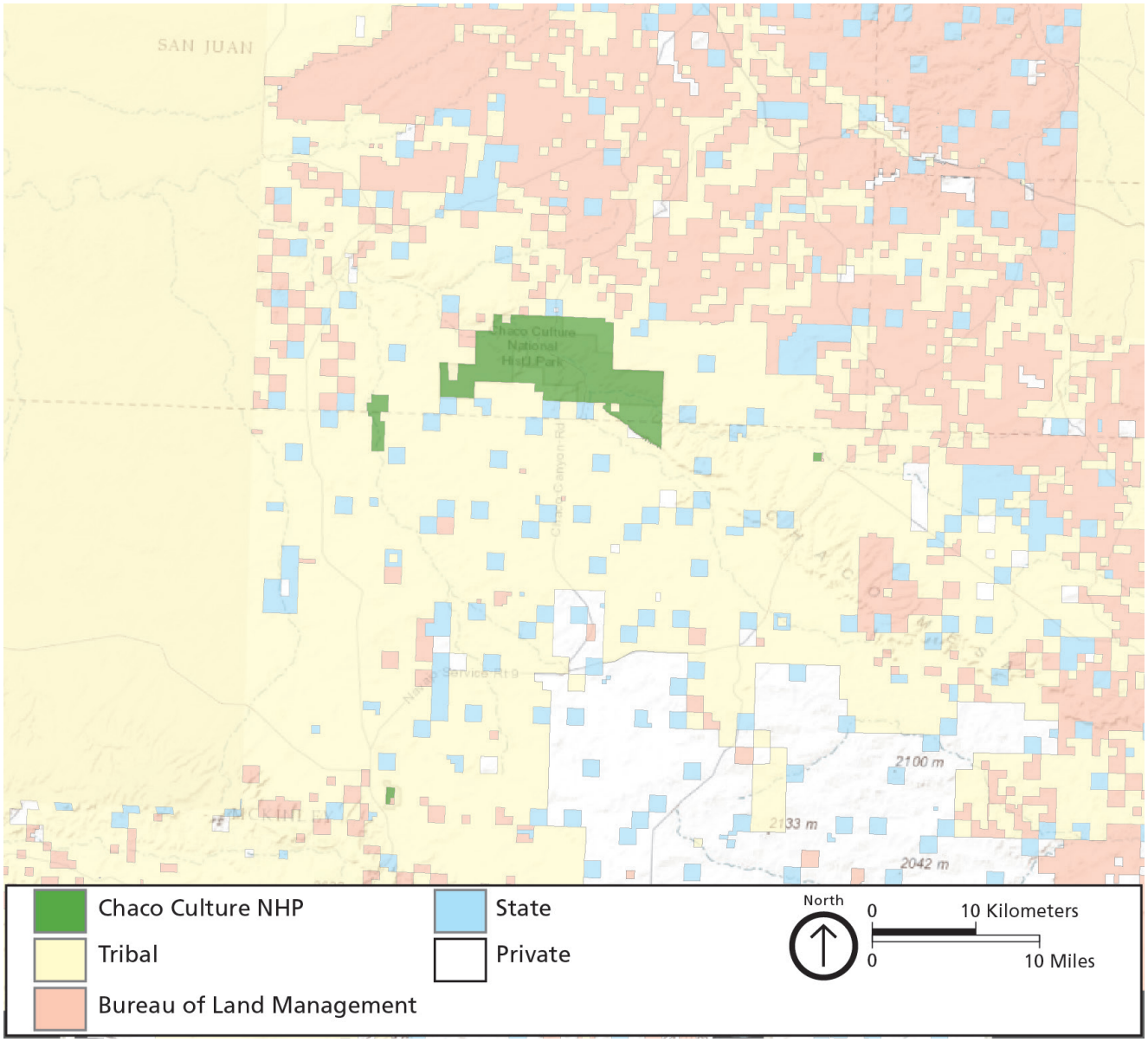

Figure 39. Map of surface ownership. Chaco Culture National Historical Park is surrounded by the Navajo Nation, individual allotments, and Bureau of Land Management lands. Some of these lands are available for oil and gas leasing. Surface ownership data compiled by the Bureau of Land Management and available online: http://www.blm.gov/nm/st/en/prog/more/geographic_sciences/spatial_data_metadata.html (accessed 28 September 2015). Map by Jason Kenworthy (NPS Geologic Resources Division).

Mexico are economically disadvantaged, and the dramatic increase of oil and gas production in the San Juan Basin would provide royalties for individual Indian families, as well as encourage economic growth and job creation on Indian lands (Bureau of Indian Affairs 2013; Montoya Bryan 2014).

In the event that an owner of one of the eight allotments wanted to explore or develop his/her mineral rights, the National Park Service would require that the owner follow the Code of Federal Regulations 36, Part 9, Subpart B (see Appendix B of this report). With respect to horizontal drilling, an allotment owner would not have the right to drill horizontally under NPS lands through "federal minerals"; the owner would have to stay within the allotment. Additionally, the allotment owner would need a New Mexico state permit to drill an exploration well. The National Park Service would work with the state, owner, and the operator to reduce or eliminate impacts to park resources (Kerry Moss, NPS Geologic Resources Division, External Energy and Minerals Program coordinator, email communication, 2 May 2014).

Federal acquisition of these private inholdings and all outstanding mineral rights would eliminate concern over future energy development within the boundaries of the park. The 1980 enabling legislation for Chaco Culture National Historical Park directed the National Park Service to acquire all lands within its administrative boundary, including these eight allotments, through exchange or purchase. The National Park Service is working with the Bureau of Indian Affairs and the Bureau of Land Management to identify acquisition opportunities (Jim Von Haden, Chaco Culture National Historical Park, Natural Resources Program manager, telephone communication, 4 September 2014).

With respect to oil and gas development, the National Park Service formally consults with the Navajo Nation at a government-to-government level. The NPS Geologic Resources Division can provide technical assistance to park managers to strive to reduce or eliminate impacts to NPS resources and values. The mutual concern of the National Park Service and Navajo Nation in protecting sensitive cultural resources is a point of agreement for conversations and consultation about oil and gas development within or near the park (Jim Von Haden, Chaco Culture National Historical Park, Natural Resources Program Manager, telephone communication, 15 April 2014).

About 18% of the land surrounding Chaco Culture National Historical Park is federally owned and managed by the Bureau of Land Management (BLM). In August 2014, the National Park Service and Bureau of Land Management signed a memorandum of understanding that formally included the National Park Service as a cooperating agency in planning to address issues relating to oil and gas in the Mancos Shale and Gallup Sandstone (Jim Von Haden, Chaco Culture National Historical Park, Natural Resources Program Manager, telephone communication, 4 September 2014; see Bureau of Land Management 2014).

Coal Resources and Mining

Geologic setting determines whether coal is present and determines whether coal beds are thick and flat-lying enough to be mined with available technology. Other factors that affect the potential for mining include coal quality (sulfur content and heating value), ash content, proximity to available transportation networks, market competition, and land-use restrictions such as ownership and access (Hoffman 2002; Hoffman and Jones 2011).

Coal-bearing units in the San Juan Basin formed in peat swamps contemporaneous with the Western Interior Seaway. Most of the San Juan Basin coals that are thick enough to have economic potential developed as the seaway retreated to the northeast. Slow, uneven retreat of the seaway allowed for substantial buildup of organic material in swamps, which became preserved as coal in the rock record (Broadhead and Hoffman 2002).

The Crevasse Canyon, Menefee, and Fruitland formations are the major coal-bearing rocks in the San Juan Basin. Within Chaco Culture National Historical Park, the Crevasse Canyon Formation (**Kcg**) and Menefee Formation (**Kmf**, **Kmft**, **Kmfa**, **Kmfaj**, and **Kmfal**) contain coal (see poster, in pocket). The GRI GIS data include coal resource occurrence and development source maps by Berge Exploration Inc. and Dames & Moore (see "Geologic Map Data" chapter). Linear geologic units in the data mark coal beds.

At present, coal seams in the Crevasse Canyon Formation are not being mined in the San Juan Basin. The Menefee Formation has two coal-bearing

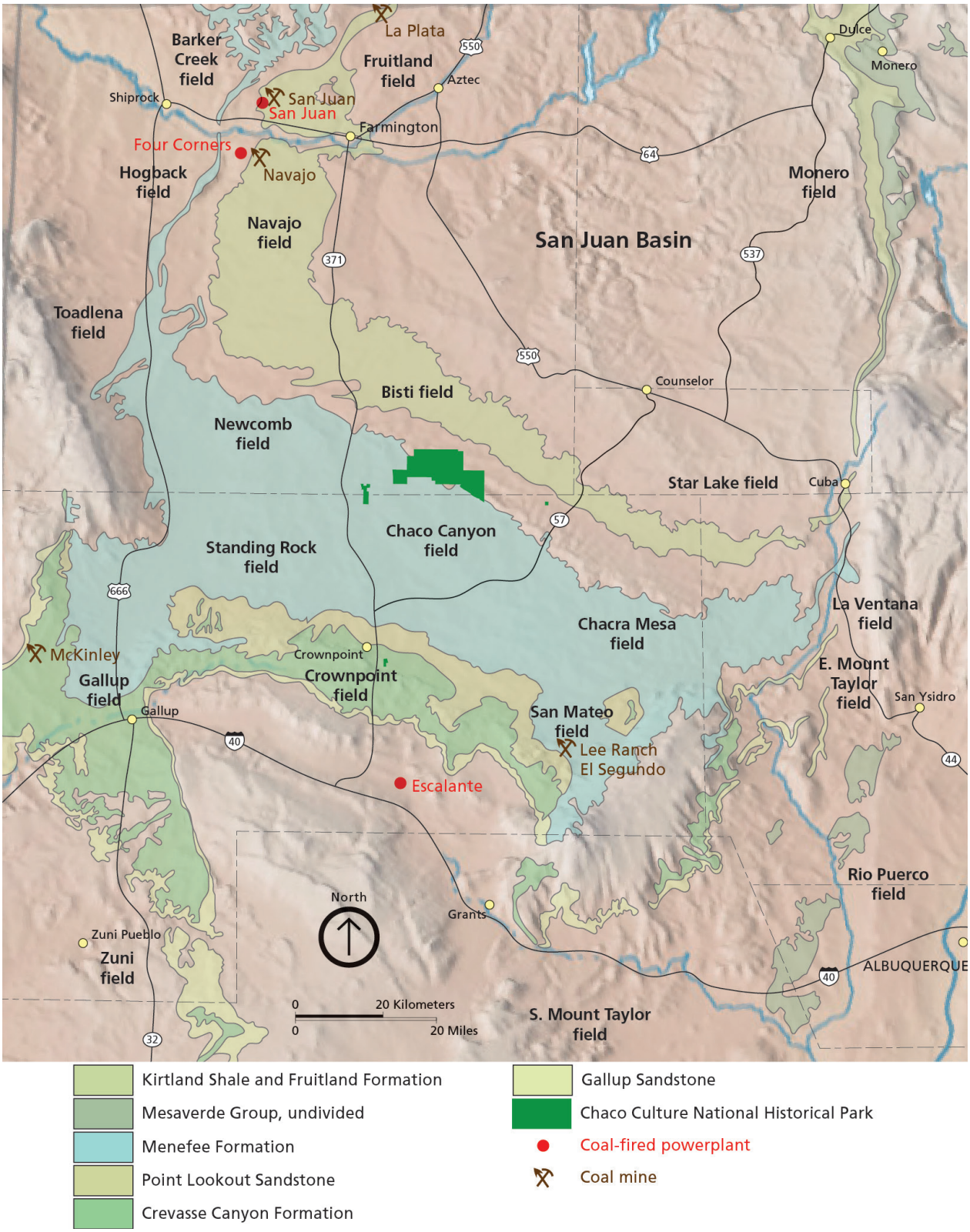

Figure 40. Map of coal fields in the San Juan Basin. Upper Cretaceous rocks in the San Juan Basin contain coal resources. The Standing Rock field is currently the primary area for coal extraction near Chaco Culture National Historical Park. The Lee Ranch and El Segundo mines produce coal in this field. The Cleary Coal Member of the Menefee Formation is mined. Graphic by Trista Thornberry-Ehrlich after Hoffman (2002, figure 2). Base map by Tom Patterson (National Park Service).

sequences: the Cleary Coal Member (**Kmfc**; see GRI GIS data) at the base, and the upper coal member at the top. The Cleary Coal Member is actively being mined in the Standing Rock field (see description below). The Fruitland Formation is actively being mined west of Farmington (Hoffman 2002).

In the 1970s, coal beds in southern Chaco Canyon and the La Vida Mission areas were of interest for mining (Shomaker et al. 1971). Coal in these areas was probably used by Indian inhabitants prior to exploration by European Americans (Nickelson 1988). Two mines are mentioned in the literature: (1) Blake mine in the La Vida Mission area and (2) Pueblo Bonito mine on the southern wall of Chaco Canyon (Nickelson 1988). In the La Vida Mission area, 907 million–1.7 billion kg (1–1.9 million tons) of strippable coal was extracted (Shomaker et al. 1971). The extent of production at the Pueblo Bonito mine is unknown (Shomaker et al. 1971).

At present, the primary area for coal extraction near Chaco Culture National Historical Park is in the Standing Rock field (fig. 40), which targets the Cleary Coal Member of the Menefee Formation (Hoffman and Jones 2011). The Lee Ranch Mine in the Standing Rock field, which is now owned by Peabody Energy, began operation in 1985. In 2008, the El Segundo Mine opened; this mine, also owned by Peabody Energy, is adjacent to the Lee Ranch Mine. These mines have access to rail transportation and ship coal to power plants. The El Segundo Mine is the most productive US mine outside of Wyoming's Powder River Basin. In 2013, it supplied 7.6 billion kg (8.4 million tons) of coal to the Arizona Public Service Company, Tucson Electric Power, and Arizona Electric Power Cooperative and Western Fuels Association (Peabody Energy 2014). These mining operations are 23 km (14 mi) east of the Kin Ya'a unit of the park. Notably, mining is restricted in the entire ¼ section (T17N R12W S28, McKinley County, New Mexico) in which the Kin Ya'a unit lies (Hoffman and Jones 2011).

Present-day owners of eight allotments within the park have the authority to extract resources such as coal on their lands. Scoping meeting participants thought this was unlikely, however, because the parcels of land are small and no one lives on them to use the coal for "personal consumption" (i.e., heating or cooking) (KellerLynn 2007).

The National Park Service has the legal authority to provide input during permitting of mining activities within a park's viewsheds, or if a federal action may in any way impact or impair park resources of values. The Surface Mining Control and Reclamation Act of 1977 controls surface coal mining and reclamation activities on both federal and nonfederal lands (see Appendix B). Surface coal mining includes activities conducted on the land surface in connection with a surface coal mine or surface operations and impacts associated with an underground mine. Section 522(e) of this act contains provisions that protect "publicly owned parks" from adverse impacts of surface coal mining.

The NPS Geologic Resources Division works with adjacent land managers and other permitting entities to help ensure that NPS resources and values are not adversely impacted by mineral exploration and development. 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 and overall degradation of the visitor experience are particular concerns. The NPS Geologic Resources Division website, http://go.nps.gov/grd_energyminerals (accessed 27 August 2015), provides additional information about energy development and mineral extraction.

Uranium Production

For nearly three decades (1951–1980), the Grants uranium district in the San Juan Basin of northwestern New Mexico produced more uranium than any other district in the United States (McLemore 2007). The Grants district extends from east of Laguna to west of Gallup and encompasses parts of Chaco Culture National Historical Park. The Chaco Canyon unit of the park is in the Chaco Canyon subdistrict; the Kin Ya'a unit is in the Church Rock–Crownpoint subdistrict (fig. 41). The exploration of uranium resulted in abandoned mineral lands (AML) sites within and near the park. These sites are discussed in the "Abandoned Mineral Lands" section.

To date, the closest mining operation to the park to have produced uranium was the Crownpoint Mine, which is about 4 km (3 mi) west of the Kin Ya'a unit (see GRI GIS data, mine point feature). In addition, the Mobil Oil Company had an in situ leaching (ISL) pilot

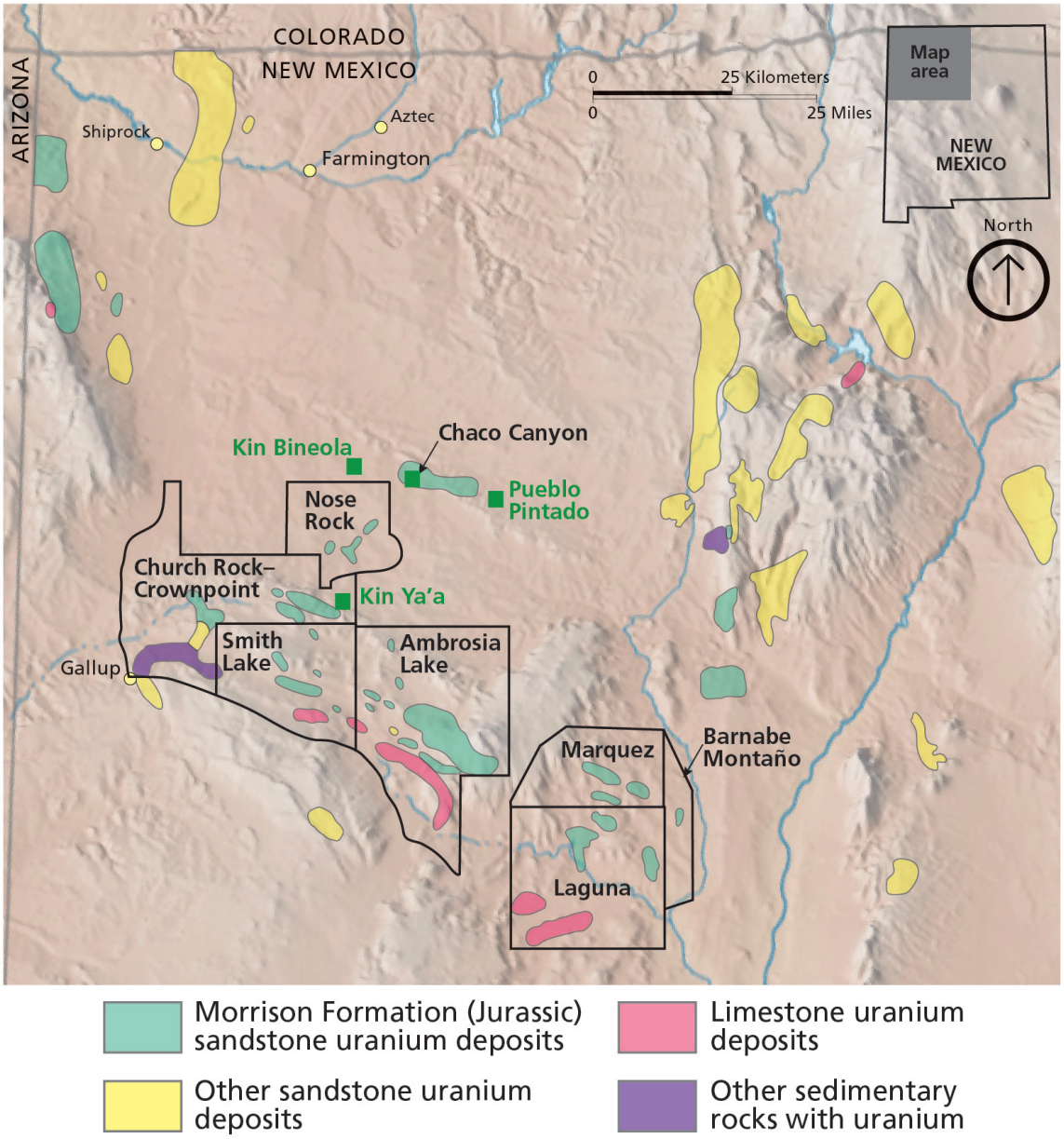

Figure 41. Map of Grants uranium district. The historically significant Grants uranium district of northwestern New Mexico encompasses parts of Chaco Culture National Historical Park. Black outlines and labels delineate uranium subdistricts. Units of the park are indicated with green boxes and/or labels. The Chaco Canyon unit of the park is in the Chaco Canyon subdistrict. The Kin Ya'a unit of the park is in the Church Rock–Crownpoint subdistrict. Although no production is occurring within the Grants uranium district today, the Morrison Formation (sandstone) retains rich uranium reserves. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after McLemore (2007, figure 1). Base map by Tom Patterson (National Park Service).

project in the Church Rock–Crownpoint subdistrict. In situ leaching, also known as solution mining, involves leaving the ore in the ground, and recovering the minerals from it by dissolving them and pumping the enriched solution to the surface where the minerals can be recovered.

The most important uranium deposits in the Grants uranium district are within the Upper Jurassic Morrison Formation (sandstone). Most of the uranium production in New Mexico has come from these deposits (McLemore 1983). Humates (organic-rich deposits) also have produced uranium (Ginger McLemore, New Mexico Bureau of Geology and

Mineral Resources, senior economic geologist, written communication, 2 September 2015). Following deposition, groundwater transported uranium into the sandstone and humates.

In the 1970s and 1980s, park managers were concerned that groundwater pumping at uranium mines might eventually affect the supply of water from the park's well. Uranium mining operations in the Crownpoint and Ambrosia Lake areas required pumping large volumes of groundwater to dewater the underground workings at these mines. The source of the park's drinking water is the Gallup Sandstone aquifer. The Gallup Sandstone, however, is separated from the uranium-rich Morrison Formation by thousands of feet of low-permeability Mancos Shale (fig. 4). Monitoring has shown that the Mancos Shale is an effective confining unit and severely restricts movement of groundwater between the Morrison Formation and Gallup Sandstone aquifers (fig. 4; Martin 2005). The source of the park's drinking water is thus protected from uranium contamination by virtue of stratigraphy and geologic conditions (Martin 2005). Furthermore, fracking of the Mancos Shale would not provide a pathway for uranium to move from the Morrison Formation into the Gallup Sandstone (Larry Martin, NPS Water Resources Division, hydrogeologist, email communication, 8 September 2014; see "Oil and Gas Development" section).

The effect of wastewater discharge upon ephemeral streams is a potential management concern resulting from uranium mining. Discharge could cause gullying, piping, or headward erosion in tributaries, or the reverse effect—the accumulation of sediment as a result of vegetation growth stimulated by an increased water supply (Simons, Li & Associates, Inc. 1982a). The greatest impacts of erosion and sedimentation would occur in tributaries adjacent to mines and mill sites.

Although the Grants district has no mines producing uranium today, energy companies have acquired uranium properties and plan to explore and develop deposits in the district (McLemore 2014). Before uranium could be produced again from the Grants uranium district and elsewhere in New Mexico, however, several challenges would need to be overcome:

- No conventional mills remain in New Mexico to process the ore, adding to the cost of producing uranium in the state;
- Permitting for new in situ leaching, especially for conventional mines and mills, will take years to complete;
- Closure plans, including reclamation, must be developed before mining or leaching begins, and modern regulatory costs will add to the cost of producing uranium in the United States;
- Some communities do not view development of uranium properties as favorable; for example, the Navajo Nation—which was severely impacted in 1979 by the Church Rock uranium mill when radioactive waste and contaminated water spilled into an arroyo that emptied into the Puerco River—has declared that no uranium production will occur on its tribal lands; and
- High-grade, low-cost uranium deposits in Canada and Australia and the large, low-grade deposits in Kazakhstan are sufficient to meet current international demands (McLemore 2007).

As low-cost technologies, such as in situ leaching techniques improve, and as global demand for uranium increases, the Grants uranium district has the potential to become an important future source, adding to its historical significance (McLemore 2014).

Abandoned Mineral Lands

Abandoned mineral lands (AML) are lands, waters, and surrounding watersheds that contain facilities, structures, improvements, and disturbances associated with past mineral exploration, extraction, processing, and transportation, including oil and gas features and operations. The National Park Service takes action under various authorities (see Appendix B) to mitigate, reclaim, or restore AML features in order to reduce hazards and impacts to resources. Resource management of AML features requires an accurate inventory and reporting. The NPS Geologic Resources Division maintains a servicewide AML database, and can provide assistance to park managers in recording AML features. An accurate inventory identifies human safety hazards and contamination issues, and facilitates closure, reclamation, and restoration of AML features. An accurate inventory also may identify opportunities for interpretation of AML features as cultural resources. Burghardt et al. (2014) and the NPS AML website, http://go.nps.gov/grd_aml (accessed 30 June 2015), provide more information.

The following is a discussion of known AML features within and near the boundaries of Chaco Culture National Historical Park. These features have not yet been documented in the servicewide AML database.

The National Park Service mined sand and gravel in the park for administrative uses until the late 1980s. The source of sand and gravel was Pleistocene terraces: one mining site was about 1.6 km (1 mi) south of the visitor center; the other was in Clys Canyon (for sand only). Moreover, building stone for the park housing area was extracted from the northern wall of Gallo Canyon.

In January 2015, park staff identified and field checked three abandoned coal mines in the park: (1) "Wetherill Mine" (also known as "Pueblo Bonita Mine") in Rafael's Rincon, (2) "CCC Mine" on the east side of South Mesa, and (3) "Hidden Mine" on the southwest side of West Mesa. Hayes (1981) mentioned a fourth mine, apparently at the foot of Chacra Mesa, but this mine could not be relocated in January 2015 (Phil Varela, Chaco Culture National Historical Park, paleontology technician, email communication, 5 January 2015).

With respect to past uranium exploration, a 1984 inventory identified two abandoned uranium test drill holes and associated access routes and drill pads in the park (Marks 1989). The locations of these particular features are unknown (John Burghardt, NPS Geologic Resources Division, geologist, email communication, 13 March 2007). The Kin Ya'a unit contains 73 drill holes. Hurley (1978) recorded these features, which were test wells drilled in 1977 and 1978 by the Mobil Oil Company, Uranium Exploration Division. Most of these drill holes are fairly evenly scattered throughout the southern part of the northeast quarter of section 28 (T17N, R12W) (Phil Varela, Chaco Culture National Historical Park, paleontology technician, email communication, 26 August 2015). The National Park Service acquired these features as a result of the 1980 boundary expansion. A primary concern associated with uranium exploration is accelerated erosion along access roads and at drilling sites (Simons, Li & Associates, Inc. 1982a).

The New Mexico Mines Database, which is maintained by the New Mexico Bureau of Geology and Mineral Resources, documents nine sites of past uranium exploration in the vicinity of the park: five separate drill holes, one quarry at Pueblo Alto, one pit in the Star Lake quadrangle, one prospect in the Kimbeto quadrangle, and a series of drill holes associated with an ISL pilot project in the Heart Rock quadrangle (see "Uranium Production" section). None of these sites produced any uranium, and future uranium production is unlikely because the mineralized layers are thin and too deep to mine economically (Ginger McLemore, New Mexico Bureau of Geology and Mineral Resources, senior economic geologist, written communication, 2 September 2015).

Disturbed Lands Restoration

Disturbed lands are those park lands where the natural conditions and processes have been directly impacted by development, including facilities, roads, dams, and abandoned campgrounds; agricultural activities such as farming, grazing, timber harvest, and abandoned irrigation ditches; overuse; or inappropriate use. Some of these features may be of historical significance, but most are not in keeping with the mandates of the National Park Service. Usually, lands disturbed by natural phenomena such as landslides, earthquakes, floods, and fires are not considered for restoration unless influenced by human activities. Restoration activities return a site, watershed, or landscape to some previous condition, commonly some desirable historic baseline. Park managers are encouraged to contact the NPS Geologic Resources Division for assistance with restoration of disturbed lands.

During the 2007 scoping meeting and 2014 conference calls, participants (see Appendix A) identified the following disturbances at Chaco Culture National Historical Park:

Grazing

In the late 1800s and early 1900s, ranchers moved large herds of sheep and cattle from Chama, New Mexico, into the Chaco Canyon area for winter grazing (Western National Park Association, publication date unknown). In 1947 the National Park Service fenced Chaco Canyon National Monument to exclude grazing; as a result native grasses, shrubs, and wildlife have returned (KellerLynn 2007). Grazing is still allowed on allotments within the administrative boundary of the park, however, and could occur in these areas in the future.

Logging

No commercial logging has occurred in the

park, although timber was collected for personal consumption on Chacra Mesa until the 1960s.

Earth Dams

Using 1975 aerial photographs, Robertson (1992) mapped an earth dam (**Qaf1**) in the Kin Ya'a unit of the park (see poster, in pocket). This dam surrounds a flowing well. Additionally, Miller et al. (1991) identified earth dams in the La Vida Mission quadrangle, including the Kin Bineola unit of the park, and included them as part of the alluvium map unit (**Qal**). According to Miller et al. (1991), earth dams were built across many washes in the La Vida Mission quadrangle to catch and retain storm water for irrigation and livestock. Dams across broader washes may be as long as 0.6 km (0.4 mi). In some places, these earth dams have altered normal drainage and sediment deposition along the Kim-me-ni-oli Wash. The effect of these dams has been deposition of silt and mud along with fine-grained sand.

When Miller et al. (1991) were conducting fieldwork, during the summer and fall months, no water was retained by any earth dam in the quadrangle. Many of the shorter dams do occasionally channel storm water into scooped-out ponds, which provide some water for sheep, goats, cattle, and a few horses that live on the range. A few scooped-out hollows are fed by water from nearby wells pumped by windmills (Miller et al. 1991).

At present, earth dams remain in place, and the National Park Service has no plans to remove them (Phil Varela, Chaco Culture National Historical Park, paleontology technician, written communication, 31 October 2014).

Solid Waste Disposal

From the 1950s to the early 1990s, the National Park Service disposed of solid waste in wide trenches, which were cut with backhoes on the eastern side of South Gap. At the time of scoping, park managers were planning to have these dumps tested for toxicity and mobility of waste (KellerLynn 2007). Since scoping, the dump sites were tested for a range of contaminants. All tested contaminants except arsenic were below the standard safety threshold, and arsenic levels at the dump site were lower than at control test points. No further testing is planned, but park staff is looking at funding options to remove the dump (Phil Varela, Chaco Culture National Historical Park, paleontology technician, written communication, 31 October 2014).

Erosion Control

In 1934, the National Park Service, Soil Conservation Service, and Civilian Conservation Corps (CCC) undertook an extensive program of erosion control that included planting 94,000 seedlings of willow, tamarisk, wild plum, and cottonwood in Chaco Arroyo (Hall 2010). GRI scoping participants noted that planting of exotic species has affected stream-channel morphology. Park staff is now controlling tamarisk in certain areas where spreading is extensive, channel morphology is changing, and cultural resources are affected (KellerLynn 2007). Other past erosion-control efforts included planting native grasses; building revetments, jetties, gabions, and fences in arroyos; plowing parts of the alluvial canyon floor and building dikes; exterminating rodents to preserve dikes; and artificially straightening the inner channel (National Park Service 1988).

During an erosion control study by Simons, Li & Associates (1982a), 58 cross sections were surveyed along Chaco Wash. These cross sections, however, were not well documented and park staff could not relocate them in the late 1990s. In 1999, with assistance from the NPS Water Resources Division (WRD), park staff established 13 well-documented and benchmarked transects throughout the park for the purpose of monitoring channel morphology. In 2005, WRD staff resurveyed these transects, and the Southern Colorado Plateau Network resurveyed them in 2008 and 2012. The network's plan is to repeat these surveys at approximately five-year intervals (Stephen Monroe, NPS Southern Colorado Plateau Network, hydrologist, written communication, 30 October 2014).

Rockfall

The stratigraphic arrangement of rocks—mudstone under sandstone—sets the stage for rockfall at Chaco Culture National Historical Park. Mudstone (Menefee Formation) erodes from beneath sandstone (Cliff House Sandstone). The unsupported sandstone then breaks away in blocks or slabs along a joint or local weakness in the rock. The movement of a block or slab away from a cliff allows other joints to open up some distance back (Bryan 1954). This stepwise erosion produces the prominent cliff faces in Chaco Canyon and the slopes of debris, called talus, at their bases (fig. 42).

Figure 42. Photograph of talus. Snow covers the talus slope next to the parking area at the visitor center in Chaco Culture National Historical Park. The talus deposit is composed of the lower sandstone (Kchl) of Cliff House Sandstone, which broke away from the upper cliff face shown in the figure. The base of the cliff consists of sandstone, shale, and coal of the Menefee Formation (Kmf). US Geological Survey photograph available at http://3dparks.wr.usgs.gov/chcu/html2/chaco429.html (accessed 13 January 2014).

Where erosive processes encroach from several directions, a landform may become segmented, producing a large singular rock mass. Fajada Butte formed in this manner over the last 10,000 years (National Park Service 2014a). In May 2012, a large rockfall occurred at Fajada Butte, illustrating the ongoing nature of this process in Chaco Canyon (Bilderback and Pranger 2013).

Threatening Rock

Since occupation of Chaco Canyon, rockfall has been a hazard. When ancient builders were constructing Pueblo Bonito, an immense slab of sandstone stood precariously behind the site (fig. 43). Apparently aware of the danger, ancient builders propped up the cliff with slanted pine posts embedded in rubble; the rubble was weather-proofed by masonry. An enormous buttress supported the masonry (Keur 1933; Judd 1959, 1964).

The slab was first described in 1901 and referred to as the "Elephant." The Navajos called it "Braced-up Cliff," and the National Park Service coined "Threatening Rock" (National Park Service 2014a).

On 22 January 1941, Threatening Rock fell, destroying 60 rooms in Pueblo Bonito (fig. 44). This event

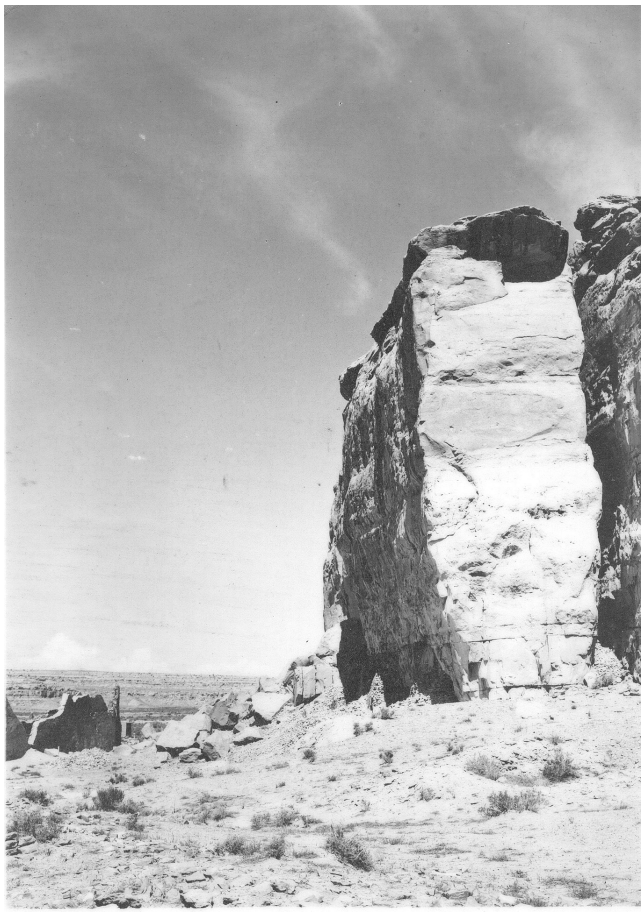

Figure 43. Photograph of Threatening Rock. Schumm and Chorley (1964) investigated and reported on the fall of Threatening Rock. They estimated that original movement began in 550 CE. In the last five years that Threatening Rock stood over Pueblo Bonito, the National Park Service monitored its movement monthly. The rate of movement increased steadily until it fell, with 25 cm (10 in) of outward movement occurring in the final month. NPS staff measured/monitored the hazard on the day it fell, 22 January 1941. Note the wall of Pueblo Bonito on the lower, left side of the photograph. National Park Service photograph by George Grant (taken in 1929).

constitutes one of the most dramatic examples of rockfall in the National Park System. It was an extraordinary instance when the geologic processes that shaped the canyon over millennia were observed by people in historic times (National Park Service 2014a).

In an attempt to predict the fall of Threatening Rock and document movement, the National Park Service began monthly monitoring in 1935. Schumm and Chorley (1964), who investigated and reported on the fall, used data gathered by NPS personnel in

Figure 44. Satellite imagery of Pueblo Bonito. Pueblo Bonito, meaning "pretty village" in Spanish, is a distinctive D-shaped great house in Chaco Canyon. Its Navajo name—tse biyaa anii'ahi—means "leaning rock gap" and refers to a monolith of rock that separated from the cliff wall behind the pueblo. On 22 January 1941, the rock known as "Threatening Rock" in English fell and crushed the northeastern part of Pueblo Bonito. Landsat image (taken 24 June 2014) accessed via Google Earth.

their analysis. These data yielded information about the type, rate, and approximate timing of original movement, which Schumm and Chorley (1964) estimated as beginning in 550 CE. In the last five years that Threatening Rock stood over Pueblo Bonito, the rock monolith moved 56 cm (22 in). The rate of movement increased steadily until it fell, with 25 cm (10 in) of outward movement in the final month. Monthly measurements indicated that the rock was periodically stationary for several months, but would show movements, relatively rapid or slow, during other periods. Notably, the periods of rapid movement always occurred in winter, when snow had collected behind the rock. This may have been an important factor in its eventual failure.

On the day the rock fell, which happened to be a day of monitoring, NPS staff heard the rock popping and cracking. The rock moved outward 0.08 cm (1/32 in) during measuring. According to eyewitness accounts, the rock fell in a combination of tilting and sliding (fig. 45). It initially appeared to settle and move (en masse) away from the cliff and subsequently tilted, probably due to a shift in its center of gravity beyond the underlying shale support (Schumm and Chorley 1964).

Present-Day Hazards and Monitoring

Rockfall continues in the park, with events in developed areas occurring several times per year (KellerLynn 2007). The foundation document identified rockfall as a threat to the core canyon communities and associated architectural features (considered fundamental resources) in the park (National Park Service 2015). The two areas of greatest concern for rockfall are the housing area and Gallo Campground, which are commonly occupied by people and are located below highly jointed cliffs of sandstone (fig. 46). The Menefee Formation is exposed to a much greater extent in the housing area than other areas of the park, adding to the

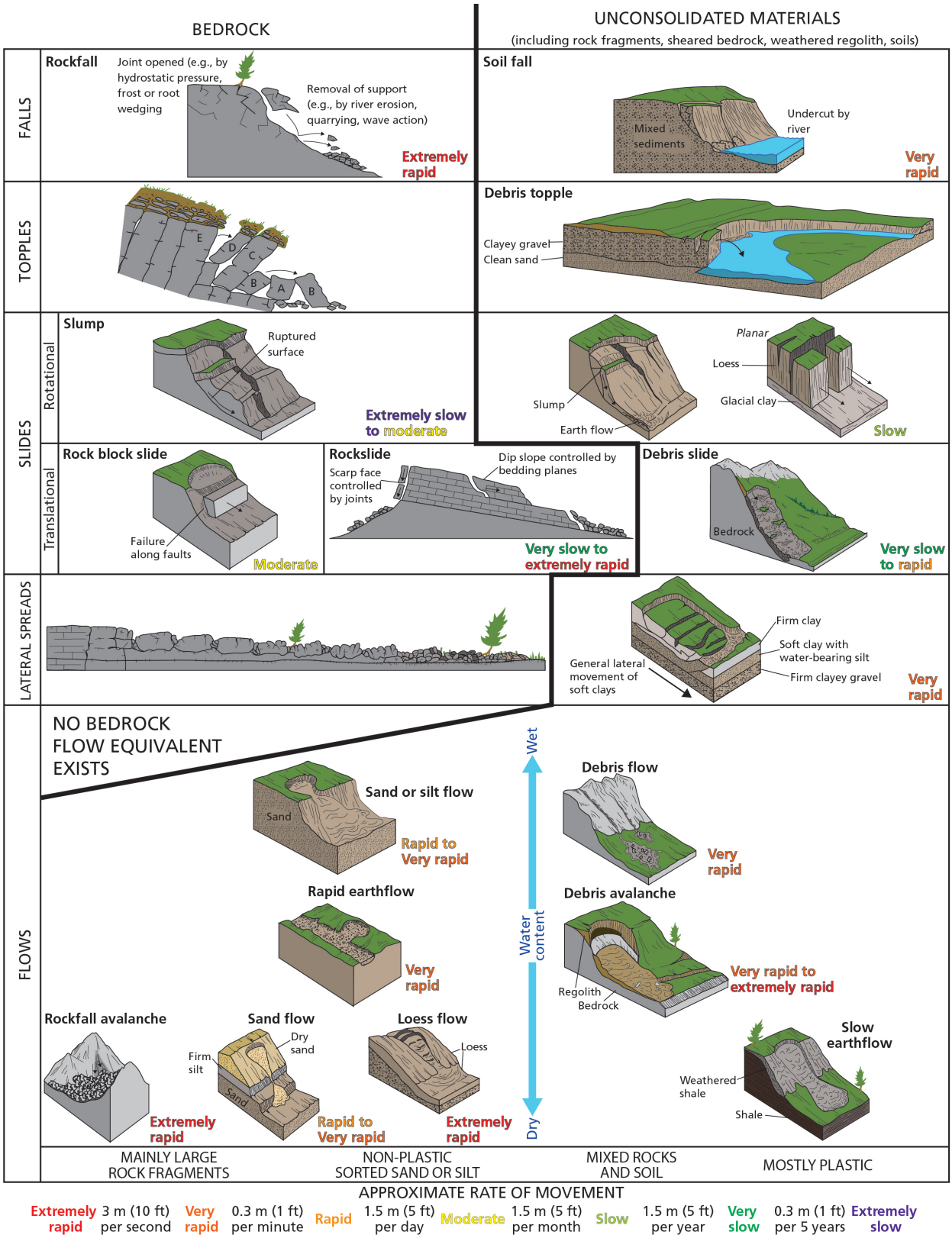

Figure 45. Schematic illustration of slope movements. Different categories of slope movement are defined by material type, nature of the movement, rate of movement, and moisture content. The fall of Threatening Rock involved falling, toppling, and some sliding movements. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Varnes (1978, figure 4.33 and information therein).

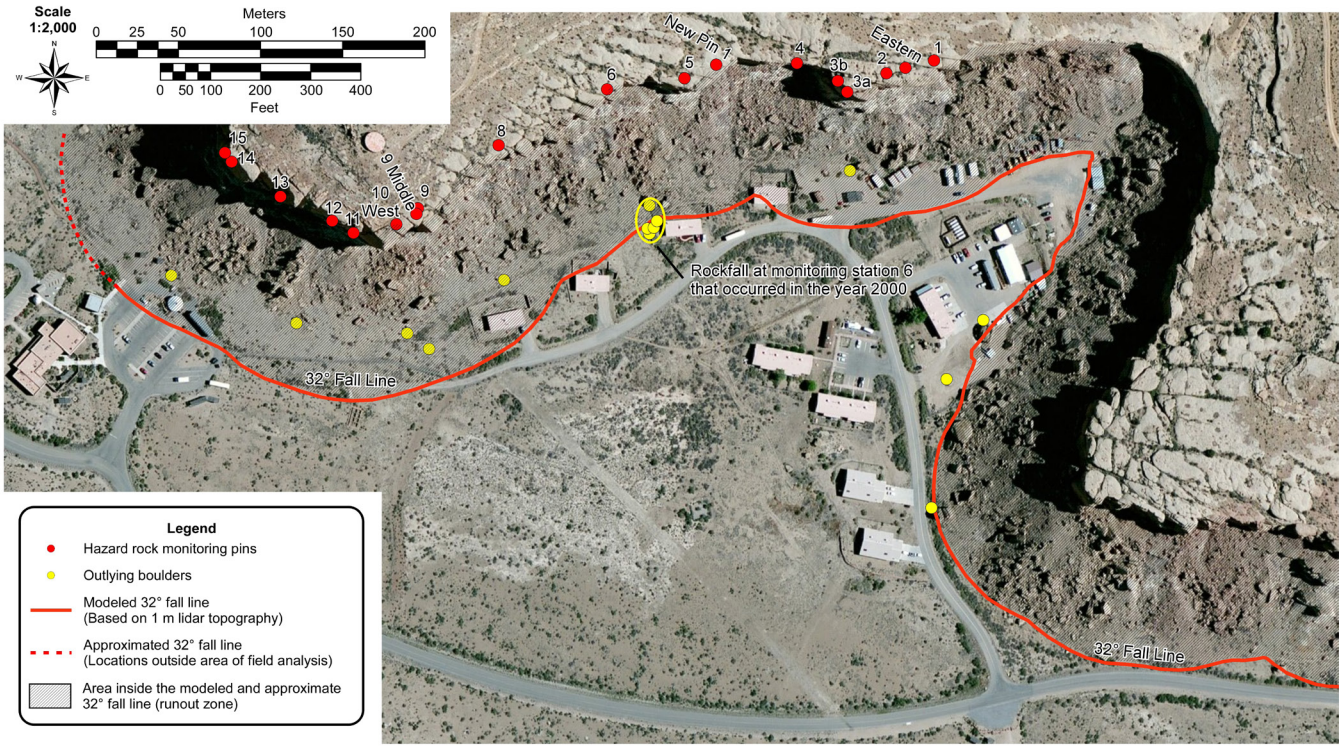

Figure 46. Photograph of rockfall hazard areas. The "fall line" (red line on the figure) indicates the best fit angle (30°) that defines a runout zone for a rockfall from the cliffs at the housing area. The line was generated using the CONEFALL model (Jaboyedoff and Labiouse 2003, 2011), a USGS digital elevation model of the area, and field measurements of outlying boulders (see Bilderback and Pranger 2013). The fall line is subject to some variability and serves as a guide rather than a definitive border. The yellow oval on the figure marks the resting locations of rocks that detached from monitoring station 6 on the Cliff House Sandstone cliff above the housing area in 2000 (see fig. 47). National Park Service graphic from Bilderback and Pranger (2013).

hazard at this location (Bilderback and Pranger 2013). Environmental weathering factors, which weaken the rock, and mechanisms that trigger rockfall (e.g., earthquakes, unusually wet periods, an abundance of freeze-thaw cycles, or construction vibrations) are the same at the housing area and campground. Conditions governing rockfall runout at the Gallo Campground, however, are different from those of the housing area. At about 15 m (50 ft) above the campground, the cliffs are not as high as those above the housing area, and the Menefee Formation only crops out at the base of these cliffs. The slope below the Menefee Formation serves as a ramp between the rockfall source area (Cliff House Sandstone) and the canyon floor, reducing potential impacts. Several constructed tent pads are very close to the cliff face, however, and are within the fall zone of even a small volume rockfall event (Bilderback and Pranger 2013).

Based on a rockfall hazard assessment by Wachter (1985), park staff established monitoring sites on the cliffs above the housing area. Depending on adequate staffing, however, monitoring has been sporadic over the years (Bilderback and Pranger 2013). Since 2011, the sites have been monitored quarterly (Phil Varela, Chaco Culture National Historical Park, paleontology technician, written communication, 31 October 2014).

In 2000, one of the hazardous rocks that had been monitored above the housing area fell, fractured, and came to rest less than 9 m (30 ft) from a residence (Bilderback and Pranger 2013). These rocks included four fragments weighing 140–230 kg (300 to 500 lbs), and one boulder weighing an estimated 180,000 kg (400,000 lbs or 200 tons) (fig. 47).

In 2012, monitoring indicated that a hazardous rock above the campground had moved 3 cm (1.2 in). Although this measurement was later determined to be incorrect, concern resulted in the submission of a technical assistance request by park managers to the NPS Geologic Resources Division (GRD). Investigation

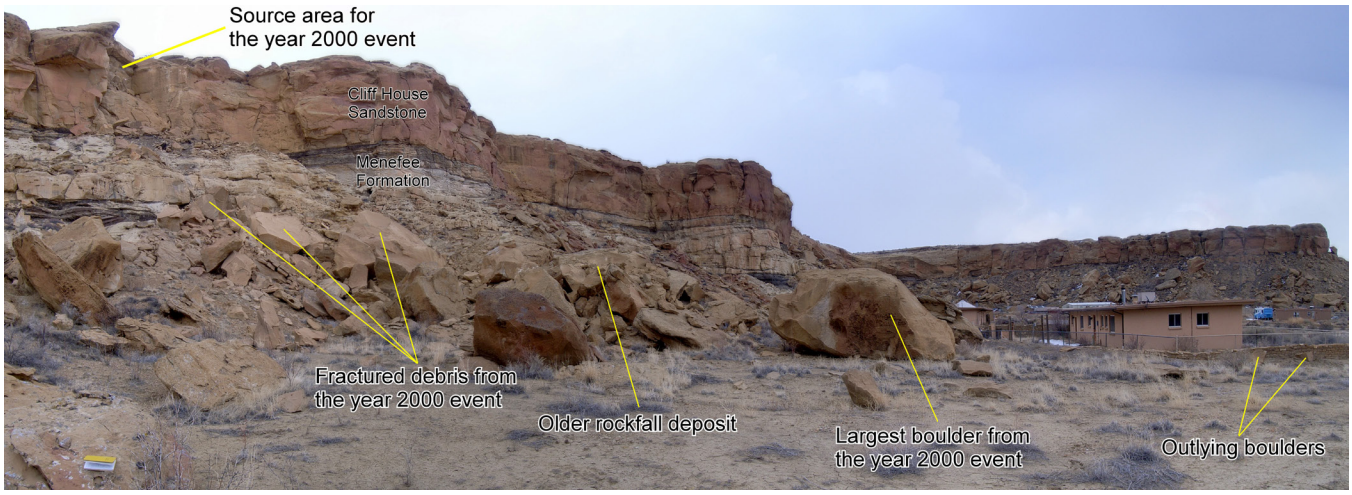

Figure 47. Photograph of rockfall at Chaco Culture National Historical Park. In 2000, a block detached from a nearly vertical cliff composed of Cliff House Sandstone and fractured upon impact with the underlying, sloping outcrop of Menefee Formation. The event left a trail of debris on the slope. The main block and possibly several smaller pieces continued down the slope, skipping or rolling over an older significant rockfall deposit. This event shows the large blocks present in the talus deposit do not necessarily provide protection from future rockfall and should not be viewed as a rockfall barrier. Outlying boulders came to rest in and just outside the enclosed yard of one of the park residences (yellow oval on fig. 46). This event provides a baseline from which to evaluate the risk from future rockfall along this section of the Chaco Canyon wall. National Park Service graphic from Bilderback and Pranger (2013).

during a site visit on 19–21 August 2013 determined the monitoring error, but also resulted in improvements to the procedure, including inscribed metal site labels, site photos, and precise GPS locations. GRD staff recommended that park staff continue monitoring at the established sites on a quarterly basis. Clearly labeled monitoring pins at precisely recorded locations should allow for quicker and more accurate monitoring (Bilderback and Pranger 2013).

Information about monitoring rockfall hazards is provided by Wieczorek and Snyder (2009) in *Geological Monitoring* (Young and Norby 2009). Moreover, during the 2007 scoping meeting, participants suggested that sheet joints parallel to cliff faces could be used as indicators of rockfall hazards not currently fitted with monitoring devices (KellerLynn 2007). Although geologic source maps, and thus the GRI GIS data, do not include these features, scoping meeting participants thought that this information could be retrieved from aerial photos and incorporated into the park's GIS. Such a project has the potential to be funded through the Geoscientists-In-the-Parks Program (see http://go.nps.gov/gip; accessed 18 July 2014).

GRD staff also completed a risk assessment of rockfall hazards in the housing area in 2013. This assessment places the risk in a societal context. Park staff members are encouraged to contact the NPS Geologic Resources Division with questions about this assessment. A rockfall hazard plan is a medium priority planning need identified in the foundation document (National Park Service 2015).

Paleontological Resource Inventory and Monitoring

Paleontological resources are an important resource in Chaco Culture National Historical Park as defined by the foundation document (National Park Service 2015). All paleontological resources are non-renewable and subject to science-informed inventory, monitoring, protection, and interpretation as outlined by the 2009 Paleontological Resources Preservation Act (see Appendix B). Department of Interior regulations associated with the act are under development. A variety of publications and resources provide park-specific or servicewide information and guidance. For example, 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) provided an inventory and monitoring report about paleontological resources in

the Southern Colorado Plateau Network, including Chaco Culture National Historical Park. This report included background information about the park; preliminary recommendations for management of paleontological resources within the park; and discussions about in situ fossils in Upper Cretaceous rocks and Quaternary deposits, fossil specimens in park collections, and records of fossils found in cultural resource contexts.

An ongoing field inventory, starting in 2005, of the Upper Cretaceous rocks at the park has revealed abundant and widespread paleontological resources, shedding light on the potential scientific significance of the fossil-bearing strata in the area (Varela 2013b). The two most fossiliferous rock units within the park are the Menefee Formation and the Cliff House Sandstone (see "Upper Cretaceous Rocks and Fossils" section). As of the end of the 2013 field season, investigators had identified and mapped more than 300 fossil localities within the park, including 148 plant, 95 vertebrate, 49 invertebrate, and 10 localities with a combination of plant, vertebrate, and invertebrate fossils (Varela 2013a). Very little research has been done on these resources, but preliminary results from the inventory indicate that the potential for new and scientifically significant material is very high, especially in the Menefee Formation (Varela 2013b). Findings thus far show that the paleoflora and paleofauna at Chaco Culture National Historical Park are much more diverse that previously suspected, with promising areas for potential future investigations, especially the Menefee Formation, which is poorly studied in the region (Varela 2013b).

In 2013, managers at Chaco Culture National Historical Park submitted a technical assistance request to the NPS Geologic Resources Division for development of a paleontological resource management plan, which would cover fossils in a geologic context within park strata and fossils that occur in a cultural resource context. A principal focus of the plan is to evaluate the variables associated with management of park fossils at archeological sites. An objective is to develop strategies for enabling scientific research and education without placing archeological resources at risk (Vincent Santucci, NPS Geologic Resources Division, senior geologist/paleontologist/Washington liaison, email communication, 25 June 2014). Completion of this initial inventory is considered a medium priority data need for the park (National Park Service 2015).

In April 2014, NPS staff from Chaco Culture National Historical Park and the Geologic Resources Division met with representatives of 28 American Indian tribes. The meeting at Chaco Culture National Historical Park may have been the first of its kind for the National Park Service, and perhaps any Department of Interior bureau (Vincent Santucci, NPS Geologic Resources Division, senior geologist/paleontologist/Washington liaison, email communication, 25 June 2014). During the meeting, the National Park Service presented information about the paleontological resources in the park and discussed the development of a paleontological resource management plan. The presentation prompted an engaged discussion among NPS and tribal participants related to Chaco Culture's fossils. The tribal participants provided insight on their perspectives of fossils and the relationship of fossils to their cultural origins and history. As a result of this meeting, tribal representatives requested further targeted meetings with the National Park Service regarding fossils.

In November 2014, park managers hosted a meeting with professional paleontologists to develop a strategy for future paleontological research and resource management at Chaco Culture National Historical Park (Phil Varela, Chaco Culture National Historical Park, paleontology technician, written communication, 31 October 2014). Recommendations from this meeting will be incorporated into the paleontological resource management plan (Vincent Santucci, NPS Geologic Resources Division, senior geologist/paleontologist/Washington liaison, email communication, 25 June 2014).

Piping

Piping is a type of subsurface erosion that is infringing on and endangering archeological sites at Chaco Culture National Historical Park (Simons, Li & Associates, Inc. 1982a). It is also threatening park roads (Zschetzsche and Clark 2004). In addition, piping has affected fill soils at archeological sites such as Chetro Ketl, where reburial using fill is a conservation strategy (Ford et al. 2004). Scoping participants also noted that piping creates bat habitat (KellerLynn 2007).

Simons, Li & Associates, Inc. (1982a) described the sequential development of pipes (narrow conduits, tunnels, or "pipes" through which soil or sediment is removed) at Chaco Culture National Historical

Figure 48. Photograph of piping. Subsurface erosion, called "piping," is one of several processes by which tributary arroyos form. It also creates bat habitat. Natural Resources Conservation Service photograph from Zschetzsche and Clark (2004, figure 4).

Park. Materials subject to piping include alluvium and colluvium that contain clay, silt, and fine sand; shale that contains montmorillonite and bentonite clays; and loess (Simons, Li & Associates, Inc. 1982a). In semiarid areas like Chaco Canyon where long dry periods are interspersed with intense rainfall, the drying out of soil (particularly those containing montmorillonite) and subsequent cracking determine vertical flow routes (Simons, Li & Associates, Inc. 1982a).

Notably, Chaco Arroyo did not form via piping; it incised along a meandering stream (Love 1980). Hodges (1975) found that piping has a pronounced effect on tributary-arroyo development but plays an insignificant role in the main wash. Pronounced bank collapse of the arroyo walls, however, may be associated with piping (Simons, Li & Associates, Inc. 1982a).

Piping is one of several processes by which tributary arroyos form (Love 1980). As pipes enlarge over time, overlying material collapses into a subsurface void and a small side ravine to the main arroyo forms (fig. 48). Some pipes extend hundreds of feet. Many, but not all, have an outlet in the walls of Chaco Arroyo. Whether or not a soil pipe connects to Chaco Arroyo appears to be a function of depth of the desiccation cracks and the lateral and vertical distribution of permeable layers interspersed with impermeable layers above the arroyo (i.e., water flows along the impermeable layers). Where outlets do exist, most are in walls of Chaco Arroyo, that is, below the floor of Chaco Canyon and above the

Figure 49. Photograph of Pueblo del Arroyo. Pueblo del Arroyo, meaning "town by the arroyo" in Spanish, is a classic D-shaped great house located next to Chaco Wash about 275 m (900 ft) west of Pueblo Bonito. It differs from other great houses in the canyon because it was not built near the northern cliff face and is oriented to the east rather than to the south. Due to its location, the site has been threatened in the past by erosion caused by floodwaters in the wash. Its soils are also subject to piping. National Park Service photograph available at http://www.nps.gov/chcu/photosmultimedia/photogallery.htm (accessed 12 May 2014).

active inner channel and floodplain (KellerLynn 2007).

Ebert and Brown (1981; scale 1:1,200) mapped piping at the park and identified some of the more prominent areas as Wijiji Ruins, Bradley site, northeastern side of Gallo Wash (northwest of the visitor center), western side of Fajada Wash near the confluence of Gallo Wash and Mockingbird Canyon, north of Casa Rinconda along the wash, and Pueblo del Arroyo. Additionally, Simons, Li & Associates, Inc. (1982b) completed a soil piping study in the vicinity of Pueblo Bonito, which analyzed drainage patterns and provided site-specific improvement plans for Chetro Ketl, Pueblo Bonito, Pueblo del Arroyo, and Kin Kletso. Of these four major sites, only one—Pueblo del Arroyo (fig. 49)—was directly threatened by erosion due to piping (Simons, Li & Associates, Inc. 1982b).

During a soils scoping session at Chaco Culture National Historical Park, participants addressed the issue of piping. The NPS Soils Program worked with park staff to identify problem areas. Park staff is referred to *Soil Survey of Chaco Culture National Historical Park, New Mexico* (Zschetzsche and Clark 2004). Piping is a

specific problem within the Notal and Battlerock soils at the park (Pete Biggam, NPS Geologic Resources Division, soil scientist, email communication, 23 February 2007).

Seismicity

Seismicity—the phenomenon of earth movements—includes all vibrations induced by natural processes and human activities. Vibrations may be caused by movement along a fault (earthquakes), landslides, blasting, drilling, road building, and vehicular traffic (King et al. 1985, 1991). The primary concern regarding seismicity at Chaco Culture National Historical Park is that ground shaking could damage archeological structures. It may also induce rockfall (see "Rockfall" section).

King et al. (1985) analyzed the seismic risk to the larger archeological structures at the park. Based on normal blasting practices in the area, conventional rail traffic, use of road building equipment, and vehicular traffic patterns, the investigation 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. Moreover, that investigation found the Kin Kletso complex "exceptional" because parts of it rest on sandstone bedrock, and sandstone bedrock is also directly beneath the highway at this site. Bedrock is a concern because it attenuates the induced vibrations at a much lower rate than the sandy, unconsolidated sediments underlying other sites. Thus limiting heavy equipment on the road near Kin Kletso and keeping the road surface smooth are significant for preservation. King et al. (1991) also recommended that within 45 m (150 ft) of the structure, no heavy equipment be used, no parking lots be located, and traffic be controlled. As a result of these recommendations, in 1995 the National Park Service rerouted a segment of the park road to mitigate seismically induced damage to cultural sites. The route had passed within 15 m (50 ft) of Kin Kletso, Casa Chiquita, and Pueblo del Arroyo. This reroute closed State Road 57 from the park's northern boundary, down Cly Canyon, to Pueblo del Arroyo (Dabney Ford, Chaco Culture National Historical Park, cultural resource manager, email communication, 19 March 2007).

Generally speaking, activities associated with coal production such as blasting, mining, and transportation have the potential to produce vibrations that could damage sensitive structures at the park. The nearest potential mining site is about 13 km (8 mi) north of Pueblo Bonito (King et al. 1985), and scoping participants surmised that such activities are not close

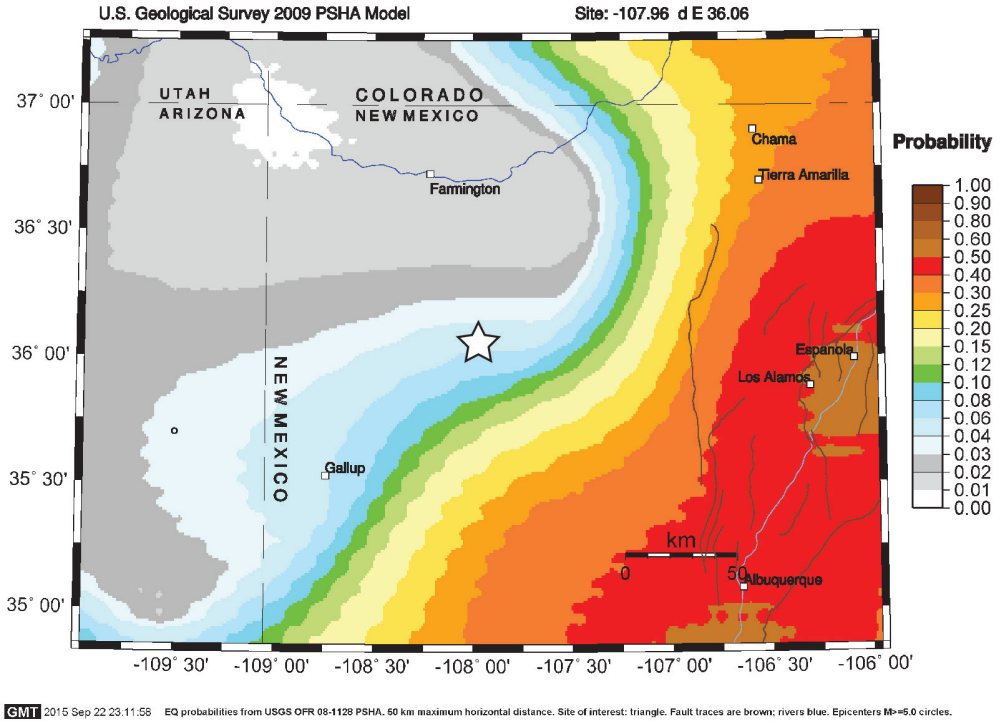

Figure 50. Map of earthquake probability. The map shows the probability of an earthquake with magnitude >5.0 during the next 100 years. Star indicates the location of the Chaco Canyon unit of the park and is centered on Pueblo Bonito. Map generated using the 2009 US Geological Survey earthquake probability mapping program (https://geohazards.usgs.gov/eqprob/2009/index.php; accessed 22 September 2015).

enough to cause damage to park structures (KellerLynn 2007). Hydraulic fracturing, which is now occurring in the San Juan Basin (see "Oil and Gas Development" section), could cause mild shaking (conference call participants, telephone communication, 13 February 2014).

The probability of a moderate earthquake (magnitude 5) shaking the Chaco Canyon unit over the next 100 years is relatively low, between 0.04 and 0.10 (4% to 10% "chance"). However, the probability increases to between 0.50 and 0.60 (50% to 60% "chance") east of the park near Valles caldera in the Los Alamos and Santa Fe area (fig. 50; see GRI report for Bandelier National Monument by KellerLynn 2015).

Eolian Processes

"In the late 1800s—before the advent of the first archeological protection laws—travelers, vandals, and pothunters repeatedly knocked massive holes into the back wall of Pueblo Bonito, removing the contents of the rooms this way, rather than digging into the rooms from above *through many feet of windblown sand* [italics added]" (National Park Service 2006, stop 6). This description is an indication of the persistence of eolian processes—windblown erosion, transportation, and deposition of sediments (see Lancaster 2009)—occurring at Chaco Culture National Historical Park. It also illustrates the potential for windblown sand to serve as a preservation strategy via reburial of archeological sites (see Ford et al. 2004).

Eolian processes are the cause of a variety of resource management issues at the park:

- Windstorms. During spring, the average wind speed at the park is 16 kph (10 mph) with velocities exceeding 40 kph (25 mph) about 1% of the time. Windstorms lasting one to two days with velocities of 60–80 kph (40–50 mph) are not unusual (King et al. 1985). Scoping participants noted that dust storms occur frequently at this time of year (KellerLynn 2007). During dust storms, even the most immediate visibility becomes impaired (Maruca 1982).
- Blowing sand. Before the park road was rerouted, eolian transport and deposition of sand and the formation of dunes across the old entry road (north) into the park, was a maintenance issue (KellerLynn 2007).
- Rockfall. Eolian processes may aid rockfall hazards by removing sediment between a loosened (protruding) rock and a cliff face (Phil Varela, Chaco Culture National Historical Park, paleontology technician, written communication, 31 October 2014; see "Rockfall" section).
- Wind-induced vibrations. King et al. (1985) observed that winds impose a considerable force on exposed walls of archeological structures, initiating vibrations and swaying. Wind gusts cause movement on two-, three-, and four-story walls and are a factor in collapses (Dabney Ford, Chaco Culture National Historical Park, chief, Cultural Resources, email communication 13 August 2014). The bracing of the walls by large timbers and steel rods generally increases the natural frequencies of these structures. Higher natural frequencies may then approach the predominant frequencies of the winds in the canyon. King et al. (1985) warned that modern rebuilding methods using concrete will result in different structural engineering characteristics than those of the ancient adobe-stone methods. The newer construction methods may introduce a more rigid structure which could be more susceptible to the vibrations induced by wind.
- Wind erosion. Sandblasting is a minor concern associated with high winds, which carry sand particles.

In the event that park managers choose to monitor eolian processes, Lancaster (2009)—the chapter in *Geological Monitoring* (Young and Norby 2009) about eolian features and processes—described the following methods and vital signs for monitoring: (1) frequency and magnitude of dust storms, (2) rate of dust deposition, (3) rate of sand transport, (4) wind erosion rate, (5) changes in total area occupied by sand dunes, (6) areas of stabilized and active dunes, (7) dune morphology and morphometry, (8) dune field sediment state (supply, availability, and mobility), (9) rates of dune migration, and (10) erosion and deposition patterns on dunes.

Efflorescence

The great houses and other built structures at Chaco Culture National Historical Park are more than 1,000 years old. Like other historic buildings, they require constant and appropriate care. Wind, summer monsoonal rains, snow, and extreme daily freeze–

thaw cycles all take their toll on these architectural monuments (National Park Service 2014c).

Although a discussion of preservation techniques is beyond the scope of this report, one natural process—"efflorescence," also called "salt crystallization" (Ford et al. 2004) or "salt weathering" (Doehne 2002)—is worthy of mention in a geologic resources inventory. Efflorescent minerals, that is, soluble salts such as gypsum and halite (Neuendorf et al. 2005), appear on building stone as a result of evaporation of water brought to the surface by capillary action (fig. 51). In arid regions, efflorescence commonly appears as a whitish, fluffy or crystalline powder, and is particularly prevalent at the bases of walls. Geologic factors in efflorescence are rock porosity, pore size and shape; colloidal effects (for clay and iron); and processes such as wind velocity and direction.

Erosion of stone and mortar by this process is a management concern at the park because it may contribute to the deterioration of archeological structures by accelerating stone and mortar erosion. Efflorescence also may accelerate the deterioration of roof surfaces in natural cave shelters (Phil Varela, Chaco Culture National Historical Park, paleontology technician, written communication, 31 October 2014; see "Cave Shelters" section).

Typical damaging behaviors for salts can include surface scaling, deep cracking, expansion, granular disintegration, surface powdering, and microcracking (Doehne 2002). Not all salt behaviors result in deterioration, however. For example, efflorescence may be highly visible, but generally results in little damage (Doehne 2002). Likewise, salt creep can move salts over the surface of materials but, as the name implies, is a surficial process. Furthermore, salts such as magnesium sulfate can actually bind together (i.e., cement) previously fractured material (Doehne 2002).

Managers at Chaco Culture National Historical Park use the presence of efflorescence as an indicator of water penetration, drainage problems, and stone deterioration. Also, efflorescence indicates that preservation efforts may be using (or have used in the past) replacement mortars that are less permeable than the original fabric, thus indicating the need to reevaluate mortar mixes. Park managers have tried to find alternatives to using mortar additives that add salts to the already high concentrations because of the corrosive damage to sandstone (Dabney Ford, Chaco Culture National Historical Park, chief, Cultural Resources, email communication, 13 August 2014).

Doehne (2002) noted more than 1,800 references in the scientific literature (e.g., geomorphology, geochemistry, environmental science, geotechnical and material sciences, and architectural conservation) on the topic of salt weathering, and provided a review of recent work, focusing on articles about conservation. Doehne (2002) supplied an organizing framework for considering the complexity of salt weathering, which park managers may find useful in the prevention, mitigation, and treatment of salt weathering at Chaco Culture National Historical Park.

Figure 51. Photograph of efflorescence. Also called "salt crystallization" or "salt weathering," efflorescence (white "powder" on the stone wall in the photograph) is a management concern at Chaco Culture National Historical Park because it may accelerate erosion of stone and mortar and thus contribute to the deterioration of archeological structures. National Park Service photograph (taken in 2014).

Geologic History

This chapter describes the chronology of geologic events that formed the present landscape of Chaco Culture National Historical Park.

The rocks and unconsolidated deposits at Chaco Culture National Historical Park record the following geologic events spanning 100 million years:

- Inundation by the Western Interior Seaway;
- Downwarping of the San Juan Basin during the Laramide Orogeny and filling of the basin with terrestrial sediment;
- Widespread erosion and development of present drainages, including Chaco Canyon;
- Dynamic sedimentation in Chaco Canyon;
- Development of Chaco Arroyo and incision of the active inner channel; and
- Human activities as part of the geologic record.

Late Cretaceous Period: Western Interior Seaway

The oldest geologic event recorded in the rocks at Chaco Culture National Historical Park is sea level rise and inundation by a vast inland sea—the Western Interior Seaway. The seaway stretched across the North American continent and prevailed for 30 million years, from about 100 million to 70 million years ago, reaching its greatest extent about 90 million years ago. The seaway first moved into New Mexico about 96 million years ago. The Dakota Sandstone records this initial transgression (advance) of marine waters (fig. 6 and table 1). Dakota Sandstone is not exposed in the park, though it occurs in many places in northern New Mexico (Price 2010).

The rock record at Chaco Culture National Historical Park preserves the western coastline of the Western Interior Seaway (fig. 3). Continental, coastal, and marine sediments are well exposed in canyon walls and on mesa tops, and include the following rock formations in ascending order (oldest to youngest):

- Crevasse Canyon Formation (map units **Kcg** and **Kcda**; see poster, in pocket)—a succession of lagoon, tidal or estuarine channel, and beach sediments, which were deposited as the shoreline built outward into the sea (Kirk and Zech 1977; Robertson 1986, 1992).
- Menefee Formation (**Kmf**, **Kmft**, **Kmfa**, **Kmfaj**, and **Kmfal**)—lowland swamps, lagoons, and alluvial plains with stream channels that lay landward of the shoreline to the northeast (Scott et al. 1984).
- Cliff House Sandstone (**Kch**, **Kchu**, **Kchwu**, **Kchwl**, **Kchm**, **Kchi**, and **Kchl**)—multiple, separate barrier-island complexes that built upward and prograded seaward as sediment accumulated (Donselaar 1989; Love 2010).
- Lewis Shale (**Kl**)—marine sand and silt deposited in deep water during an advance of the Western Interior Seaway to the southwest (Scott et al. 1984; Mytton and Schneider 1987).
- Pictured Cliffs Sandstone (**Kpc**)—mostly coastal sand in delta front, beach, and stream channels, representing the final retreat of the Western Interior Seaway from the San Juan Basin (Scott et al. 1984; Mytton and Schneider 1987).

As the seaway retreated to the northeast, coal swamps and coastal plains covered the area. The Fruitland Formation (**Kf**) and Kirtland Shale (**Kk**) represent these settings. These rocks crop out in the Chaco River headwaters, east of the park.

Close of the Cretaceous Period: San Juan Basin

As the Western Interior Seaway made its final retreat, the landscape of western North America was dramatically changed by the Laramide Orogeny. For more than 30 million years (approximately 75 million to 40 million years ago), compressive deformation associated with this massive mountain-building event uplifted areas, including the Rocky Mountains, caused episodes of volcanism in parts of New Mexico, and created many structural features, including the San Juan Basin. Erosion of highlands associated with Laramide uplift shed terrestrial sediments into the San Juan Basin atop previously deposited and subsequently downwarped Upper Cretaceous marine and coastal rocks. More than 900 m (3,000 ft) of Paleocene through Oligocene (65 million–25 million years ago; see fig. 2) silt, sand, and gravel covered the site of Chaco Culture National Historical Park before erosive forces

stripped them away. Although none of these terrestrial rocks remain in the park area today, the Nacimiento Formation in Aztec Ruins National Monument to the north is representative of these sedimentary deposits (see GRI report by KellerLynn in review).

Pleistocene Epoch: Chaco Canyon

After overlying sedimentary units were removed by widespread erosion, the Chaco River drainage most likely incised into the Fruitland-Kirtland interval, which consisted of more than 200 m (660 ft) of non-resistant shale, siltstone, sandstone, and coal (Love 1980). A possible scenario begins with a meandering ancestral stream flowing across a relatively low-relief, plain composed of the Fruitland Formation and Kirtland Shale, then incising the plain and breaching the Pictured Cliffs Sandstone as erosion proceeded. Erosion along strike of the Lewis Shale followed. Eventually, incision reached Cliff House Sandstone, and the ancestral Chaco River slipped down-dip to the northwest, cutting Chaco Canyon nearly parallel to strike of the Cliff House Sandstone (Love 1980).

Although investigation has not revealed an absolute age of the entrenchment of Chaco Canyon, the canyon probably incised to its present depth during the middle Pleistocene Epoch (about 780,000 to 126,000 years ago) (David W. Love, New Mexico Bureau of Geology and Mineral Resources, geologist, email communication, 25 July 2014). The pattern of the Chaco drainage was superimposed onto bedrock early in the history of the drainage. Tributary drainages would have been established at about the same time (Love 1980).

In the Chaco Canyon area, severe erosion continued through the late Pleistocene Epoch, and most of the early and middle Pleistocene stream deposits and stream-cut surfaces were removed. Deposits of Pleistocene gravelly sand (**Qgs7**, **Qgs6**, and **Qgs5**) remain as the only evidence of a former landscape (fig. 52). These deposits occur as sheets overlying pediment-like surfaces that cut across nonresistant bedrock and slope toward the Chaco River or other local major valleys. At least seven erosion surfaces and their associated gravelly sand deposits are recognized in the drainage basin of the Chaco River. Each reflects an erosional episode related to changes in the grade of the Chaco River or the San Juan River. These remnants show that the ancestral Chaco River and its tributaries were more powerful than modern streams, having transported gravel instead of only sand, silt, and clay. As mapped by Scott et al. (1984), these high-elevation erosion surfaces are all late Pleistocene in age (126,000–11,700 years old). They are mapped as highest/oldest (**Qgs1**) to lowest/youngest (**Qgs7**) and are distinguished from one another by their height above the modern Chaco River and major tributaries. The three youngest levels (**Qgs7**, **Qgs6**, and **Qgs5**) are preserved in Chaco Culture National Historical Park, and are 18 to 60 m (60 to 200 ft) above the local drainage (Scott et al. 1984). In addition, Mytton and Schneider (1987) mapped a gravel-covered surface (**Qg**) overlying the Cliff House Sandstone at the northern end of West Mesa.

Pleistocene and Holocene Epochs: Dynamic Sedimentation

After incision of Chaco Canyon into bedrock, sediments began to fill it. As much as 38 m (125 ft) of alluvium, eolian sand, and sheetwash and slope-wash sediments have flowed, blown, and washed over the canyon floor from mesas, tributary canyons, and the headwaters area. Dunes near the mouth of Chaco Wash at Escavada Wash probably have been present in some form since the end of the Pleistocene Epoch, approximately 11,700 years ago. They probably interfinger with alluvium from Chaco Wash (David W. Love, New Mexico Bureau of Geology and Mineral Resources, geologist, email communication, 25 July 2014). The large climbing dunes in some of the tributary canyons, such as Weritos Rincon, are suspected to have existed for much longer and may have stratigraphic layers composed of developed soils (as an indication of age). The youngest sand cover on these dunes is probably upper Holocene, but much older eolian sand is likely in the subsurface (David W. Love, New Mexico Bureau of Geology and Mineral Resources, geologist, email communication, 25 July 2014). Dunes in the vicinity, though outside Chaco Canyon, are known to have developed during the Pleistocene Epoch (see Schultz 1983; McFadden et al. 1983).

The alluvial stratigraphy of Chaco Canyon spans the middle–late Pleistocene Epoch to the present (Hall 1977, 2010). The oldest documented deposit is middle–late Pleistocene gravel, which is best exposed in a quarry along Chaco Wash near the park's visitor center (Hall 1983). Hall (1977, 2010) referred to this gravel deposit as "Fajada gravel" (figs. 52 and 53). Some investigators mapped this deposit as sheetwash alluvium (**Qsw**), but multiple cross-beds in the unit indicate

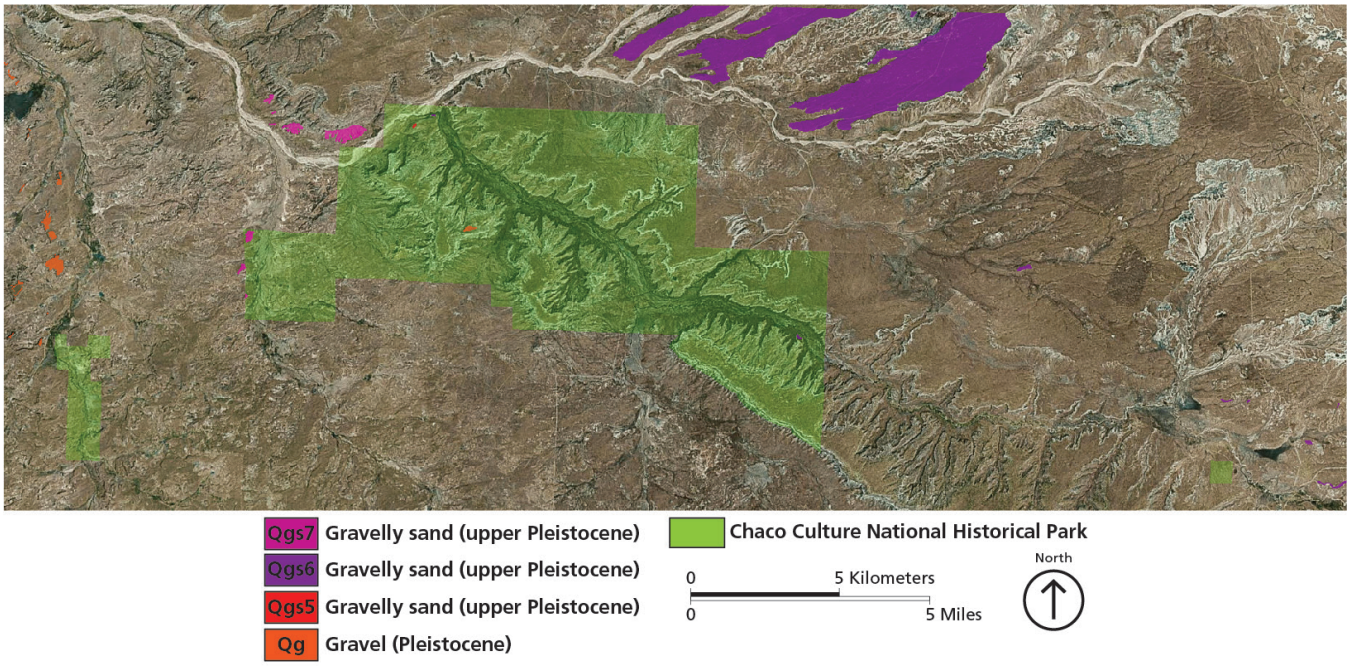

Figure 52. Satellite imagery of erosion surfaces. Above Chaco Canyon, gravelly sand (Qg7, Qg6, and Qg5) and gravel (Qg) associated with pediment-like erosion surfaces are evidence of a Pleistocene landscape when an ancestral river incised Chaco Canyon. At least seven erosion surfaces and their associated gravelly sand deposits are recognized in the Chaco River drainage basin. Each elevated surface reflects an erosional episode related to changes in the grade of the Chaco River or the San Juan River. Graphic by Trista Thornberry-Ehrlich (Colorado State University) using GRI GIS data for Chaco Culture National Historical Park. Base imagery by ESRI World Imagery.

swiftly flowing water and a fluvial origin (Hall 1983). Formation of the gravel deposit is probably related to inception of either the Bull Lake glaciation (more than 140,000 years ago) or Pinedale glaciation (80,000–70,000 years ago) (see Pierce 2004).

After the gravel was deposited, the canyon fill was eroded to the bedrock floor. Erosion of the gravel, deposition of colluvium and eolian sediments, and the formation of a reddish brown paleosol, referred to as the "Fajada paleosol" by Hall (1977, 2010), helped to build up the canyon floor since that time (approximately the past 70,000 years; Love 1980).

Holocene Epoch: Cut-and-Fill Cycles

Using radiocarbon dating, Hall (2010) provided ages of the fill exposed in Chaco Canyon since 7,600 years before present (BP, where "present" is 1950 CE), and separated the fill into four units: (1) pre-Gallo (undated), (2) Gallo (6,700–2,800 years BP), (3) Chaco (2,100–1,000 years BP), and (4) Bonito (800–100 years BP) (fig. 53).

Pre-Gallo Fill

The pre-Gallo fill is thin-bedded sand with abundant pine pollen; it is exposed as a small erosional remnant that may be late Pleistocene or early Holocene in age (Hall 2010).

Gallo Fill

The hot, dry climate of the mid-Holocene Epoch and accompanying low streamflow resulted in the accumulation of sand in Chaco Canyon, forming Gallo fill. Yellowish-brown, locally derived sand (from Cliff House Sandstone) dominates this alluvial fill, although layers of grayish brown silt (from Fruitland Formation and Kirtland Shale at the headwaters) show that the canyon floor was periodically flooded (figs. 34 and 35). By 2,500 years ago, a shift to less arid conditions and increased streamflow flushed out much of the Gallo sand from the canyon.

Chaco Fill

Between 2,100 and 1,000 years BP, greater streamflow throughout the drainage basin resulted in flooding across the canyon floor, forming Chaco fill. Sedimentation filled in the channel left by the erosion

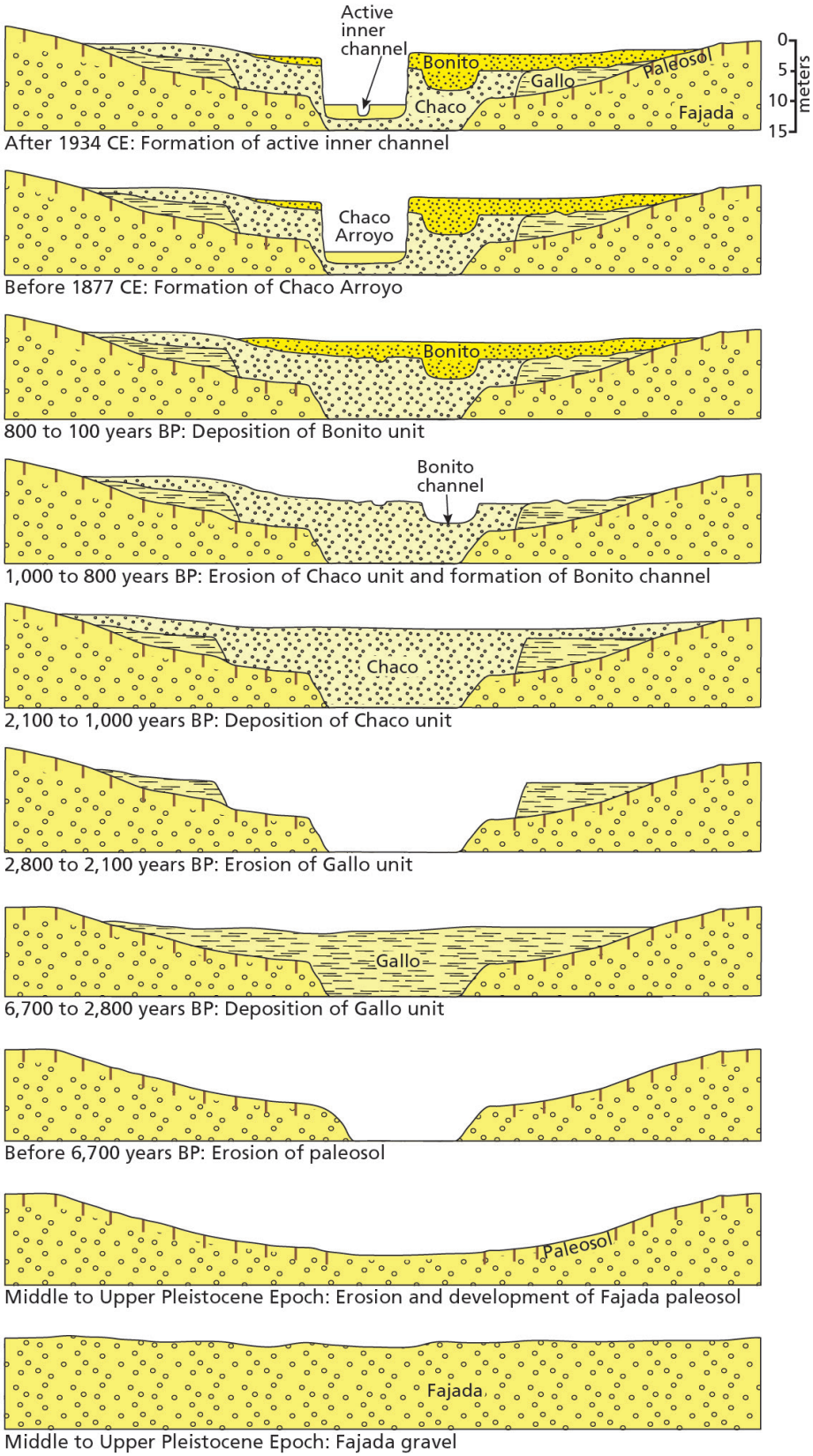

Figure 53. Diagram of Chaco Canyon through time. Most of the sediment exposed in the walls of Chaco Arroyo is Holocene alluvium, although the sedimentary record also includes a terrace gravel deposit and an ancient soil, referred to as the "Fajada gravel" and "Fajada paleosol," respectively. As described by Hall (1977, 2010), the alluvial fills in Chaco Canyon are pre-Gallo (not dated, but estimated as late Pleistocene or early Holocene age), Gallo (6,700–2,800 years BP), Chaco (2,100–1,000 years BP), and Bonito (800–100 years BP). Chaco Arroyo had incised into the floor of Chaco Canyon by 1877, and the active inner channel developed after 1934. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Hall (1977, figure 5).

and downcutting of Gallo fill. Chaco fill is mostly grayish-brown, headwater-dominated clay, which spread over the canyon floor in the absence of an arroyo channel (Hall 1983). Abundant freshwater snails in the clay suggest wet conditions during seasonal flooding. Accumulation of the Chaco unit ended about 1,000 years BP with a shift in climate to dry conditions. The Bonito channel—an arroyo that existed between 800 and 100 years BP—formed at that time (figs. 52 and 53).

Bonito Fill

The Bonito channel was filling with clayey, grayish-brown, headwater-dominated material by 800 years BP, based on buried potsherds. Fewer freshwater gastropods occur in the Bonito fill than the Chaco fill, indicating less moist conditions 800–100 years ago than when the Chaco fill was deposited (Hall 2010). Deposition of the Bonito unit ended with incision of Chaco Arroyo (fig. 53).

Holocene Epoch: Chaco Arroyo and Active Inner Channel

The dynamics of Chaco Canyon include the formation of channels (arroyos). The floor of Chaco Canyon has alternated between being deeply gullied with arroyo channels, as it is currently, and having no gullies (Love 2010). At least seven arroyos have been present during the history of Chaco Canyon (fig. 54; Love 1977). The amount of time it takes for an arroyo channel to downcut and backfill may be no more than 200 years (Hall 1986, 1990).

Chaco Arroyo represents the most recent episode of arroyo cutting. The arroyo formed along a meandering channel that had not previously existed on the canyon

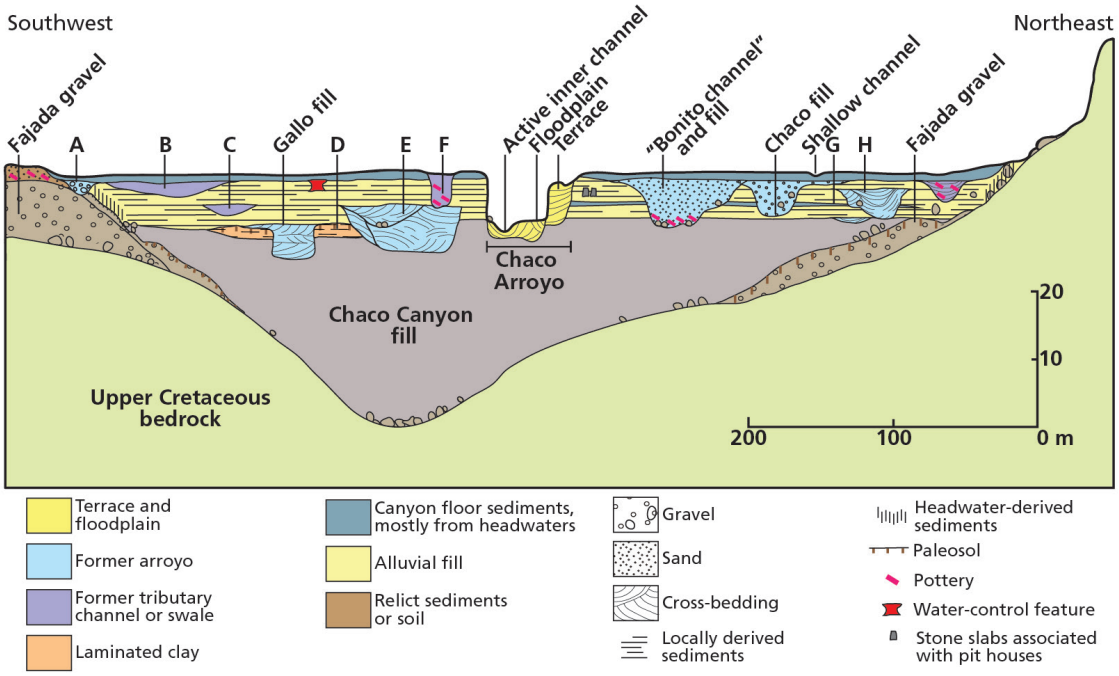

Figure 54. Schematic illustration of Chaco Canyon. Chaco Canyon has at least 38 m (125 ft) of fill above the bedrock floor. The uppermost 11 m (36 ft) show a dynamic sequence of cut-and-fill cycles and canyon-wide alluviation. The canyon floor was inundated by sediments from the headwaters that are connected to filled-in entrenched channels, swales with laminated clay, and yazoo channels. Remnants of earlier fill occur along the margins of the canyon and are partially buried by modern alluvium. Chaco Canyon has been cut by arroyos (light blue on figure) at least seven times during its history. Each of these Chaco Canyon channels may have correlative channels (and fills) in tributaries (purple on figure). A—gravel reworked into later channel. B—broad swale filled by laminated clay derived from the headwaters, overlain by canyon floor deposits. C—swale filled with laminated clay associated with 3,700-year-old fill in buried channel to right. D—deeply buried laminated silty clay with soils developed on top of deposit. E—undated buried channel. F—pottery-bearing channel, 3–4 m (10–13 ft) deep filled to present surface of canyon floor. G—thin wedge-shaped headwater-derived deposits pinch out against deposits from the canyon margin. H—complex arroyo cut-and-fill deposit about 3,700 years old. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Love (1983, figure 4). Named fills (i.e., Fajada, Gallo, Chaco, and Bonito) are correlated from Hall (1977, 2010).

floor (Love 1977). Simpson (1850) reported that an intermittent channel or succession of pools had developed on the floor of Chaco Canyon by 1849. Incision apparently began before 1877, when Jackson (1878) reported a channel more than 4 m (13 ft) deep. Photographs and channel measurements beginning in 1896 describe an incising arroyo with little vegetation and a flat bottom until the early 1930s (Love 1980).

After incision of Chaco Arroyo began, an alluvial terrace (fig. 34) developed as an inner floodplain and channel similar to the modern inner floodplain and channel (Love 1977). The abandoned floodplain and channel aggraded 3–4 m (10–13 ft). When it was within 1.5 m (5 ft) of overtopping the arroyo walls, chute cutoffs formed, floods swept gravel out of the channel, and the arroyo became re-entrenched.

Following re-entrenchment, Chaco Arroyo widened, eroding most of the terrace. The channel became braided from wall to wall. By 1934, the braided channel was no longer stable, and by 1939, the arroyo channel had changed from braided to a narrow inner channel between partially stabilized point bars and an inner floodplain; this is today's active inner channel (Love 1977).

Minor accretion on the active inner channel's floodplain and minor shifts in the channel continue to take place, but the channel is more or less stable. The active inner channel and floodplain gradually disappear toward the head of Chaco Canyon. Above the canyon, the arroyo has a braided channel (Love 1977).

Holocene Epoch: Human Populations in Chaco Canyon

Prehistoric Indians were in the San Juan Basin by at least 13,000 years ago. The earliest abundant evidence of people in Chaco Canyon dates from the Archaic Period, which ranges from about 7,000 to 1,500 years ago. Beginning about 500 CE, people designated as Basketmakers raised crops in Chaco Canyon and built semi-subterranean structures known as pit houses. By 500 CE, Chaco Canyon looked similar to present geomorphic conditions, though the level of the canyon floor was slightly (1–3 m [3–10 ft]) lower, and the margins of the canyon were slightly different than today as a result of eolian processes, erosion, and rockfall yet to occur (Love 1980). Aboveground structures, in contrast to subterranean pit houses, gradually appeared and evolved into pueblos by 770 CE. Pit houses acquired ceremonial significance and evolved into kivas.

The major Chacoan building phase that included multistoried great houses and large kivas began about 1050 CE; this phase ended sometime after 1127 CE. During that time, arroyos were present, notably when Pueblo Bonito was under construction. Moreover, Pueblo del Arroyo was built in the center of the canyon floor, apparently while a major channel, the "Bonito channel," existed south of the pueblo (fig. 54). When the Bonito channel began to aggrade and flooding of the canyon floor occurred, occupants of Pueblo del Arroyo built a wall south of the site along the margin of the arroyo. Even later, the occupants piled stones in a shallow channel at the surface of the aggraded channel (Love 1980).

During a period of widespread flooding after the Bonito channel filled, vegetation was sparse and wind transported gray clay to the canyon margins. Sometime after the gray-clay layer (i.e., Bonito unit of Hall 2010) was deposited, a small arroyo (predating Chaco Arroyo) cut and filled in Chaco Canyon (F on fig. 54). Pottery found along the channel base is not diagnostic enough to date the channel, but it cuts deposits overlying the Bonito channel so is younger than 1250 CE (Love 1983).

Chaco Canyon was occupied sporadically by Pueblo people and later by Navajo until the time of James Hervey Simpson's visit in 1849 (Vivian and Mathews 1964).

Holocene Epoch: Geoarcheology

Since Simpson's visit, scientists in the field of geoarcheology have studied the relationships between prehistoric humans and the environment at Chaco Canyon (see "Geologic Setting and Significance" chapter). As an interdisciplinary study, geoarcheology strives to understand archeological sites in their natural contexts, in particular, human response to a changing environment. At Chaco Culture National Historical Park and throughout the Southwest, small climate changes have noticeably altered the landscape and affected plant (at least one to extinction; see "Quaternary Fossils" section) and animal species (Malde 1964). Geoarcheologists use many "geologic" methods, including mapping of alluvial fill, to understand the life ways of ancient people. The attraction of Chaco Canyon for research has continued to the present day.

Geologic Map Data

This chapter summarizes the geologic map data available for Chaco Culture National Historical Park. A poster (in pocket) displays the GRI GIS data draped over imagery of the park and surrounding area. The Map Unit Properties Table (in pocket) summarizes this report's content for each geologic map unit. Complete GIS data are available at the GRI publications website: http://go.nps.gov/gripubs.

Source Maps

Geologic maps facilitate an understanding of an area's geologic framework and the evolution of its present landscape. The American Geosciences Institute website, http://www.agiweb.org/environment/publications/mapping/index.html (accessed 27 August 2015), provides more information about geologic maps and their uses.

The GRI team digitizes paper geologic maps and converts digital geologic data to conform to the GRI GIS data model. GRI GIS data include essential elements of source maps such as map unit descriptions, geologic unit correlation tables, legends, cross sections, figures, and references. The GRI team used the following source maps to produce the GRI GIS data for Chaco Culture National Historical Park. These sources also provided information for this report.

Dillinger, J. K. 1990. Geologic map and structure contour maps of the Gallup 30' × 60' quadrangle, McKinley County, New Mexico (scale 1:100,000). Miscellaneous Investigations Series Map I-2009. US Geological Survey, Denver, Colorado. http://pubs.er.usgs.gov/publication/i2009 (accessed 14 January 2014).

Kover, A. N. 1960. Photogeologic map of the Chaco Canyon-2 quadrangle, McKinley County, New Mexico (scale 1:62,500). Miscellaneous Investigations Series Map I-315. US Geological Survey, Washington, DC. http://pubs.er.usgs.gov/publication/i315 (accessed 21 January 2014).

Miller, R. L., M. A. Carey, and C. L. Thompson-Rizer. 1991. Geology of the La Vida Mission quadrangle, San Juan and McKinley counties, New Mexico (scale 1:24,000). Bulletin 1940. US Geological Survey, Denver, Colorado. http://pubs.er.usgs.gov/publication/b1940 (accessed 14 January 2014).

Mytton, J. W., and G. B. Schneider. 1987. Interpretive geology of the Chaco area, northwestern New Mexico (scale 1:24,000). Miscellaneous Investigations Series Map I-1777. US Geological Survey, Denver, Colorado. http://pubs.er.usgs.gov/publication/i1777 (accessed 14 January 2014).

O'Sullivan, R. B., G. R. Scott, and D. L. Weide. 1979. Preliminary geologic map of the Kin Klizhin Ruins quadrangle, San Juan and McKinley counties, New Mexico (scale 1:24,000). Miscellaneous Field Studies Map MF-1094. US Geological Survey, Reston, Virginia. http://pubs.er.usgs.gov/publication/mf1094 (accessed 15 January). Note: Used for geologic contacts only.

Robertson, J. F. 1986. Geologic map of the Crownpoint quadrangle, McKinley County, New Mexico (scale 1:24,000). Geologic Quadrangle Map GQ-1596. US Geological Survey, Reston, Virginia. http://pubs.er.usgs.gov/publication/gq1596 (accessed 14 January 2014).

Robertson, J. F. 1992. Geologic map of the Heart Rock quadrangle, McKinley County, New Mexico (scale 1:24,000). Geologic Quadrangle Map GQ-1697. US Geological Survey, Reston, Virginia. http://pubs.er.usgs.gov/publication/gq1697 (accessed 14 January 2014).

Scott, G. R., R. B. O'Sullivan, and D. L. Weide. 1984. Geologic map of the Chaco Culture National Historical Park, northwestern New Mexico (scale 1:50,000). Miscellaneous Investigations Series Map I-1571. US Geological Survey, Denver, Colorado. http://pubs.er.usgs.gov/publication/i1571 (accessed 14 January 14, 2014).

Weide, D. L., G. R. Scott, and J. W. Mytton. 1980. Geologic map of the Pueblo Pintado quadrangle, McKinley County, New Mexico (scale 1:24,000). Miscellaneous Field Investigations Map MF-1219. US Geological Survey, Reston, Virginia. http://pubs.er.usgs.gov/publication/mf1219 (accessed 14 January 2014).

In addition, the following sources identified and mapped outcrops of coal beds, drill holes for oil and gas, and test holes for coal zones associated with the Crevasse Canyon and Menefee formations and the Cliff House Sandstone. This information is included in the GRI GIS data.

Berge Exploration Inc. 1979a. Federal coal resource occurrence and coal development potential maps of the Crownpoint 7½-minute quadrangle, McKinley County, New Mexico (scale 1:24,000). Open-File Report OFR-79-1125. US Geological Survey, Washington, DC. http://pubs.er.usgs.gov/publication/ofr791125 (accessed 21 January 2014).

Berge Exploration Inc. 1979b. Federal coal resource occurrence and coal development maps of the Heart Rock 7½-minute quadrangle, McKinley County, New Mexico (scale 1:24,000). Open-File Report OFR-79-642. US Geological Survey, Washington, DC. http://pubs.er.usgs.gov/publication/ofr79642 (accessed 21 January 2014).

Berge Exploration Inc. 1979c. Federal coal resource occurrence and coal development maps of the Kin Klizhin Ruins 7½-minute quadrangle, San Juan and McKinley counties, New Mexico (scale 1:24,000). Open-File Report OFR-79-1047. US Geological Survey, Washington, DC. http://pubs.er.usgs.gov/publication/ofr791047 (accessed 21 January 2014).

Berge Exploration Inc. 1979d. Federal coal resource occurrence and coal development maps of the Milk Lake 7½-minute quadrangle, McKinley County, New Mexico (scale 1:24,000). Open-File Report OFR-79-1377. US Geological Survey, Washington, DC. http://pubs.er.usgs.gov/publication/ofr791377 (accessed 21 January 2014).

Berge Exploration Inc. 1979e. Federal coal resource occurrence and coal development maps of the Nose Rock 7½-minute quadrangle, McKinley County, New Mexico (scale 1:24,000). Open-File Report OFR-79-641. US Geological Survey, Washington, DC. http://pubs.er.usgs.gov/publication/ofr79641 (accessed 21 January 15, 2014).

Berge Exploration Inc. 1979f. Federal coal resource occurrence and coal development maps of the Seven Lakes NE 7½-minute quadrangle, McKinley County, New Mexico (scale 1:24,000). Open-File Report OFR-79-638. US Geological Survey, Washington, DC. http://pubs.er.usgs.gov/publication/ofr79638 (accessed 15 January 2014).

Berge Exploration Inc. 1979g. Federal coal resource occurrence and coal development maps of the Seven Lakes NW 7½-minute quadrangle, McKinley County, New Mexico (scale 1:24,000). Open-File Report OFR-79-1123. US Geological Survey, Washington, DC. http://pubs.er.usgs.gov/publication/ofr791123 (accessed 21 January 2014).

Berge Exploration Inc. 1979h. Federal coal resource occurrence and coal development maps of the La Vida Mission 7½-minute quadrangle, San Juan and McKinley counties, New Mexico (scale 1:24,000). Open-File Report OFR-79-1378. US Geological Survey, Washington, DC. http://pubs.er.usgs.gov/publication/ofr791378 (accessed 21 January 2014).

Dames & Moore. 1979a. Coal resource occurrence maps and coal development potential map of the Pueblo Pintado quadrangle, McKinley County, New Mexico (scale 1:24,000). Open-File Report OFR-79-113. US Geological Survey, Washington, DC. http://pubs.er.usgs.gov/publication/ofr79113 (accessed 21 January 2014).

Dames & Moore. 1979b. Coal resource occurrence maps of the Pueblo Bonito quadrangle, San Juan and McKinley counties, New Mexico (scale 1:24,000). Open-File Report OFR-79-156. US Geological Survey, Washington, DC. http://pubs.er.usgs.gov/publication/ofr79156 (accessed 21 January 14, 2014).

Dames & Moore. 1979c. Coal resource occurrence maps of the Sargent Ranch quadrangle, San Juan and McKinley counties, New Mexico (scale 1:24,000). Open-File Report OFR-79-157. US Geological Survey, Washington, DC. http://pubs.er.usgs.gov/publication/ofr79157 (accessed 21 January 2014).

GRI GIS Data

The GRI team implements a GIS data model that standardizes map deliverables. The data model is 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 Chaco Culture National Historical Park using data model version 2.2. The GRI Geologic Maps website, http://go.nps.gov/geomaps, provides more information about GRI map products.

GRI digital geologic data are 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.

The following components are part of the data set:

- A GIS readme file (chcu_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 (table 2);
- Federal Geographic Data Committee–compliant metadata;
- An ancillary map information document (chcu_geology.pdf) that contains information captured from source maps;
- An ESRI map document (chcu_geology.mxd) that displays the digital geologic data; and
- A KML/KMZ version of the data viewable in Google Earth (table 2).

The different component maps are aslo available separately and are identified by the following prefixes:

- CCNH – Chaco Culture National Historical Park area map (Kin Klizhin Ruins and Sargent Ranch quadrangles, and northern third of the Pueblo Bonito quadrangle)
- CHC2– northern Chaco Culture-2 15' quadrangle (Seven Lakes NE and Seven Lakes NW quadrangles)
- CHCO – Chaco Culture National Historical Park area coal resources map (all park quadrangles)
- CRWN – Crownpoint 7.5' quadrangle

- GALL – northeast portion of the Gallup 30' x 60' quadrangle (Milk Lake and Nose Rock quadrangles)
- HERO – Heart Rock 7.5' quadrangle
- LVMI – La Vide Mission 7.5' quadrangle
- PUBO – portion of the Pueblo Bonito 7.5' quadrangle (southern two-thirds)
- PUPI – Pueblo Pintado 7.5' quadrangle.

GRI Map Poster

A poster showing GRI GIS data draped over a shaded relief image of Chaco Culture National Historical Park and surrounding area is included with this report. Not all GIS feature classes are included on the poster (table 2). Selected geographic features, including park features, have been added to the poster. 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 NPS Geologic Resources Division for assistance locating these data.

Map Unit Properties Table

The Map Unit Properties Table (in pocket) lists the geologic time division, map unit symbol, and a simplified description for each of the geologic units mapped within Chaco Culture National Historical Park. The table also notes the park unit in which each map unit occurs. Following the structure of the report, the table summarizes 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 on the information provided here. Please contact the NPS Geologic Resources Division with any questions.

Minor inaccuracies may exist regarding the locations of geologic features relative to other geologic or geographic features on the poster. Based on the source map scales and US National Map Accuracy Standards, geologic features represented in the GRI GIS data are horizontally within 12 m (40 ft) of their true locations on 1:24,000-scale maps, 32 m (104 ft) on 1:62,500-scale maps, 25 m (82 ft) on 1:50,000-scale maps, and 51 m (167 ft) on 1:100,000-scale maps.

Table 2. GRI GIS data for Chaco Culture National Historical Park

Data Layer	On Poster?	Google Earth Layer?
Geologic Cross Section Lines	No	No
Geologic Attitude Observation Localities	No	No
Geologic Measurement Localities (fault displacement amount)	No	No
Geologic Observation Localities (geologic photograph localities)	No	No
Mine Point Features	No	No
Structure Contour Lines, Base of the Dakota Sandstone (Kd)	No	No
Geologic Line Features (coal zones and beds)	Yes	Yes
Fault and Fold Symbology	Yes	No
Folds	Yes	Yes
Faults	Yes	Yes
Linear Geologic Units	Yes	Yes
Mine Area Feature Boundaries	No	No
Mine Area Features	No	Yes
Geologic Contacts	Yes	Yes
Geologic Units	Yes	Yes

Glossary

These are brief definitions of selected geologic terms relevant to this report. Definitions are based on those in the American Geosciences Institute Glossary of Geology (5th edition; 2005). Additional terms are defined at http://geomaps.wr.usgs.gov/parks/misc/glossarya.html.

adit. A horizontal passage into a mine from the surface.

aggradation. The building up of Earth's surface by depositional processes.

alluvial fan. A low, relatively flat to gently sloping, fan-shaped mass of loose rock material deposited by a stream, especially in a semiarid region, where a stream issues from a canyon onto a plain or broad valley floor.

alluvial terrace. A stream terrace composed of unconsolidated alluvium produced by a rejuvenated stream via renewed downcutting of the floodplain or valley floor, or by the covering of a terrace with alluvium.

alluvium. Stream-deposited sediment.

Altithermal. A dry postglacial interval (from about 8,000 to 4,000 calendar years ago) during which temperatures were higher than at present.

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

aquifer. A rock or sedimentary unit that is sufficiently porous to hold water, sufficiently permeable to allow water to move through it, and saturated to some level.

arroyo. A small, deep, flat-floored channel or gully of an ephemeral stream in the arid and semiarid regions of the southwestern United States.

artesian. Describes groundwater confined under hydrostatic pressure.

artesian well. A well that taps confined groundwater. Water in the well rises above the level of the top of the aquifer under artesian pressure.

badlands. Eroded topography characterized by steep slopes and surfaces with little or no vegetative cover; composed of unconsolidated or poorly cemented clays or silts.

backwater. A body of water that is parallel to a river but is stagnant or little affected by the river's currents.

barchan dune. A crescent-shaped dune in which the arms or horns of the crescent point downwind; characteristic of inland desert regions.

barrier island. A long, low, narrow island consisting of a

basin (structural). A doubly plunging syncline in which rocks dip inward from all sides.

basin (sedimentary). Any depression, from continental to local scale, into which sediments are deposited.

bathymetry. The measurement of ocean or lake depths and the charting of the topography of the ocean or lake floor.

beach. The unconsolidated material at the shoreline that covers a gently sloping zone, typically with a concave profile, extending landward from the low-water line to the place where there is a definite change in material or physiographic form (e.g., a cliff), or to the line of permanent vegetation (usually the effective limit of the highest storm waves).

bed. The smallest sedimentary stratigraphic unit, commonly ranging in thickness from about 1 cm (0.4 in) to 1 to 2 m (40 to 80 in) and distinguishable from beds above and below.

bedding. Depositional layering or stratification of sediments.

bedrock. Solid rock that underlies unconsolidated sedimentary deposits and soil.

benthic. Pertaining to the ocean bottom or organisms living on or in substrate; also, referring to that environment.

bentonite. Soft clay or greasy claystone composed mostly of the clay mineral smectite, formed by the chemical alteration of glassy volcanic ash in contact with water.

bioturbation. The reworking of sediments by organisms.

bituminous. Describes rocks that contain (and sometimes rocks smell of) asphalt, tar, or petroleum.

bituminous coal. An organic sedimentary rock referred to as "soft coal," resulting from deeper burial with rising pressures and temperatures, driving hydrogen and other volatiles and leaving a fixed carbon content of 50% to 60%.

bivalve. Having a shell composed of two distinct, but equal or nearly equal, movable valves, which open and shut.

blowout. A general term for a small saucer-, cup-, or trough-shaped hollow or depression formed by wind erosion on a preexisting dune or other sand deposit, especially in an area of shifting sand or loose soil, or where protective vegetation is disturbed or destroyed.

body fossil. Evidence of past organisms such as bones, teeth, shells, or leaf imprints.

braided stream. A sediment-clogged stream that forms multiple channels that divide and rejoin.

burrow. A tubular or cylindrical hole or opening, made in originally soft or loose sediment by a mud-eating worm, mollusk, or other invertebrate; may be later filled with clay or sand and preserved.

calcareous. Describes a substance that contains calcium carbonate. When applied to a rock name it implies that as much as 50% of the rock is calcium carbonate.

calcium carbonate. $CaCO_3$. A solid occurring in nature as primarily calcite and aragonite.

calcite. A carbonate (carbon + oxygen) mineral of calcium, $CaCO_3$; calcium carbonate. It is the most abundant cave mineral.

caliche. A hard layer of cemented calcium carbonate, commonly on or near the surface in arid and semiarid regions.

capillary action. The action by which a fluid, such as water, is drawn up in small interstices or tubes as a result of surface tension.

carbonaceous. Describes a rock or sediment with considerable carbon, especially organic material, hydrocarbon, or coal.

cement (sedimentary). Mineral material, usually chemically precipitated, that occurs in the spaces among the individual grains of a sedimentary rock, thus binding the grains together.

cementation. The process by which clastic sediments become lithified or consolidated into hard, compact rocks, usually through deposition or precipitation of minerals in the spaces among the individual grains of the sediment; may occur simultaneously with sedimentation or at a later time.

channel. The bed where a natural body of surface water flows or may flow. Also, a natural passageway or depression of perceptible extent containing continuously or periodically flowing water, or forming a connecting link between two bodies of water.

clast. An individual constituent, grain, or fragment of a rock or unconsolidated deposit, produced by the mechanical or chemical disintegration of a larger rock mass.

clay. Minerals and sedimentary fragments that are less than 1/256 mm (0.00015 in) across.

clay mineral. Any mineral occurring in the clay-sized fraction with the understanding that size imposes physical and chemical characteristics.

claystone (sedimentary). An indurated rock with more than 67% clay-sized minerals.

climbing dune. A dune formed by aeolian piling-up of sand by wind against a cliff or mountain slope.

coal. An organic sedimentary rock consisting of carbon, hydrogen, and oxygen, with some sulfur and nitrogen. Formed by the destructive distillation of plant remains under anaerobic and progressively rising pressures and temperatures until coal with a very high fixed carbon content is attained. Differences in the kinds of plant materials (type), in degree of metamorphism (rank), and in the range of impurity (grade) are characteristic of coal and are used in classification.

coastal plain. Any lowland area bordering a sea or ocean, extending inland to the nearest elevated land, and sloping very gently seaward; may result from the accumulation of material along a coast.

colluvium. A loose, heterogeneous, and incoherent mass of rock fragments and soil material deposited via surface runoff or slow continuous downslope creep; usually collects at the base of a slope or hillside, but includes loose material covering hillsides.

concretion. A hard, compact aggregate of mineral matter, rounded to irregularly shaped; composition generally differs from that of the rock in which it occurs.

contact. The surface between two types or ages of rocks.

continental. Formed on land rather than in the sea. Continental deposits may be of lake, swamp, wind, stream, or volcanic origin.

creep. The slow, imperceptible downslope movement of mineral, rock, and soil particles under gravity.

cross-bed. A single bed, inclined at an angle to the main planes of stratification; the term is commonly restricted to a bed that is more than 1 cm (0.4 in) thick.

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

cross section. A graphic interpretation of geology, structure, or stratigraphy based on mapped and measured geologic extents and attitudes, depicted in a vertical plane (i.e., a cut or profile view).

deformation. The process of folding, faulting, shearing, or fabric development in rocks as a result of Earth stresses.

delta. The low, nearly flat, alluvial tract of land at or near the mouth of a river, commonly forming a triangular or fan-shaped plain of considerable area; resulting from the accumulation of sediment supplied by the river in such quantities that it is not removed by tides, waves, and currents.

delta fan. A deposit formed by the merging of an alluvial fan with a delta.

depth zone. One of five oceanic environments, or ranges of oceanic depths: (1) littoral zone, between high and low tides; (2) neritic zone, between low-tide level and 200 m (660 ft) above the continental shelf; (3) bathyal zone, between 200 and 3,500 m (660 and 11,500 ft); (4) abyssal zone, between 3,500 and 6,000 m (11,500 and 20,000 ft); and (5) hadal zone 6,000 m (20,000 ft) and deeper.

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

discharge. The rate of flow of surface water or groundwater at a given moment, expressed as volume per unit of time.

displacement. The relative movement of the two sides of a fault; also, the specific amount of such movement.

downcutting. Stream erosion in which cutting is directed primarily downward, as opposed to laterally.

downwarping. Subsidence of Earth's crust on a regional scale as a result of crustal loading by ice, water, sediments, or lava flows.

drainage. The manner in which the waters of an area flow off in surface streams or subsurface conduits; also, the processes of surface drainage of water from an area by streamflow and sheet flow, and the removal of excess water from soil by downward flow.

drainage basin. A region or area bounded by a drainage divide and occupied by a drainage system, specifically the tract of country that gathers water originating as precipitation and contributes it to a particular stream channel or system of channels, or to a lake, reservoir, or other body of water.

dune. A low mound or ridge of sediment, usually sand, deposited by the wind.

ebb-tidal delta. A tidal delta formed on the seaward side of a tidal inlet.

efflorescence. A whitish fluffy or crystalline powder produced as a surface encrustation on a rock or soil in an arid region by evaporation of water brought to the surface by capillary action; it may consist of one or several minerals, commonly soluble salts such as gypsum and halite. Also, the process by which an efflorescent salt or crust is formed.

entrenched stream. A stream, often meandering, that flows in a narrow canyon or valley (i.e., "trench") cut into a plain or relatively level upland; specifically a stream that has inherited its course from a previous cycle of erosion and that cuts into bedrock with little modification of the original course.

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

ephemeral lake. A short-lived lake.

ephemeral stream. A stream that flows briefly, only in direct response to precipitation, and whose channel is always above the water table.

epicontinental. Describes a geologic feature on the continental shelf or interior.

escarpment. A steep cliff or topographic step resulting from vertical displacement on a fault or as a result of slope movement or erosion. Synonymous with "scarp."

facies (sedimentary). The depositional or environmental conditions reflected in the sedimentary structures, textures, mineralogy, fossils, and other components of a sedimentary rock.

fault. A break in rock characterized by displacement of one side relative to the other.

fine-grained. Describes sediment or sedimentary rock and texture in which the individual constituents are too small to distinguish with the unaided eye, specifically sediment or rock whose particles have an average diameter less than 1/16 mm (0.002 in), that is, silt-size particles and smaller. Also, describes a crystalline or glassy rock and texture in which the individual minerals are relatively small, specifically an igneous rock whose particles have an average diameter less than 1 mm (0.04 in).

floodplain. The surface or strip of relatively smooth land composed of alluvium and adjacent to a river channel, constructed by the present river in its existing regimen and covered with water when the river overflows its banks. A river has one floodplain and may have one or more terraces representing abandoned floodplains.

floodplain splay. A small alluvial fan or other outspread deposit formed where an overloaded stream breaks through a levee (artificial or natural) and deposits its material (often coarse-grained) on the floodplain. Synonymous with "overbank splay," "sand splay," "channel splay," or simply "splay."

flood-tidal delta. A tidal delta formed on the landward side of a tidal inlet.

fluvial. Of or pertaining to a river or rivers.

fold. A curve or bend in an originally flat structure, such as a rock stratum, bedding plane, or foliation; usually a product of deformation.

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

fossil. A remain, trace, or imprint of a plant or animal that has been preserved in the Earth's crust since some past geologic time; loosely, any evidence of past life.

fracture. The breaking of a mineral other than along planes of cleavage. Also, any break in a rock such as a crack, joint, or fault.

freeze-thaw. The mechanical weathering process caused by alternate or repeated cycles of freezing and thawing water in pores, cracks, and other openings of rock and unconsolidated deposits, usually at the surface.

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

geoarcheology. The application of concepts and methods of the earth sciences to archaeological problems and vice versa. It provides evidence for the development, preservation, and destruction of archaeological sites, and for regional-scale environmental change and the evolution of the physical landscape, including the impact of human groups.

geodetic surveying. Surveying that takes into account the figure and size of Earth, with corrections made for curvature; used where the areas or distances involved are so great that the desired accuracy and precision cannot be obtained by plane (ordinary field and topographic) surveying.

geodesy. The science concerned with the determination of the size and shape of the Earth and the precise location of points on its surface.

geology. The study of Earth, including its origin, history, physical processes, components, and morphology.

geomorphology. The study of the general configuration of surface landforms and their relationships to underlying structures, and of the history of geologic changes as recorded by these surface features.

gradient. A degree of inclination (steepness of slope), or a rate of ascent or descent, of an inclined part of Earth's surface with respect to the horizontal; expressed as a ratio (vertical to horizontal), a fraction (such as m/km or ft/mi), a percentage (of horizontal distance), or an angle (in degrees).

gravel. An unconsolidated, natural accumulation of typically rounded rock fragments resulting from erosion; consists predominantly of particles larger than sand; that is, greater than 2 mm (1/12 in) across.

groundwater. That part of subsurface water that is in the zone of saturation, including underground streams.

gully. A small channel produced by running water in unconsolidated material.

gypsum. A sulfate (sulfur + oxygen) mineral of calcium and water, $CaSO_4 \cdot 2H_2O$.

halite. A halide (chlorine or fluorine) mineral composed of sodium and chloride, NaCl. Synonymous with "native salt," "rock salt," and "common salt."

hematite. An oxide mineral composed of oxygen and iron, Fe_2O_3.

hydrology. The study of liquid and solid water properties, circulation, and distribution, on and under the Earth's surface and in the atmosphere.

incision. Downward erosion by a stream, resulting in a deepened channel and commonly a narrow, steep-walled valley.

intertonguing. The overlapping of markedly different rocks through vertical succession of wedge-shaped layers; results in the disappearance of sedimentary bodies in laterally adjacent masses.

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

kaolinite. A common white clay mineral composed of mostly aluminum oxide.

karren. Channels or furrows caused by solution on massive bare limestone surfaces.

lacustrine. Describes a process, feature, or organism pertaining to, produced by, or inhabiting a lake.

lagoon. A narrow body of water that is parallel to the shore and between the mainland and a barrier island; characterized by minimal or no freshwater influx and limited tidal flux, which cause elevated salinities. Also, a shallow body of water enclosed or nearly enclosed within an atoll.

landslide. A collective term covering a wide variety of slope-movement landforms and processes that involve the downslope transport of soil and rock material en masse under the influence of gravity.

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

levee. A long broad low embankment of sand and coarse silt built by floodwater overflow along both banks of a stream channel.

lignite. An organic sedimentary rock, referred to as "brown coal," with a low fixed carbon content of 25% caused by compaction by overlying sediments.

limestone. A carbonate sedimentary rock consisting of more than 95% calcite and less than 5% dolomite.

littoral. Pertaining to the benthic ocean environment or depth zone between high water and low water; also, pertaining to the organisms of that environment. Synonymous with "intertidal."

loess. Windblown silt-sized sediment.

meander. One of a series of sinuous curves, bends, or turns in the course of a stream, produced by a mature stream swinging from side to side as it flows across its floodplain or shifts its course laterally toward the convex side of an original curve.

medium-grained. Describes an igneous rock and texture in which the individual crystals have an average diameter in the range of 1 to 5 mm (0.04 to 0.2 in.). Also, describes sediment or sedimentary rock and texture in which the individual particles have an average diameter in the range of 1/16 to 2 mm (0.002 to 0.08 in), that is, sand size.

member. A lithostratigraphic unit with definable contacts; a subdivision of a formation.

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

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

montmorillonite. A clay mineral of the smectite group, which is common in soils, sedimentary rocks, and some mineral deposits. They are derived from the alteration of volcanic glass and the weathering of primary silicates.

mudflow. A general term for a landform and process characterized by a flowing mass of predominantly fine-grained earth material possessing a high degree of fluidity during movement.

mollusk. A solitary invertebrate such as gastropods, bivalves, and cephalopods belonging to the phylum Mollusca. Range: Lower Cambrian to Holocene.

orogeny. A mountain-building event.

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

oxbow. A closely looping meander in a stream that resembles the U-shaped collar of an ox yoke. Synonymous with "horseshoe bend."

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

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

paleosol. An soil layer preserved in the geologic record.

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

peat. An unconsolidated deposit of semicarbonized plant remains in a water-saturated environment, such as a bog or fen, and of persistently high moisture content (at least 75%). It is an early stage or rank in the development of coal; carbon content is about 60% and oxygen content is about 30% (moisture-free).

pebble. A small rounded rock, especially a waterworn stone, between 4 and 64 mm (0.16 and 2.5 in) across.

pediment. A gently sloping, erosional bedrock surface at the foot of a mountain or plateau escarpment.

permeability. A measure of the relative ease with which a fluid moves through the pore spaces of a rock or unconsolidated deposit.

piping. Erosion or solution by percolating water in a layer of subsoil, resulting in the formation of narrow conduits, tunnels, or "pipes" through which soluble or granular soil material is removed.

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

point bar. A low ridge of sand and gravel deposited in a stream channel on the inside of a meander, where flow velocity slows.

porosity. The percentage of total void space in a volume of rock or unconsolidated deposit.

progradation. The seaward building of land as a result of sedimentary deposition.

quartz. Silicon dioxide, SiO_2. The only silicate (silicon + oxygen) mineral consisting entirely of silicon and oxygen. Synonymous with "crystalline silica."

radiocarbon age. An isotopic age expressed in years and calculated from the quantitative determination of the amount of carbon-14 remaining in an organic material. Synonymous with "carbon-14 age."

rincon. Meaning "inside corner or nook" in Spanish and used in the southwestern United States for a square-cut recess or hollow in a cliff or a reentrant in the borders of a mesa or plateau. Also used for a small, secluded valley, and for a bend in a stream.

rock. An aggregate of one or more minerals (e.g., granite), a body of undifferentiated mineral matter (e.g., obsidian), or a body of solid organic material (e.g., coal).

rockfall. The most rapid type of slope movement in which a newly detached fragment of bedrock of any size falls from a cliff or other very steep slope, traveling straight down or in a series of leaps and bounds down a slope.

sand. A clastic particle smaller than a granule and larger than a silt grain, with a diameter ranging from 1/16 to 2 mm (0.0025 to 0.08 in).

sand sheet. A sheetlike body of surficial sediment, commonly sand, that veneers the underlying stratigraphic units (unconsolidated deposits or bedrock) and can range in thickness from a few centimeters to tens of meters, with a lateral persistence of a few meters to tens of kilometers.

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

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

sedimentary. Pertaining to or containing sediment.

sedimentary rock. A rock resulting from the consolidation of loose sediment that has accumulated in layers; it may be "clastic," consisting of mechanically formed fragments of older rock; "chemical," formed by precipitation from solution; or "organic," consisting of the remains of plants and animals. One of the three main classes of rock—igneous, metamorphic, and sedimentary.

sedimentation. The process of forming or accumulating sediment into layers, including the separation of rock particles from parent rock, the transportation of these particles to the site of deposition, the actual deposition or settling of the particles, the chemical and other changes occurring in the sediment, and the ultimate consolidation of the sediment into solid rock.

seismic. Pertaining to an earthquake or Earth vibration, including those that are artificially induced.

seismicity. The phenomenon of movements in the Earth's crust. Synonymous with "seismic activity."

septaria. A large, 8–90 cm (3–35 in) across, roughly spheroidal concretion characterized by a series of radiating cracks that are invariably filled or partly filled by crystalline minerals, most commonly calcite.

sequence. A succession of geologic events, processes, or rocks, arranged in chronologic order to show their relative position and age with respect to geologic history as a whole. Also, a rock-stratigraphic unit that is traceable over large areas and defined by sediment associated with a major sea level transgression–regression.

shale. A clastic sedimentary rock made of clay-sized particles and characterized by fissility.

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

sheetflood. A broad expanse of moving, storm-borne water that spreads as a thin, continuous, relatively uniform film over a large area in an arid region and that is not concentrated into well-defined channels; its distance of flow is short and its duration is measured in minutes or hours, commonly occurring after a period of sudden and heavy rainfall.

sheet flow. The downslope movement or overland flow of water, in the form of a thin, continuous film, over relatively smooth soil or rock surfaces and not concentrated into channels larger than rills.

sheetwash. A sheetflood occurring in a humid region. Also, the material transported and deposited by the water of a sheetwash. Used as a synonym of "sheet flow" and "sheet erosion."

silicate. A mineral group composed of silicon (Si) and oxygen (O) plus an element or elements, for example, quartz, SiO_2; olivine, $(Mg, Fe)_2SiO_4$; and pyroxene, $(Mg,Fe)SiO_3$; as well as the amphiboles, micas, and feldspars.

silt. Clastic sedimentary material intermediate in size between fine-grained sand and coarse clay, 0.0039 to 0.063 mm (0.00015 to 0.0025 in) across.

silting. The accumulation of silt suspended throughout a body of standing water or in some considerable portion of it. In particular, the choking, filling, or covering with stream-deposited silt behind a dam or other place of retarded flow, or in a reservoir. Synonymous with "siltation."

siltstone. A clastic sedimentary rock composed of silt-sized grains.

slope. The inclined surface of any part of Earth's surface, such as a hillslope. Also, a broad part of a continent descending into an ocean.

slope movement. The gradual or rapid downslope movement of soil or rock under gravitational stress. Synonymous with "mass wasting."

slope wash. Soil and rock material that is or has been transported down a slope under the force of gravity and assisted by running water not confined to channels; also, the process by which slope-wash material is moved.

soil. The unconsolidated portion of the Earth's crust modified through physical, chemical, and biotic processes into a medium capable of supporting plant growth.

spring. A place where groundwater flows naturally from a rock or the soil onto the land surface or into a body of surface water.

stage. A major subdivision of a glacial epoch, particularly one of the cycles of growth and disappearance of the Pleistocene ice sheets.

strata. Tabular or sheetlike layers of sedimentary rock that are visually distinctive from other layers above and below. The singular form of the term is stratum, but is less commonly used.

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

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

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

stream channel. A long, narrow depression shaped by the concentrated flow of stream water.

stream terrace. A planar surface alongside a stream valley representing the remnants of an abandoned floodplain, stream bed, or valley floor produced during a former stage of erosion or deposition.

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

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

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

subbituminous. Describes black coal, intermediate in rank between lignite and bituminous coal; distinguished from lignite by higher carbon and lower moisture content.

subsidence. The sudden sinking or gradual downward settling of part of Earth's surface.

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

tectonic. Describes a feature or process related to large-scale movement and deformation of Earth's crust.

terrace. Any long, narrow, relatively level or gently inclined surface (i.e., a bench or steplike ledge) that is bounded along one edge by a steeper descending slope and along the other edge by a steeper ascending slope, thus breaking the continuity of the slope; commonly occurs along the margin and above the level of a body of water, marking a former water level.

terrestrial. Describes a feature, process, or organism related to land, Earth, or its inhabitants.

tidal delta. A delta formed at the mouth of a tidal inlet on either the seaward or the lagoon side of a barrier island or baymouth bar by changing tidal currents that sweep sand in and out of the inlet.

tidal inlet. Any inlet through which water alternately floods landward with the rising tide and ebbs seaward with the falling tide; specifically a natural inlet maintained by tidal currents.

tongue. An extension, projection, or offshoot of a larger body of rock, commonly occurring as wedges that disappear away from the main body.

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

trace fossil. A fossilized feature such as a track, trail, burrow, or coprolite (dung), that preserves evidence of an organism's life activities, rather than the organism itself. Compare to "body fossil."

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

trend. The direction or bearing of an outcrop of a geologic feature such as an ore body, fold, or orogenic belt.

uplift. A structurally high area in Earth's crust produced by movement that raises the rocks.

upwarping. Upward flexing of Earth's crust on a regional scale as a result of the removal of ice, water, sediments, or lava flows.

wash. A broad, gravelly, dry stream bed, generally in the bottom of a canyon that is periodically swept by a torrent of water. The term is used especially in the southwestern United States.

weathering. The physical, chemical, and biological processes by which rock is broken down, particularly at Earth's surface.

yazoo. A tributary that is parallel to the main stream channel for a considerable distance before joining it, especially a stream forced to flow along the outer base of a natural levee formed by the main stream. The type example is the Yazoo River in western Mississippi, joining the Mississippi River at Vicksburg.

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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 August 2015. 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
  Energy and Minerals; Active Processes and Hazards; Geologic Heritage:
  http://nature.nps.gov/geology/
- NPS Geologic Resources Inventory: http://www.nature.nps.gov/geology/inventory/index.cfm
- NPS Geoscientist-In-the-Parks (GIP) internship and guest scientist program:
  http://www.nature.nps.gov/geology/gip/index.cfm
- NPS Views program (geology-themed modules are available for Geologic Time, Paleontology, Glaciers, Caves and Karst, Coastal Geology, Volcanoes, and a variety of geologic parks):
  http://www.nature.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://nature.nps.gov/geology/monitoring/index.cfm
- 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 Societies

- 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/

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://tapestry.usgs.gov/Default.html

Appendix A: Scoping Participants

The following people attended the GRI scoping meeting for Chaco Culture National Historical Park, held on 14 February 2007; a follow-up conference call on 13 February 2014; or a conference call that focused on oil and gas issues on 15 April 2014. Discussions during this meeting and calls 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
Tim Connors	NPS Geologic Resources Division	Geologist
Dabney Ford	Chaco Culture National Historical Park	Cultural Resource Manager
Katie KellerLynn	Colorado State University	Geologist/Research Associate
Dave Love	New Mexico Bureau of Geology and Mineral Resources	Geologist
Lisa Norby	NPS Geologic Resources Division	Geologist
Brad Shattuck	Chaco Culture National Historical Park	Natural Resource Manager
Phil Stoffer	US Geological Survey	Geologist
Heather Stanton	Colorado State University	Geologist/Research Associate
Barbara West	Chaco Culture National Historical Park	Superintendent

2014 Conference Call Participants

Name	Affiliation	Position
Eric Bilderback	NPS Geologic Resources Division	Geologic Hazards and Disturbed Lands Program Lead
Dabney Ford	Chaco Culture National Historical Park	Cultural Resources Chief
Katie KellerLynn	Colorado State University	Geologist/Research Associate
Jason Kenworthy	NPS Geologic Resources Division	Geologist/GRI Reports Coordinator
Dave Love	New Mexico Bureau of Geology and Mineral Resources	Geologist
Steve Monroe	NPS Southern Colorado Plateau Network	Hydrologist
Hal Pranger	NPS Geologic Resources Division	Geologic Features and Systems Branch Chief
Vincent Santucci	NPS Geologic Resources Division	Senior Geologist/Paleontologist/Washington Liaison
Phil Varela	Chaco Culture National Historical Park	Paleontology Technician
Jim Von Haden	Chaco Culture National Historical Park	Natural Resources Program Manager

2014 Oil and Gas Issues Conference Call Participants

Name	Affiliation	Position
Tim Connors	NPS Geologic Resources Division	Geologist/GRI Maps Coordinator
Katie KellerLynn	Colorado State University	Geologist/Research Associate
Jason Kenworthy	NPS Geologic Resources Division	Geologist/GRI Reports Coordinator
Kerry Moss	NPS Geologic Resources Division	External Energy and Minerals Program Coordinator
Lisa Norby	NPS Geologic Resources Division	Energy and Minerals Branch Chief
Jim Von Haden	Chaco Culture National Historical Park	Natural Resources Program Manager
Katie Earp	Chaco Culture National Historical Park	Physical Science Technician

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 August 2015. 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.
Caves and Karst Systems	**Federal Cave Resources Protection Act of 1988, 16 USC §§ 4301 – 4309** requires Interior/Agriculture to identify "significant caves" on Federal lands, regulate/restrict use of those caves as appropriate, and include significant caves in land management planning efforts. Imposes civil and criminal penalties for harming a cave or cave resources. Authorizes Secretaries to withhold information about specific location of a significant cave from a Freedom of Information Act (FOIA) requester. **National Parks Omnibus Management Act of 1998, 16 USC § 5937** protects the confidentiality of the nature and specific location of cave and karst resources.	**36 CFR § 2.1** prohibits possessing/destroying/disturbing…cave resources…in park units. **43 CFR Part 37** states that all NPS caves are "significant" and sets forth procedures for determining/releasing confidential information about specific cave locations to a FOIA requester.	**Section 4.8.1.2** requires NPS to maintain karst integrity, minimize impacts. **Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.2** requires NPS to protect caves, allow new development in or on caves if it will not impact cave environment, and to remove existing developments if they impair caves. **Section 6.3.11.2** explains how to manage caves in/adjacent to wilderness.

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 I**ndian 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).

The Department of the Interior protects and manages the nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its special responsibilities to American Indians, Alaska Natives, and affiliated Island Communities.

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