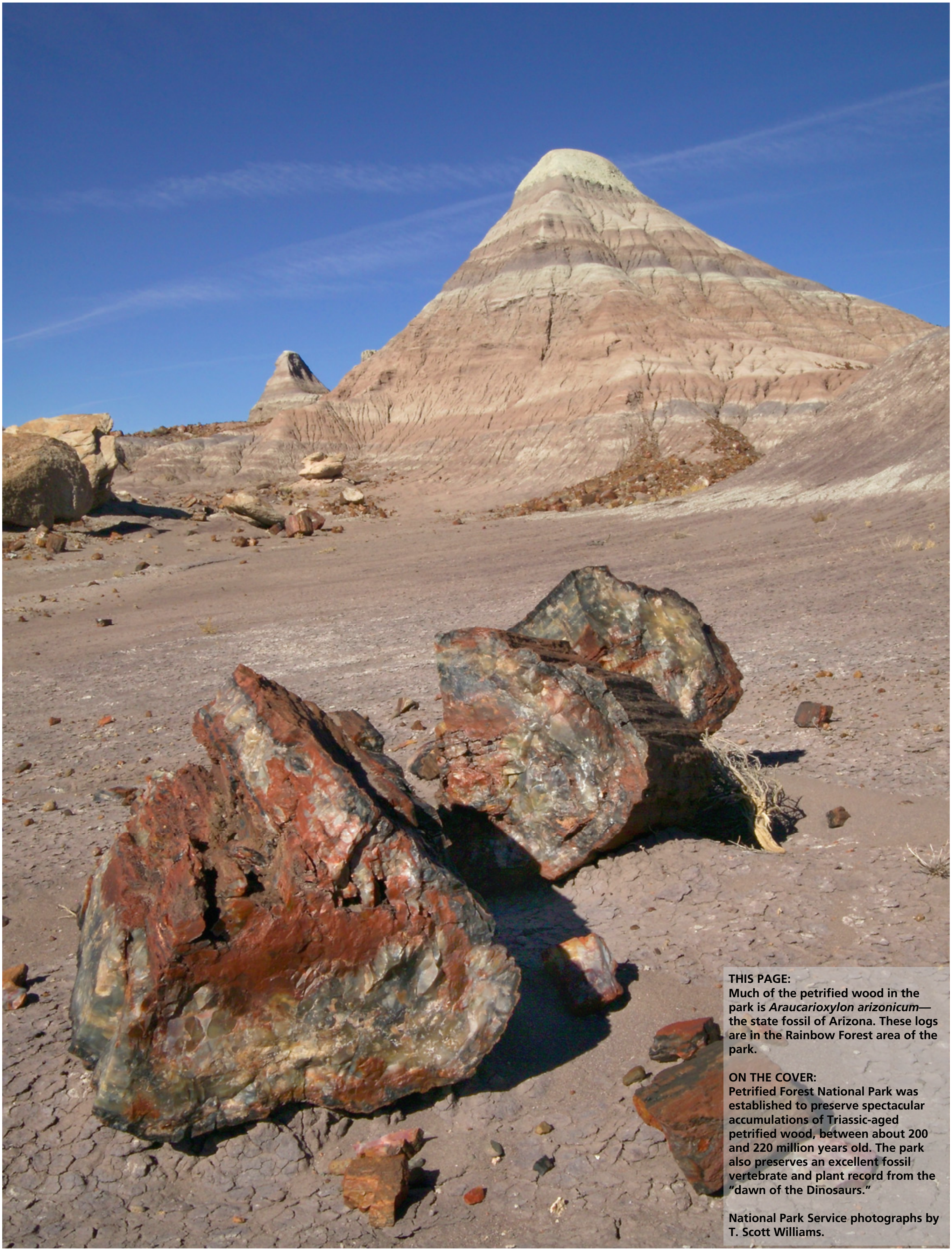
National Park Service
U.S. Department of the Interior

Natural Resource Program Center

Petrified Forest National Park

Geologic Resources Inventory Report

Natural Resource Report NPS/NRPC/GRD/NRR—2010/218



THIS PAGE:
Much of the petrified wood in the park is *Araucarioxylon arizonicum*—the state fossil of Arizona. These logs are in the Rainbow Forest area of the park.

ON THE COVER:
Petrified Forest National Park was established to preserve spectacular accumulations of Triassic-aged petrified wood, between about 200 and 220 million years old. The park also preserves an excellent fossil vertebrate and plant record from the "dawn of the Dinosaurs."

National Park Service photographs by T. Scott Williams.

Petrified Forest National Park

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Geologic Resources Division
Natural Resource Program Center
P.O. Box 25287
Denver, Colorado 80225

June 2010

U.S. Department of the Interior
National Park Service
Natural Resource Program Center
Ft. Collins, Colorado

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

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

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

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

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Executive Summary

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

The excellent exposures and accessibility of the Upper Triassic Chinle Formation make Petrified Forest National Park a world-renowned natural laboratory for paleontology and other geologic disciplines such as sedimentology, stratigraphy, geomorphology, and structural geology. Petrified Forest National Park contains one of the largest and most colorful deposits of mineralized wood in the world. The park's forests of petrified wood and other Upper Triassic fossil flora and fauna are globally significant because they provide a distinct record of diverse terrestrial ecosystems during "the dawn of dinosaurs" about 220 million years ago. This period tracks the evolutionary transition of nonmarine animals, especially tetrapods. Scientists now recognize Petrified Forest National Park as one of the best places in the world to study these changes in the geologic record.

In addition to scientific study, the following issues could require attention from resource managers at Petrified Forest National Park:

- Petrified Wood. Congress set aside Petrified Forest National Park in order to preserve an incredible concentration of petrified wood. Over the years, attitudes about protection have ranged from permissible collection to today's "zero tolerance" policy. The findings from social science studies about wood theft vary widely, making any estimates or analysis of the problem uncertain and questionable. However, the loss of the resource from within the expanded boundary and the invasive techniques used to unearth the buried remains highlight the need for continued protection. Furthermore, many visitors seem unable to resist the lure of taking a souvenir of petrified wood.
- Paleontological Resource Damage. The ongoing paleontological inventory at Petrified Forest National Park has revealed that erosion and "poor science" are the primary causes of damage to vertebrate fossil resources. The National Park Service (NPS) has compiled various guidance documents, primarily the Natural Resource Management Reference Manual 77, to help managers avoid damage to paleontological resources. In addition, the Geological Society of America published a resource monitoring manual that suggests vital signs for paleontological resources. Active management remains the key to fossil preservation.
- Paleontological Resource Inventory. In 2001, resource managers at Petrified Forest National Park began to relocate and document all known paleontological sites, beginning with those containing vertebrate fossils. Although the scientific community and the public have recognized the fossil resources of the area for more than 150 years, the inventory has revealed anew the incredible wealth of fossil resources at the park. Petrified Forest National Park hosts a total of 555 documented sites; the inventory has relocated more than 200 of these. However, the more than 20,200 ha (50,000 ac) of very fossiliferous deposits puts a strain on the park's small resource staff. Additional staff and trained volunteers would facilitate paleontological resource inventory and monitoring.
- Paleontological Research. Since 2000, park and cooperating paleontologists have published more than 40 papers about the park's paleontological resources, particularly fossil vertebrates but also fossil plants and microinvertebrates. Scientists from outside institutions who request and receive research permits have accomplished much of the paleontological research. The permitting system includes provisions to ensure that research activities comply with both Servicewide and park-specific requirements. Researchers provide copies of field data and submit an investigator's annual report. Analysis identified the need for suitable space to conduct laboratory, office, and collection activities for on-site research. The lack of space for researchers could inhibit continued research.
- Revisions to Stratigraphy. The stratigraphic nomenclature at Petrified Forest National Park has been undergoing revisions since the early 1990s. Over the years, correlation of strata at the park has been contentious, and investigators have separated, combined, translated, and renamed various portions of the Chinle Formation. The exact age of the Chinle Formation is uncertain, but detailed geologic mapping and ongoing investigations will help define and clarify the formation's age and significance.
- Bentonite. The picturesque mudstone beds of the Chinle Formation shape the beautiful badlands within the park. These beds contain bentonite—clay that has the ability to absorb large quantities of water accompanied by a large increase in volume. Rocks with bentonite swell when wet and shrink when dry, causing the ground surface to heave and buckle. The presence of bentonite, which contributes to the bare slopes and rapid erosion of badlands development, also creates sinkholes and pipes and affects the integrity of roads and buildings.
- Mass Wasting. Features of mass wasting such as the downslope movement of bentonitic mudstone in the Chinle Formation, slump blocks along the cliffs of

Pintado Point, and cliff retreat near Newspaper Rock and along Blue Mesa could be of interpretive interest to park visitors. Such features could require attention and mitigation by resource managers. The severity of such problems is directly related to the extent of infrastructure in the affected areas. Early recognition, avoidance, or corrective engineering can mitigate the effects of mass wasting.

- Subsidence. The downward displacement of surface material affects the resources at Petrified Forest National Park on both small and large scales. For example, in 2005, a subsidence crack on the Blue Mesa Loop Road and the mesa edge required the technical assistance of the NPS Geologic Resources Division. On a larger scale, subsidence creates topographic features on the park's landscape such as the Blue Mesa sink—a solution-collapse depression covering 1 km (0.6 mi) in diameter with surface relief of about 30 m (100 ft).
- Potash. The dramatic increase in the price of potash, driven by the demand for fertilizer, has renewed interest in Arizona deposits, namely within the Holbrook Basin, which underlies a significant portion of Petrified Forest National Park. The stratigraphic location of the deposit would allow for underground mining techniques to exploit the potash, meaning that surface mining within the expanded boundaries of the park could be avoided. A single surface location could access the deposit, centralizing impacts; however, because of the deposit's size, the surface footprint could cover hundreds of acres and require multiple work areas.
- Liquefied Petroleum Gas Storage. Eleven storage caverns, part of Ferrell Liquefied Petroleum Gas Storage Facility, are located immediately west of the park boundary along the Burlington Northern Santa Fe Railway. These caverns do not present any immediate hazard to park resources, personnel, or visitors. However, because evacuation and closure of the park road east of the facility could be necessary in the event of a large spill or fire, the park superintendent should verify that they are on the storage facility's emergency notification list. Park staff should maintain a good working relationship with state regulators and Ferrell Gas management.
- Uranium. The sandstone beds of the Chinle Formation are known to contain uranium. However, the potential for uranium mining on lands in or near the park is very low. Uranium exploration did occur in the Twin Buttes area of the park, but the nearest uranium mines are outside the park, north of Holbrook. The main resource management concern regarding uranium is protection of groundwater quality. Most of the observed radioactivity in the alluvial aquifer in the vicinity of the park is from natural sources rather than from effluent from mining and milling operations. Nevertheless, the U.S. Geological Survey and NPS Water Resources Division recommend that park managers continue annual sampling of the alluvial groundwater to determine whether significant water quality changes have taken place.
- Adjacent Development. The primary purpose of the 2004 boundary expansion was to protect natural resources; however, it could have unforeseen consequences, namely population growth in the immediate vicinity of the park. At present, lands surrounding the park remain remote, with no access to water and no easy access to transportation routes. However, studies have shown that more and more people are choosing to move to "wilderness areas" based on quality of life choices. Adjacent development to the park and wilderness area could result in an increase in infrastructure, loss of important wildlife habitat, and threats to biodiversity. It could also drive up housing prices, resulting in a shortage of affordable rental units. Adjacent development could provide greater access to paleontological resources, and associated construction could increase erosion and reactivate eolian processes (e.g., dust storms).

The glossary contains definitions for many geologic terms used throughout this report and on the Map Unit Properties Table. For a geologic time scale, refer to figure 20.

Acknowledgements

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

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

Special thanks to: T. Scott Williams (Kalaupapa National Historical Park) who provided many NPS photographs for the report. Pat O'Dell (NPS Geologic Resources Division) provided information regarding potash mining and mineral rights in the Petrified Forest National Park area.

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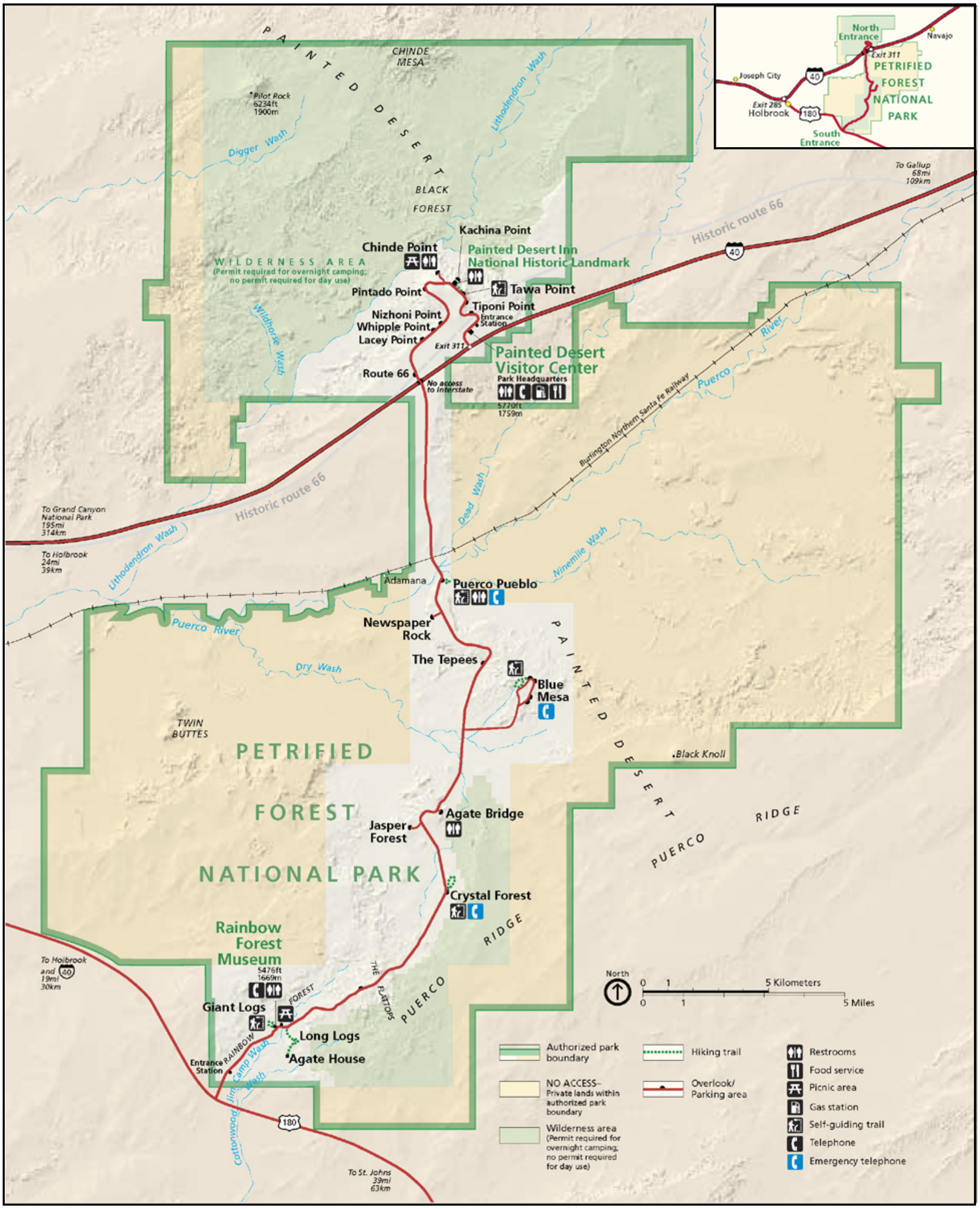

Figure 1. Map of Petrified Forest National Park. National Park Service graphic.

Introduction

The following section briefly describes the National Park Service Geologic Resources Inventory and the regional geologic setting of Petrified Forest National Park.

Purpose of the Geologic Resources Inventory

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

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

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

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

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

Park Setting

Humans have inhabited the Petrified Forest National Park (fig. 1) area for at least 13,000 years (National Park Service 2010). Prehistoric peoples created a variety of legends regarding the petrified-wood deposits in the area. For example, the southern Utah Paiute interpreted petrified logs to be the arrow shafts of their thunder god Shinuav while the Navajo believed the logs represented the monster Yietso, slain by Navajo ancestors (Mayor 2005; National Park Service 2010). In addition to incorporating the fossil resources into their legends and culture, prehistoric peoples used petrified wood as building material (fig. 2) and for making projectile points (fig. 3).

The first Euro-Americans (Spaniards) passed through the Petrified Forest National Park area of Arizona in 1540; however, it wasn't until the mid-1800s that the area received recognition as a result of a U.S. Army survey report of trees that had turned to stone. After examining the area in 1899, U.S. Geological Survey (USGS) paleontologist Lester F. Ward recommended that homesteaders no longer be allowed to claim land in this area. This recommendation and the growing excitement over the area's scenic and scientific values spurred the General Land Office to withdraw the area from homestead entry. However, the petrified forests remained vulnerable to wood theft, which reached alarming proportions with the completion of the railroads in this area (National Park Service 1990). Railroad passengers would take excursions from a coaling and watering stop in nearby Adamana, Arizona, to "Chalcedony Park," as the area was then known. These collectors would load railroad boxcars with petrified wood for shipment to eastern states for the manufacturing of table tops, mantel pieces, and other ornaments. In a short time, collectors and souvenir hunters had hauled off tons of petrified wood, as well as quartz crystals and American Indian artifacts. In 1906, a huge rock crusher threatened to pulverize petrified logs from the area for the manufacturing of abrasives. On December 8, 1906, President Theodore Roosevelt (who, three months earlier, had signed An Act for the Preservation of American Antiquities) proclaimed the Petrified Forest as a National Monument to curtail the alarming rate at which wood was disappearing from the area. Petrified Forest National Monument became the first "fossil park" in the National Park System, giving the National Park Service stewardship over 24,596 ha (60,776 ac) of petrified wood sites.

Over the years, numerous changes have occurred to the boundaries of the monument (fig. 1). In 1962, the U.S. Congress redesignated the monument as Petrified Forest National Park. In 1970, as a result of the Wilderness Act of 1964, 20,340 ha (50,260 ac) of parkland were set aside as wilderness. This area, along with a portion of Craters of the Moon National Monument (Idaho), became the first wilderness areas in the National Park System (National Park Service 2000). In December 2004, the size of the authorized boundary of Petrified Forest National Park more than doubled; this expansion included the West Rim of the Painted Desert. While the top two priorities for addition of lands to the park in 2004 were preserving paleontological and archaeological resources, the boundary change also protects the very important "first view" of the Painted Desert, which visitors see when approaching the park from the west on Interstate 40 (I-40) (National Park Service 2006).

Before I-40 ushered in visitors, Petrified Forest National Park was crossed by the old 35th Parallel Route, the railroad (presently the Burlington Northern Santa Fe Railway), and Route 66. These routes followed the lay of the land in the low-gradient Puerco River valley. Federal government surveyors charted a course for a possible cross-country railroad line in December 1853. Managers of the Atlantic & Pacific Railroad chose this route, completing tracks through northern Arizona in 1882. Route 66, the famed "Mother Road," paralleled the same route and opened the region to auto travelers in the 1930s (Houk 2005).

Colorado Plateau

The Petrified Forest is part of the Colorado Plateau physiographic province—a high-elevation region of basins, plateaus, and canyons, roughly centered on the Four Corners area of Colorado, New Mexico, Utah, and Arizona (fig. 4). The uplift that elevated the plateau is a relatively recent geologic event, occurring within the past 70 million years. Numerous National Park System units are situated on the Colorado Plateau. The Uinta Mountains of Utah and the Rocky Mountains of Colorado define the northern and northeastern boundaries of the plateau. The Mogollon Rim—an erosional cuesta that separates the Colorado Plateau from the extensively faulted Basin and Range physiographic province—marks the southern boundary. The Rio Grande Rift Valley in New Mexico defines the eastern boundary. A broad transition zone—where geologic features typical of Colorado Plateau and Basin and Range comingle—lies to the west.

Globally Significant Upper Triassic Exposures

The lack of overburden in the park provides excellent exposures, making these Triassic deposits (about 220 to 200 million years old) some of the most accessible for study. Furthermore, the Petrified Forest National Park Expansion Act of 2004 added 26 km (16 mi) of the 35-km (22-mi) Chinle escarpment, which contains the world's most significant record of fossils from the Upper Triassic Period. The petrified logs were always considered beautiful and technically interesting, but scientists now realize that the scenic and scientific values greatly exceed a "collection of curiosities," as they were once viewed by visitors. Today, this resource is known to be part of an ancient ecosystem that represents an especially significant time in the evolution of life on Earth—a time of transition when the earliest dinosaurs evolved (National Park Service 1990). Scientists are able to relate the fossils to their environment of deposition, further enhancing their scientific value. These fossils are of particular interest because few Upper Triassic terrestrial fossils are known, and the concentration of so many representatives of an ancient ecosystem in such a small area is rare.

Figure 2. Agate House Pueblo. Ancestral Puebloan peoples from the Pueblo III period (between about 1150 and 1300 CE [Common Era; preferred to "AD"]) built the structure from petrified logs. The Civilian Conservation Corps partially reconstructed Agate House in 1934. National Park Service photograph.

Figure 3. Petrified wood projectile points. Prehistoric peoples utilized the abundant petrified wood of the Petrified Forest region as raw material for projectile points. Not to same scale. National Park Service photographs by T. Scott Williams.

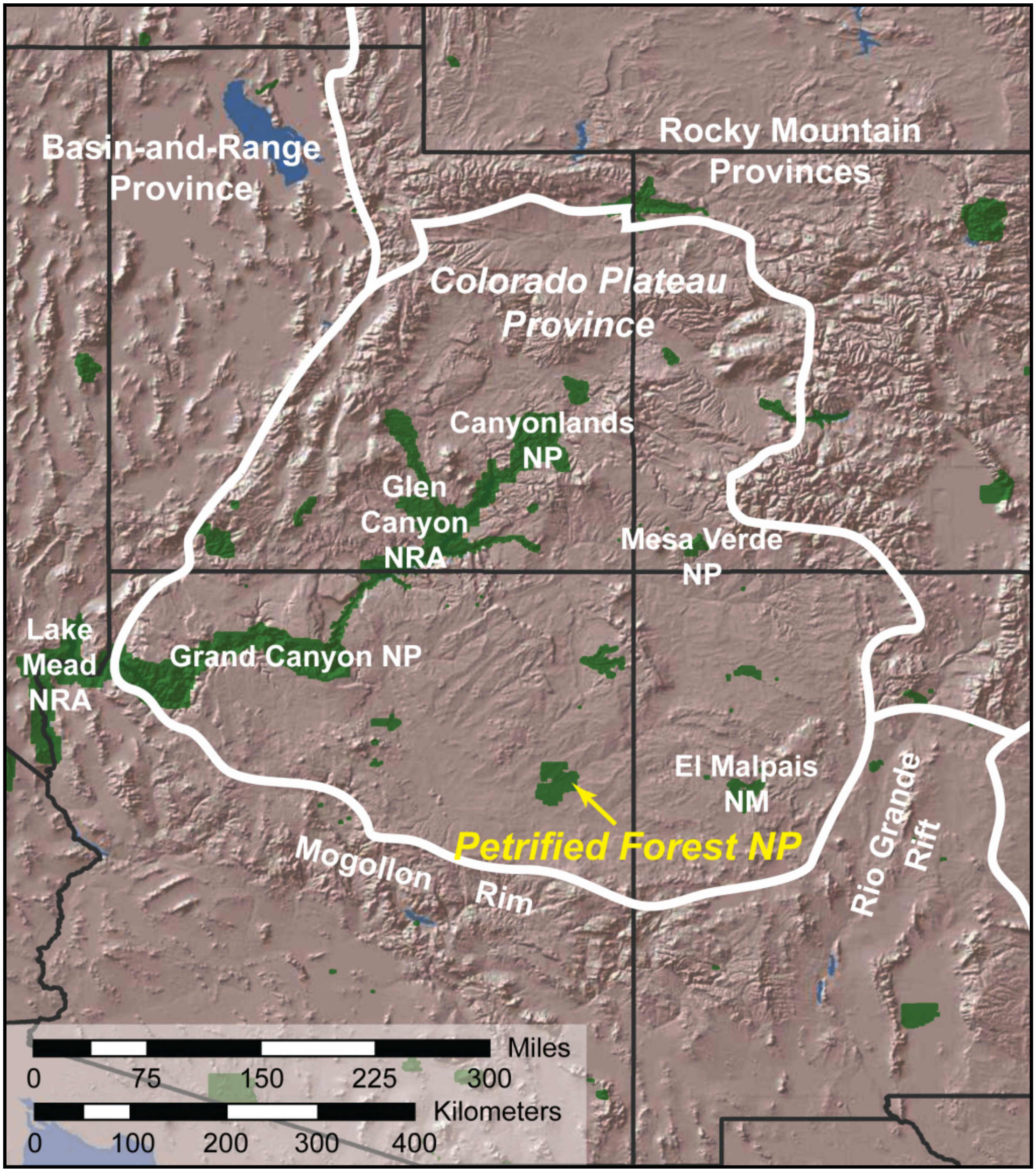

Figure 4. Colorado Plateau. Among many other National Park System units, Petrified Forest National Park is situated on the Colorado Plateau. This region of high elevation composes the Four Corners area of Utah, Colorado, Arizona, and New Mexico. The green areas on the figure represent National Park System units, a small selection of which are labeled. Shaded relief imagery compiled by Jason Kenworthy (NPS Geologic Resources Division) from ESRI Arc Image Service, ESRI World Shaded Relief.

Geologic Issues

The Geologic Resources Division held a Geologic Resources Inventory scoping session for Petrified Forest National Park on June 27–28, 2001, to discuss geologic resources, address the status of geologic mapping, and assess resource management issues and needs. This section synthesizes the scoping results, in particular those issues that may require attention from resource managers. Contact the Geologic Resources Division for technical assistance.

Participants of the 2001 GRI scoping session identified two main resource management concerns for Petrified Forest National Park: (1) resource theft, specifically with regard to petrified wood; and (2) bentonitic (swelling) soils. According to the scoping summary, "currently, the greatest issue facing park resource management is dealing with the threat of resource theft, as tons of petrified wood are stolen from the park on a yearly basis." Thus, the digital geologic map for the park was produced at a higher resolution (scale of 1:24,000 rather than 1:48,000) to "aid in defining areas at highest risk to resource theft" (see Map Unit Properties section and Appendix A). Note the map was produced prior to the 2004 boundary expansion.

Based on the results of the scoping meeting, paleontological resources and bentonite are prioritized are discussed first in this section. Discussions of other issues of possible concern for resource managers follow.

Petrified Wood

Aptly named and simply stated, Petrified Forest National Park was set aside to preserve one of the Earth's largest and most colorful concentrations of petrified wood (fig. 5). Recent research has shown the significance of the fossilized wood in its paleoenvironmental context (revealing the evolutionary histories of Triassic plants and animals), validating one of the primary purposes of park management: the protection of the petrified wood.

Over the years, attitudes about the protection of petrified wood have evolved: the earliest caretakers of the monument were allowed to sell the pieces of the colorful resource to supplement their $1 per year "salaries" (National Park Service 1990) Today, the park has a "zero tolerance" policy with regard to the illegal collection of petrified wood (Bill Parker, Petrified Forest National Park, e-mail, October 29, 2008). Nevertheless, since the petrified forests were first recognized and appreciated, it has been a known fact that petrified wood disappears at the hands of collectors—piece-by-piece or by the ton. As stated in *Petrified Forest Natural and Cultural Resources Management Plan and Program* (National Park Service 1986), "visitors annually remove approximately 12 tons of petrified wood from the park" (p. 3). This anecdotal 12-ton amount has been woven into the fabric of the park's resource identity, but its empirical validity has yet to be proven (Bill Parker, Petrified Forest National Park, e-mail, October 29, 2008). Through the years, investigators have undertaken studies to estimate the amount of petrified wood removed from the park. In 1990, investigators used 45 "baited plots" along visitor pathways and suggested that visitors stole 8,129 pounds [4.065 tons] of petrified wood per day (Scher 1990). Furthermore, this study estimated that 1.01 pounds of petrified wood were stolen per person and 2.73 pounds of petrified wood were stolen per car. Also, for every 416 pounds of wood stolen, one pound was recovered (Scher 1990). The wood samples in the baited plots were near gem quality (and presumably harder to resist). Wood previously confiscated from vehicle inspection stations was used in the baited plots. Another study observed visitor behavior at Long Logs and Crystal Forest, two popular petrified wood sites. During this 1993 study, investigators observed 125 people stealing petrified wood over 122 hours of observation (Roggenbuck et al. 1997). This rate averages about 1.02 thieves per hour (Roggenbuck et al. 1997).

These widely varying findings lead to questionable estimates and make quantitative analysis of the issue difficult. However, the consensus is that too many people are unable to resist the pocketing of a park "souvenir" in the form of a small piece of petrified wood.

The park's history is replete with programs aimed at minimizing the pilfering of petrified wood by souvenir collectors (Monkevich et al. 1994; Roggenbuck et al. 1997). Through the years, park managers have tried various methods to prevent the loss of this resource. For example, small souvenir-sized pieces of petrified wood were purchased from outside sources and given to visitors as an incentive to prevent them from "shoplifting" souvenir chips from the park. Studies have shown that both written materials and personal contacts are effective in gaining visitor compliance (Roggenbuck et al. 1997; Widner and Roggenbuck 2000; Attarian 2003). Therefore, an intensive signing program was instituted to inform visitors that no more of the resource was being made, so they should leave it for future generations to enjoy. Employees both in and out of uniform have been stationed at potential theft sites to try to prevent or reduce theft (National Park Service 1986).

National Park Service Management Policies 2006 states, "The sale of original paleontological specimens is prohibited in parks" (National Park Service 2006b, p. 55). However, this policy is waived for Petrified Forest National Park because research suggests that banning wood sales in park gift shops could lead to an increase in wood theft (National Park Service 2006a). Park managers require that park concessionaire makes buyers aware that the wood being sold is not collected from within the park. Roggenbuck et al. (1997) found that 65.5% of visitors surveyed strongly agreed that being able to buy petrified wood in the park gift shops reduced the temptation to take a piece from park grounds.

Roggenbuck et al. (1997) made a number of recommendations for reducing fossil theft within the park. A variety of print, web-based, and on-the-ground interpretation techniques maximizes the potential to educate visitors regarding park regulations and the stewardship mission of the NPS. For example, the researchers found that the park brochure was the most used informational document for learning about the park's rules and regulations (76% of the visitors surveyed). Web-based outreach could reach visitors prior to their travels to the park.

The issue is also addressed in the form of a children's story, *The Tourist, the Park Ranger, and the Petrified Forest*, at http://www.nps.gov/archive/pefo/Story/story_titlepage.htm (accessed November 13, 2009). This tale discusses the consequences of theft and promotes moral reasoning and change in behavior.

Petrified Forest National Park was highlighted on the Park Spotlight page of the NPS Web site at http://www.nps.gov/parkoftheweek/pefo.htm (accessed November 13, 2009). At the end of the text is a list of NPS priorities that clearly state the concern about resource theft, including petrified wood:

> **Resource Theft:** Everything in a national park is referred to as resources, including the plants, animals, geological formations, archaeological artifacts, and even the air. Resource theft is a continuing problem for the park. Each year several tons of petrified wood is stolen. Many areas have been stripped clean of small, easily removed pieces. Visitors also pilfer other minerals and cultural artifacts (pottery shards, arrowheads) from park sites.
>
> Park staff work very hard to slow the theft of resources through strict enforcement of park regulations via fines or arrest. Staff also educates the visiting public about the significance of the environment and the irreplaceable information it contains. Park publications, displays and exhibits are designed to increase visitor awareness of these resources, leading to a stewardship ethic and desire to protect Petrified Forest National Park for these and future generations.

Petrified Wood Collection within the Expanded Boundary

Most of the sizable logs have been removed from land acquired as part of the 2004 boundary expansion (National Park Service 2008a). Although collection of petrified wood is prohibited on federal and unleased state lands in Arizona, removal is legal on private lands within the expanded boundary of Petrified Forest National Park with the permission of the owners. Extraction of petrified wood and associated impacts could occur on nearly 32,000 ha (80,000 ac) of privately-owned lands within the expanded boundary (National Park Service 2008a).

Because of the "disappearance" of petrified wood at the surface of the expanded parklands, future recovery will involve more intrusive techniques that literally move into the realm of mining. A common technique involves removal with a ripper hook, which typically extends 1.8 to 3 m (6 to 10 ft) into the ground. As a bulldozer crisscrosses an area, the attached hook snags objects such as buried petrified logs or root balls. An excavator or backhoe is utilized to dig out the specimens (National Park Service 2008a).

Paleontological Resource Damage

Although preserved for more than 200 million years, time is taking its toll on the fossils at Petrified Forest National Park. The lack of vegetation, nature of the strata, and geomorphic character of the badlands continuously subject the park's paleontological resources to erosion. Natural weathering processes can start to damage fossils even before they are actually exposed, and once these resources are at the surface, they are quickly destroyed, often losing much of their scientific value for correlation, evolution, and understanding of past depositional environments. Active management—including location surveys, preparation, and placement in a museum collection for preservation and study—is the key to fossil preservation.

Second only to erosion, "poor science" is another factor in fossil preservation. The ongoing paleontological resource inventory at Petrified Forest National Park has revealed that some damage to vertebrate fossil resources is the result of poor science being conducted by permitted researchers (Parker and Dorn 2006). Examples of poor science include partially excavated, abandoned specimens that are later destroyed by exposure; improperly prepared or heavily damaged specimens; specimens collected without clear research plans or proper documentation; and undocumented specimens collected by untrained workers of scientists with permits.

The National Park Service has compiled various guidance documents to help resource managers avoid damage to paleontological resources, in particular, Natural Resource Management Reference Manual 77, formerly Director's Order 77 (National Park Service 2004b). In addition, the Geological Society of America published a manual for monitoring geologic resources, which includes a chapter on paleontology (Santucci et al. 2009). The monitoring strategy suggests the following five vital signs for paleontological resources. Because paleontological localities vary widely from location to location within a park and throughout the National Park System, any specific vital sign might not be useful or appropriate at all fossil sites.

Rates of Natural Erosion (Geologic Variables)

This vital sign assesses the geologic variables that contribute to increased erosion at a locality such as physical characteristics of a rock unit (e.g., rock type, hardness, and cementation), bedding, degree of slope, and geochemistry. As mentioned above, natural erosional processes, quickly impact fossils exposed at the surface within the badlands landscape of the park. This indicator allows the researcher to assess data on annual precipitation, rainfall intensity, relative humidity, wind speed, and freeze-thaw index (number of 24-hour periods per year when temperature fluctuates above and below 0°C [32°F]).

Rates of Natural Erosion (Climatic Variables)

This vital sign assesses local climatic data on annual precipitation, rainfall intensity, relative humidity, wind speed, and freeze-thaw index. Rainfall during intense summer afternoon thunderstorms at the park increase erosion of the badlands within Petrified Forest National Park.

Catastrophic Geologic Processes or Geohazards

This vital sign assesses the potential for catastrophic geologic processes or geohazards that could impact a fossil locality. Such processes include volcanism, geothermal activity, earthquakes, glacial activity, and mass-wasting events (e.g., landslides, slumps, and rockfalls). Any of these types of mass-wasting events could damage fossil resources at Petrified Forest National Park (see Mass Wasting section).

Hydrology and Bathymetry

This vital sign assesses potential impacts to fossils near water bodies, where changes in water level can affect the stability of paleontological resources. Such changes could be caused by natural fluctuations in water level or be related to storm events and flooding. Flash floods are a potential threat to fossils within the park.

Human Impacts

This vital sign assesses the potential for both intentional and unintentional human impacts on fossil resources. As noted above, humans are a primary threat to fossil resources within the park as a result of theft, vandalism, and poor science.

Paleontological Resource Inventory

In 2001, resource managers at Petrified Forest National Park began to relocate and document all known paleontological sites within the park, beginning with those containing known vertebrate fossils (Parker 2003). As part of the ongoing inventory, investigators document the sites using the following three methods: (1) plotting with global positioning systems, (2) recording the physical description, and (3) photographing the site. This field inventory involves monitoring known fossil sites, collecting locality data, tying archival and collection information to fossil sites, and collecting representative specimens for park collections (National Park Service 2004a). Park staff also assisted with the Petrified Forest section of a literature-based inventory for the entire Southern Colorado Plateau Network (Tweet et al. 2009).

Although scientists and the public have been aware of the area's rich fossil resources for more than 150 years, the inventory has underscored the incredible paleontological wealth at Petrified Forest National Park. By 2004, investigators had found 50 new vertebrate sites. Although all of the specimens found during the inventory are scientifically important, the skeleton of a large extinct crocodile-like aetosaur *(Stagonolepis wellesi)*—the second most complete aetosaur skeleton recovered from the Triassic of Arizona—was the most notable find of 2003 (Parker 2003). Discoveries in 2004 surpassed even this aetosaur specimen. In the Painted Desert area of the park, the *Revueltosaurus* quarry yielded a dozen skeletons of the pseudosuchian archosaur *Revueltosaurus callenderi*. *Revueltosaurus* was previously only known from its teeth. Thought to represent an early ornithischian dinosaur, examination of this specimen showed that this animal is more closely related to crocodiles, which has important implications for the global fossil record of early dinosaurs (Parker et al. 2005). Many other significant finds of vertebrate material (table 1) have resulted in numerous publications (see Paleontological Research section) and have identified Petrified Forest National Park as the locale to study the "dawn of dinosaurs" (Long and Padian 1986; Hunt et al. 2002).

Table 1. Discoveries of significant vertebrate fossils at Petrified Forest National Park.

Year	Fossils
2001	Partial skeleton of aetosaur *Calyptosuchus wellesi*
2002	Phytosaur skeleton, armor plates from a new species of aetosaur, skull roof of new species of phytosaur, partial skeleton of the crocodylomorph *Parrishia*
2003	Complete phytosaur (*Leptosuchus crosbiensis*) skull, plates from an aetosaur *Rioarribasuchus chamaensis*, previously known only from New Mexico; the first recorded jaw material of *Trilophosaurus* ever found in the park; a partial skeleton of the rare enigmatic reptile *Vancleavea*
2004	A dozen skeletons of the pseudosuchian archosaur *Revueltosaurus callenderi*; new species of aetosaur; remains of rauisuchians, aetosaurs, phytosaurs, lungfish, and dinosaurs
2005	Well-preserved phytosaur skull; *Revueltosaurus* skeleton; material from metoposaurs, aetosaurs, and phytosaurs
2006	*Revueltosaurus* skeleton; theropod, rauisuchian, and crocodylomorph material
2007	Phytosaur skull; aetosaur partial skeleton, including skull
2008	Five new phytosaur skulls, *Poposaurus* pelvis, metoposaur skulls
2009	Phytosaur skull, aetosaur partial skeleton

Sources: http://www.nps.gov/pefo/naturescience/research-activities.htm (accessed November 13, 2009); Bill Parker (Petrified Forest National Park), written communication, August 2009.

Future phases of the field inventory will include documentation of localities with plant, invertebrate, and trace fossils. According to the park's strategic plan (2005–2008), the park hosts a total of 555 documented sites. More than 200 of these have been relocated as a result of the inventory. However, efforts to find the remaining sites could be difficult due to the lack of specific information contained in past researchers' field notes. Nevertheless, park staff will make every effort to reach the goal of finding all documented sites (National Park Service 2005a).

As identified in the park's resources management plan (National Park Service 1994) and the foundation for planning and management (National Park Service 2006a), there is a need for more staff and trained volunteers to inventory and monitor fossil resources, which have been stretched even thinner as a result of the boundary expansion.

Paleontological Research

In 1936, Charles Newton Gould stated in his report as regional geologist, "Petrified Forest is so well known, and the geology so thoroughly understood that it is unnecessary at this time to do little more than call attention to some of the more outstanding features" (p. 1). Presumably, Gould soon realized his error because immediate, more extensive reports followed in 1937 and 1938. In 1935, the National Park Service hired the 66-year-old Gould out of his "retirement" to oversee an eight-state region in the West and Southwest. For the next five years, Gould advised the NPS on water resources, road construction, and future expansion. Before working as regional geologist, Gould had served as the first director of the Oklahoma Geological Survey and as a consulting geologist for the petroleum industry (Weaver 2007).

Today, what is not known about the geology of the park greatly exceeds what is known, and excitement grows with each new discovery (National Park Service 1990). Research has revealed that the park's strata document "the dawn of the dinosaurs" perhaps better than anywhere else in the world. By the Upper Triassic, the first dinosaurs were just beginning to appear, and some of the earliest dinosaur fossils known are from Petrified Forest National Park. In addition, mammals appeared during the Triassic, and many paleontologists now consider the Triassic as the time when modern ecosystems were being established. The rich associations of Triassic plant and animal fossils in the park promise to contain a comprehensive record of this time of transition. Petrified Forest National Park is becoming a standard (leading locality) for studying Upper Triassic terrestrial systems globally (Bill Parker, Petrified Forest National Park, e-mail, October 10, 2008).

Since 2000, park and cooperating paleontologists have published more than 40 papers about the park's paleontological resources—particularly, fossil vertebrates, but also fossil plants and microinvertebrates (http://www.nps.gov/pefo/naturescience/published-research.htm; accessed November 13, 2009). According to park paleontologist Bill Parker, "Everything we thought we knew is changing and we are finally getting closer to understanding the geological and paleontological story here" (Bill Parker, Petrified Forest National Park, e-mail, October 10, 2008). Even new evidence about the petrified trees is emerging (Savidge 2007).

The Petrified Forest National Park area has been a paleontological research laboratory for more than 150 years. Although outside researchers' projects might not necessarily be identified as a resource management priority, the findings can still be valuable for park science, interpretation, management, and planning. Researchers provide copies of field data (e.g., notes, photographs, and maps) to park managers. Researchers also submit an investigator's annual report (National Park Service 2004b). Scientists from outside institutions who request and receive research permits accomplish much paleontological study that result in significant findings. The permitting system includes provisions to ensure that scientific research activities comply with both Servicewide and park-specific requirements (National Park Service 2004b).

An analysis of fundamental resources and values identified the need for suitable space to conduct laboratory, office, and collection activities for on-site research. The lack of space for researchers could inhibit valuable research and lead to the inability to attract top scientists to Petrified Forest National Park (National Park Service 2006a).

Revisions to Stratigraphy

The stratigraphic nomenclature at Petrified Forest National Park has been undergoing revisions since the early 1990s. Most recently, investigators have reevaluated the Sonsela Member of the Chile Formation (Martz and Parker 2010) (table 2). The bulk of this effort was devoted to carefully examining exposures in the southern region of the park (Martz and Parker 2010). The Sonsela Member represents a transition from a predominantly muddy unit (mudstone) dominated by overbank deposits to a predominantly sandy unit (sandstone) dominated by channel deposits. This unit also contains an abrupt faunal overturn of the most common vertebrate fossils in the park, phytosaurs and metoposaurs (see Paleontological Resources section under "Geologic Features and Processes").

Over the years, investigators have separated, combined, translated, and renamed various portions of the Chinle Formation and even elevated it to group status (Lucas 1993). More reorganization is likely while detailed geologic mapping is ongoing. At present, the accepted terminology for the members of the Chinle Formation is as follows (from oldest to youngest): Mesa Redondo, Blue Mesa, Sonsela, Petrified Forest, and Owl Rock. An unconformity separates the Chinle Formation from the overlying Bidahochi Formation (Miocene/Pliocene) (see the Unconformities section under "Geologic Features and Processes"). Unnamed and undifferentiated Quaternary (Pleistocene and Holocene) rocks and sediments, as well as eolian dunes and sand sheets, top the sequence at the park (Blakey and Raucci 2006; Parker 2006; Woody 2006). The current "working stratigraphy" varies slightly from the digital geologic map produced in 2006 (see "Map Unit Properties" section and Appendix A).

Correlation of strata at the park has been contentious. In the early 1990s, 50 lithographic terms were applied to Upper Triassic nonmarine strata in the western United States, and the Chinle "Group" encompassed 27 formational names in nine states (Lucas 1993). A major problem in the park is relating the members of the Chinle Formation between the northern and southern portions. Approximately 6 km (4 mi) of Cenozoic alluvium covers the Puerco River area, which splits the park in half. Thus, beds so distinctive to the north and south have limited exposures across the park (Murry and Long 1989; Murry 1990). Martz and Parker (2010) demonstrate the importance of geologic mapping, "walking the contacts," and thoroughly documenting measured sections when constructing lithostratigraphic interpretations of the Chinle Formation in Petrified Forest National Park.

To further complicate matters, the exact age of the Chinle Formation is uncertain. The formation is known to be Upper (Late) Triassic, but scientists are currently scrutinizing the isotopic age of this geologic period (Walker and Geissman 2009a). The International Commission on Stratigraphy (2009) placed the age of the Upper Triassic at approximately 228.7 to 199.6 million years ago. However, the Geological Society of America brackets the same period as 228 to 201.6 million years ago (Walker and Geissman 2009b).

Table 2. Revised stratigraphy of the Chinle Formation. Refer to fig. 3 in Martz and Parker (2010) for previous interpretations and nomenclature for the Chinle Formation in the southern part of Petrified Forest NP. "Fm" = Formation.

Fm	Member	Bed
Chinle Formation	Petrified Forest Member	Flattops Bed 4
		Flattop Bed 3
		Flattop Bed 2
	Sonsela Member	Martha's Butte beds
		Jim Camp Wash beds
		Jasper Forest / Rainbow Forest Bed
		Lot's Wife beds
		Camp Butte beds
	Blue Mesa Member	
		Newspaper Rock Bed
	Mesa Redondo Member	

Source: Martz and Parker (2010).

Investigators of Chinle stratigraphy have not pinpointed the upper or lower boundaries of the formation; however, the top of the Chinle Formation is known to predate the Triassic-Jurassic boundary, which is in the overlying Wingate Sandstone (Lucas et al. 1997, 2005). Riggs et al. (2003) and Heckert et al. (2009) obtained maximum ages of 213 ± 1.7 million years and 211 ± 0.7 million years respectively for the Black Forest Bed, near the top of the Petrified Forest Member. The base of the Chinle Formation is marked by the Mesa Redondo Member, which comprises the oldest and stratigraphically lowest rocks at Petrified Forest National Park. Unfortunately, the Mesa Redondo Member is exposed only in the Tepees area of the park (Parker and Irmis 2005). However, the base of the overlying Blue Mesa Member is known to be about 219 million years old (Irmis and Mundil 2008; Mundil and Irmis 2008); therefore, the Mesa Redondo Member must be older.

Bentonite

The picturesque beds of the Chinle Formation shape the beautiful badlands of the park. They also create hazardous conditions. The purple, pink, gray, yellow, brown, and red mudstone beds in the Owl Rock, Petrified Forest, Sonsela, and Blue Mesa members contain altered volcanic ash called bentonite, which swells when wet and shrinks when dry, creating unstable foundations upon which to build infrastructure. Due to the high bentonitic content of the deposits, the surface absorbs moisture and expands, becoming sticky mud in flat areas and slumps on slopes. During heavy rainfalls, the mud on steep slopes collects in pellets that roll down into the stream channels where they disintegrate and are rapidly carried away as suspended material (Camp 1930). As the bentonite-rich deposits dry out between rainfall events, shrinkage cracks form (fig. 6). Some cracks, called "pipes," can penetrate deeply below the surface. When rainfall returns, much of the water falling onto the surface enters these cracks, moves through the pipes, and reappears at lower levels in the gullies. Gradually, the partly weathered, friable surface material is carried through the subsurface by this "piping" process. Sinkholes form at the surface as a result of piping. The sinkholes vary from a few inches deep to as much as 3 m (10 ft), making mere dimple depressions to basins 5 to 6 m (15 or 20 ft) across (Malott 1939). Piping also undermines slopes that later collapse. In some places, natural bridges can span the subterranean pipes before collapsing (Bezy and Trevena 2000). New slope profiles and sinkholes can develop in a few hours when flash floods occur (Harris and Tuttle 1990). Piping can be a major management issue in anthropogenic areas such as earthen dams and raised roads (Pete Biggam, NPS soil scientist, e-mail, February 23, 2007).

Scoping participants identified numerous problems with bentonitic clays in the park. For example, the Painted Desert Inn located in the northern portion of the park has experienced moderate to severe cracking in both exterior and interior walls, as well as movement in floor slabs (Dee 1992). Historic buildings in the southern portion of the park are not as susceptible to bentonite problems because they are built on fill and sandstone material. In addition, the presence of bentonite threatens the integrity of roads and trails. Bentonite underlies significant portions of the mainline road (Denver Service Center 1978), and scoping participants identified the Blue Mesa Trail as requiring geotechnical surveys because of bentonite problems.

In 2005, in cooperation with the University of Arizona, the National Park Service published *Maintenance Guides for the Treatment of Historic Properties, Petrified Forest National Park* (Gorski and Lovato 2005). This publication includes recommendations for drainage systems in bentonitic clays, suggesting that water should be transported as far away as possible from building foundations. In addition, the authors suggest that park managers consider water harvesting as a conservation measure and to keep water away from buildings (Gorski and Lovato 2005).

Mass Wasting

Mass wasting in Petrified Forest National Park is primarily a result of the downslope movement of mudstone in the Chinle Formation. The mudstone contains water-absorbing (expandable) bentonite clay. During summer rain events, the clay absorbs water and the mudstone becomes “plastic.” Gravity then pulls the water-saturated mudstone layers downslope, forming “slumpage terraces” (fig. 7) (Bezy and Trevena 2000).

Along the cliffs near Pintado Point is a slump block. The plateau is capped by resistant basalt of the Bidahochi Formation but is underlain by softer clay. This caprock-over-clay scenario sets up the potential for mass wasting. When saturated, the clay loses its supportive strength and causes blocks of caprock to break off, slide downslope, and rotate backward. This process called “slumping” tremendously increases the rate of cliff retreat and valley-widening in the Southwest (Bezy and Trevena 2000).

The Newspaper Rock overlook displays the process of cliff retreat. Caps of the Newspaper Rock Bed of the Chinle Formation are prone to cliff retreat when “supported” by mudstone. Rain and meltwater erode the underlying mudstone, widening fractures in the Newspaper Rock Bed, and ultimately causing slabs of rock to break off and topple to the slopes below (fig. 8). In 1984, the trail that once descended to Newspaper Rock was destroyed by the movement of large sandstone slabs (Bezy and Trevena 2000). The Blue Mesa cliff is also experiencing cliff retreat (Bill Parker, Petrified Forest National Park, written communication, June 2009).

As highlighted in *Guide to Geologic Features at Petrified Forest National Park* (Bezy and Trevena 2000), these features of mass wasting can be of interest to park visitors. Such features also can require attention and mitigation by resource managers. Wieczorek and Snyder (2009) offer background information and vital signs for monitoring mass wasting.

Blakey and Raucci (2006) included colluvium as part of undifferentiated surficial deposits (Qsu) on the geologic map of the park. These deposits indicate areas of future susceptibility to mass wasting. *Preliminary Map of Selected Mass Movement Events in Arizona* (Realmuto 1985) showed a 1984 rock slide event that occurred in the park (T18N R24E), which cost $25,000 to mitigate. In 1985, Howard J. Haiges of the Denver Service Center conducted a geotechnical survey (and submitted a technical report to the regional director of the Western Regional Office) concerning an earth flow that had developed adjacent to Newspaper Rock (Haiges 1985).

Only when such phenomena conflict with infrastructure, visitation, or cultural resources do they constitute a serious problem or hazard. The severity of such problems is directly related to the extent of development in the affected areas. Early recognition, avoidance, and corrective engineering can mitigate adverse effects (Rogers et al. 1974).

Subsidence

In 2005, park staff requested assistance from the Geologic Resources Division in evaluating a subsidence crack at the Blue Mesa Loop Road and the mesa edge (National Park Service 2005b). Although GRD staff deemed the crack relatively benign and park maintenance personnel repaired the road damage, this example illustrates the potential for subsidence to affect park infrastructure. According to Rogers et al. (1974), ground subsidence is “characterized by downward displacement of surface material by natural phenomena such as removal of underground fluids, natural consolidation, or dissolution of underground minerals, or by man-made phenomena such as underground mining” (p. 61).

On a larger scale, subsidence creates topographic features on the landscape. Colpitts (1996) reported a possible solution-collapse depression—Blue Mesa sink—in Petrified Forest National Park. Situated 12 km (8 mi) south of I-40, this semicircular collapse feature is 1 km (0.6 mi) in diameter with surface relief of about 30 m (100 ft). Sandstones of the Blue Mesa Member dip radially into the central depression at angles ranging from 5° to 15°. Colpitts (1996) proposed that the collapse structure is related to evaporate dissolution of halite and sylvite in the upper part of the underlying Schnebly Hill Formation (Permian); however, also of note is the underlying Permian Supai Formation, which contains halite and potash (see Potash section). Dissolution of halite or future underground mining of potash could cause subsidence of overlying strata.

Potash

Potash prices have skyrocketed. At the beginning of 2008, potash went for about $200 per metric ton; at its summer high, it sold for $600 per metric ton. Despite the sharply declining trend in nearly every commodity in 2008, potash prices held steady and even ticked upward (U.S. Geological Survey 2010).

This trend has renewed mining interests in Arizona deposits. Potash, which is rich in potassium, is used primarily for fertilizer, but also for ceramics, glass, and soap. The increasing price of North American ethanol corn production and the global demand for foodstuffs are creating an increased potash demand (for fertilizer) (Helmer 2008). The area of interest for Arizona is the Holbrook Basin, a 1,550-km^2 (600-mi^2) salt deposit east of Holbrook, Arizona. This basin underlies a significant portion of Petrified Forest National Park (fig. 9). The potash is a component of the Permian Supai Formation (270 to 220 million years old) and not present at the surface. The salt appears to have formed by desiccation of saline mud flats and salt pans of an inner sabkha (supra-tidal environment in arid climates). According to Rauzi (2008a), the occurrence of potash near the top of the salt deposit is due to the relative solubility of potash and salt during the evaporation of seawater across the sabkha. Repeated incursions of seawater appear to have preferentially dissolved and re-precipitated the potash, thereby separating and concentrating the potassium from the halite.

Half of the deposit occurs under a combination of private, state trust, and Native American Tribal lands. The other half is beneath Petrified Forest National Park. Approximately 20% of the potash deposit is situated under the pre-2004 boundary, which is closed to mining. Another 30% of the deposit underlies lands that became part of the national park as a result of the Petrified Forest Expansion Act of 2004 (Conway 2008). The state owns more than 100 km^2 (40 mi^2) of land in the expanded area of the park. The state could issue leases on these lands. As a result, efforts to negotiate a land management agreement with the state over state lands in the expanded boundary may be more difficult than originally envisioned (National Park Service 2008a).

According to Rauzi (2008a), "the location of the potash under [Petrified Forest National Park] will require a creative approach to full access and future development of Arizona's strategic potash deposits" (p. 2). Because the potash deposit under and around the park lies mostly between 300 and 460 m (1,000 and 1,500 ft) below the surface, underground mining techniques such as room and pillar, longwall, cut and fill, and open stope could be used to exploit the deposit. This means that surface mining in the park could be avoided, thereby leaving the petrified wood resource intact (National Park Service 2008a). "Using such techniques means that large areas can be mined from a single surface location that includes the main shaft, processing facilities, and storage and waste disposal areas. Though impacts can be centralized, the footprint may cover hundreds of acres" (National Park Service 2008a, p. 3). Furthermore, "while the nature of the mining might allow for flexibility in locating the surface works, it will not be possible to hide it given the local terrain" (National Park Service 2008a, p. 4). That is, the Holbrook deposit is roughly 50 km (30 mi) long and 25 km (15 mi) wide, which could accommodate multiple work areas at the surface. The location of federal surface land and federally owned minerals would affect the underground mine layout and possibly the placement of surface works.

Liquefied Petroleum Gas Storage

The extensive salt deposits of the Permian Supai Formation underlie about 9,100 km^2 (3,500 mi^2) of east-central Arizona and attain a maximum thickness of 200 m (655 ft) (Rauzi 2000). Gas companies dissolve the salt (halite) and use the voids (caverns) to store liquefied petroleum gas (LPG). A storage cavern is created by drilling a hole and pumping freshwater into the opening through steel piping. The freshwater dissolves the salt, and the resulting brine is pumped out of the hole. Some brine is stored at the surface for later use, and some is pumped back into deep underground rock formations. The amount and direction of freshwater pumped into the hole determines the shape and size of the cavern (Rauzi 2008a).

Eleven storage caverns, part of Ferrell Liquefied Petroleum Gas Storage Facility, are located 915 m (3,000 ft) west of the park boundary along the Burlington Northern Santa Fe Railway, which services the facility. Rail tank cars transport the gas, which is pumped into the caverns during low demand. During periods of high demand, the gas is pumped from the wells and transported to market. These caverns do not underlie the park, however, and any expansion of the facility could be accomplished outside the park boundary (James C. Woods, Geologic Resources Division, written memorandum to superintendent, Petrified Forest National Park, December 4, 2000).

The top of the salt at the LPG storage facility is about 275 m (900 ft) below the ground surface. The caverns are leached about 23 m (75 ft) below the top of the salt; they have an average radius of 18 m (60 ft) and height of 30 m (95 ft). Individual cavern volumes range from 26 to 42 million L (7 to 11 million gal) (Rauzi 2008a). This facility began operations in 1971, and currently provides total storage for 318 million L (84 million gal) of butane and propane. In addition to the storage caverns, four large brine storage impoundments, four 18,000-gallon LPG tanks, two 30,000-gallon LPG tanks, pumping equipment, and associated piping are at the surface of the facility.

In 2000, the Geologic Resources Division conducted an assessment of the storage facility at the request of park staff. The Geologic Resources Division gathered most of the information from correspondence with Dale Thompson, the facility manager at Ferrell LPG Storage Facility, and Steve Rauzi, an oil and gas administrator for the Arizona Geological Survey. The assessment findings contain a description of the facility, a discussion of safety issues (e.g., evacuation for visitor safety in the event of a spill and the potential for spills from rail cars), recommendations, and conclusions (James C. Wood, Geologic Resources Division, written memorandum to superintendent, Petrified Forest National Park, December 4, 2000). In addition, the Geologic Resources Division prepared a document highlighting all mineral development in and adjacent to Petrified Forest National Park, including the LPG storage facility (National Park Service 2008a).

The following conclusions and recommendations from these two documents concern the management of geologic resources at Petrified Forest National Park:

- No significant potential for subsidence or sinkholes, which could impact the national park, are associated with the caverns.
- A catastrophic spill event at the Ferrell LPG Storage Facility would not likely impact park resources other than causing short-term degradation in air quality.
- The park superintendent should verify that he/she is on the storage facility's emergency notification list for large-spill and fire incidences. In the event of a catastrophic spill or fire, evacuation and closure of the park road east of the storage facility might be

necessary to minimize the potential for injury to park employees and visitors.

- Park staff should maintain a good working relationship with state regulators and Ferrell Gas management.

Uranium

Generally speaking, the thin sandstone beds of the Chinle Formation contain uranium, in particular the Shinarump and Sonsela members; however, the Chinle beds exposed in the park contain no specific occurrences of uranium (Ron Blakey, Northern Arizona University, e-mail, October 30, 2008). Furthermore, the potential for uranium mining on lands in or near the park is very low (National Park Service 2008a). Uranium exploration did occur in the Twin Buttes area of the park, as evidenced by a number of boreholes, but the nearest uranium mines are outside the park, north of Holbrook. These mines operated between 1953 and 1960, but were not significant contributors to Arizona's uranium production.

Since 2003, a substantial increase in price and demand for nuclear reactor fuel has renewed mining interest in some parts of Arizona. However, most deposits in the state, including those near Petrified Forest, tend to be of lower grade and would have difficulty competing with other world sources (National Park Service 2008a).

Perhaps the main concern for resource management regarding uranium is protection of groundwater quality. Groundwater is the park's primary water resource and, until 1997, was the park's drinking water supply. In 1997, the park began purchasing potable water from the Navajo Tribal Utility Authority, thereby eliminating the need for park managers to operate water supply wells. However, park managers are still responsible for operating and maintaining the pipelines and distribution system that transport water from park facilities in the Painted Desert and Rainbow Forest areas (Martin 2004).

The National Park Service identified the uranium mine tailings that spill into the Puerco River from the United Nuclear dam site near Gallup, New Mexico, as a threat to park resources (National Park Service 1986). Investigation documented increased radiation in the Puerco River near Sander, Arizona, 50 km (30 mi) upstream from Petrified Forest National Park; however, most of the observed radioactivity in the alluvial aquifer in the Sander area was from natural sources and not from effluent from mining and milling operations (Dixon 1990). Nevertheless, the U.S. Geological Survey and NPS Water Resources Division (WRD) recommend that park managers continue annual sampling of the alluvial groundwater to determine whether significant water quality changes have taken place (Martin 2004).

In 2003, WRD staff completed a water resources scoping report for Petrified Forest National Park, which described the general geography and hydrologic environment of the park (Whealan et al. 2003). Similar to earlier findings, this report documented radionuclides in the Puerco River and alluvial groundwater as a product of both the natural erosion of uranium-bearing rock and past mining-related activities upstream of the park. Anthropogenic releases of radionuclides upstream of the park have not affected groundwater in the alluvium—the source of water for the Puerco Well No. 2.

In 2004, WRD staff prepared another report (Martin 2004) that focused solely on the park's hydrogeology and described past efforts to develop groundwater resources and made recommendations for future development.

Adjacent Development

In the 1990s, park managers began noting external threats from the encroachment of development (National Park Service 1994). Recent encroachment includes a possible casino on Navajo Nation land at the Pinte Road exit east of the park headquarters (Bill Parker, Petrified Forest National Park, written communication, June 2009).

On December 3, 2004, Petrified Forest National Park more than doubled in size, to approximately 88,448 ha (218,553 ac). Although the purpose of the expansion was to protect natural resources, it could have unforeseen consequences, namely population growth.

Rudzitis and Johansen (1989a, b) found that, on average, wilderness counties grew twice as fast as metropolitan areas. Better environmental quality, a slower pace of life, and low crime rates have become increasingly important amenities for people to consider when choosing a location in which to live (e.g., Dillman 1979). To test the importance of such values, investigators studied counties in the United States that contain or are adjacent to federally designated wilderness areas (Rudzitis and Johansen 1989a, b). Results from more than 11,000 randomly selected participants in 15 wilderness counties in the West showed that employment opportunities were important to 27% of those surveyed, while environment or physical amenities were important to 42%. The most important qualities of wilderness counties to new migrants were found to be scenery (83%), outdoor recreation (79%), environmental quality (78%), and pace of life (75%). Thus, many people seem to be willing to give up financial gain in exchange for wilderness amenities.

Everyday markets also show the economic importance (value) of quality of life. For example, a home with a view commands a higher price than an identical one without a view; the value of the view, then, is the difference in price between the two houses (Rasker and Glick 1994). Using Petrified Forest as a case study, perhaps the example can be taken a step further: a house or a piece of land near a wilderness area or national park is more valuable than one that is not. The superintendent's annual report for fiscal year 2005 seems to bear this out: "Private land sales in the expansion area boomed on eBay and elsewhere, going from $100 per acre to $2,000 per acre, and, in two sections, from 40 acre parcels split down to 1.5 acre parcels" (National Park Service 2005b, p. 1). Therefore, proximity to wilderness can result in an increase in subdivisions, loss of important wildlife habitat, and threats to biodiversity. It can also drive up housing prices, resulting in a shortage of affordable rental units. Development adjacent to the park could result in greater access to paleontological resources, and as a result of construction, increased erosion and exacerbated eolian processes (e.g., dust storms).

Figure 5. Petrified wood. Congress set aside Petrified Forest National Park to protect one of the world's largest and most colorful concentrations of petrified wood. National Park Service photograph by T. Scott Williams.

Figure 6. Bentonite. Expanding bentonite clays are found in mudstone beds of the Chinle Formation throughout the park. This photo is from the Jasper Forest area. National Park Service photograph by T. Scott Williams.

Figure 7. Slump terraces. Bentonite-rich mudstones absorb water and expand, becoming "plastic." The surface layers creep downslope forming "terraces" like these visible beneath the Kachina Point Overlook. Arizona Geological Survey image by Larry Fellows in Bezy and Trevena (2000).

Figure 8. Cliff retreat. At the Newspaper Rock overlook, hard sandstones of the Newspaper Rock Bed overlie softer mudstones. As the mudstone erodes away, unsupported slabs of overlying sandstone break along fractures. The cliff "retreats" as these broken slabs topple to the slopes below. National Park Service photograph by Jason Kenworthy (NPS Geologic Resources Division).

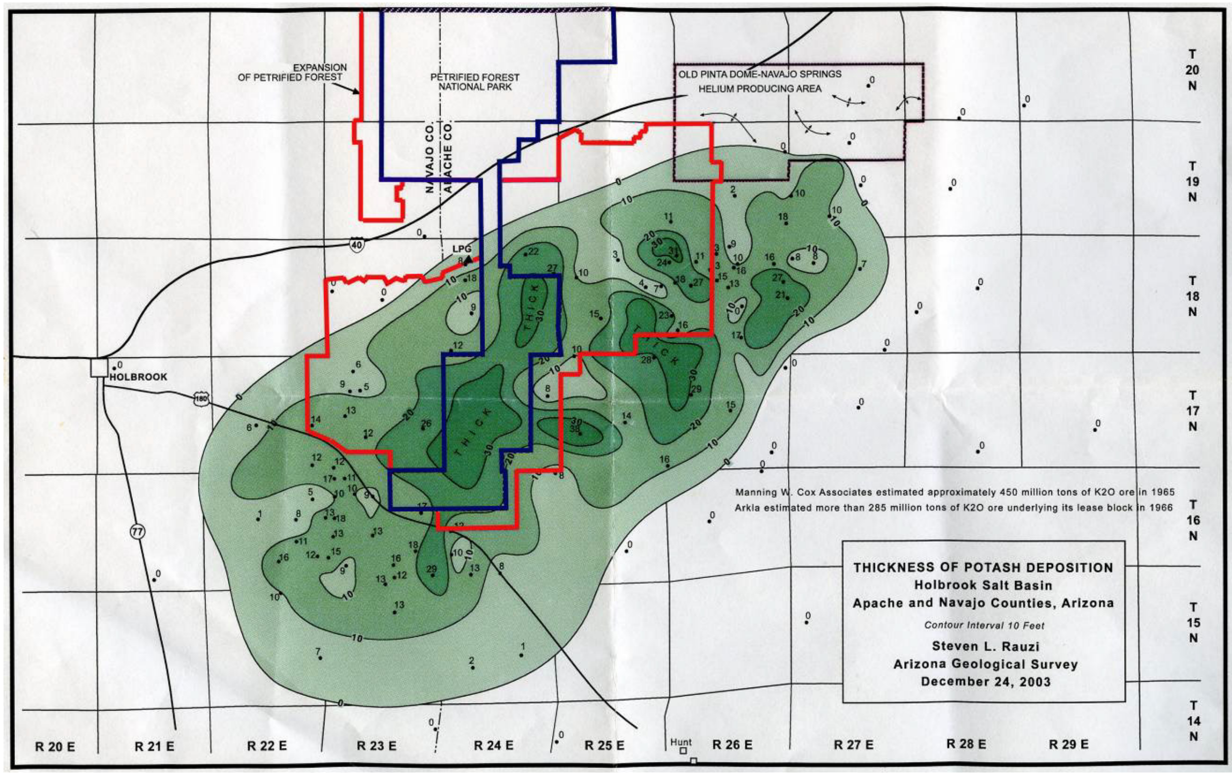

Figure 9. Holbrook Basin potash deposit. Petrified Forest National Park overlies a significant portion of the 1,550-km^2 (600-mi^2) potash deposit near Holbrook, Arizona. As a result of growing global demand for fertilizer and skyrocketing prices, mining companies are increasingly interested in this rich deposit under the park. Graphic (fig. 2) from Rauzi (2008b). Used with permission of the Arizona Geological Survey.

Geologic Features and Processes

This section describes the most prominent and distinctive geologic features and processes in Petrified Forest National Park.

Paleontological Resources

The bibliography of the paleontological resources for Petrified Forest National Park is substantial, containing hundreds of references. This section does not purport to summarize all of these references, rather to simply highlight the wealth of paleontological resources at the park. Tweet et al. (2009) summarized the paleontological resources at Petrified Forest National Park and compiled a bibliography. In addition, the park's Web site (http://www.nps.gov/pefo/naturescience/fossils.htm; accessed November 13, 2009) provides species lists and general information about the paleontological resources.

While Petrified Forest National Park is best known for its petrified trees, the Chinle Formation—the park's primary strata—hosts a diversity of other plant and animal fossils and is one of the richest Upper Triassic deposits in the world. As expressed in Houk (2005), in the Upper Triassic "an astonishing assortment of animals inhabited the land and water of this green world, including some of the earliest plant- and meat-eating dinosaurs, giant amphibians, flying lizards, fish, clams, snails, and experiments in the up-and-coming group known as mammals" (p. 66). To date, investigators have discovered fossils in the Petrified Forest, Sonsela, and Blue Mesa members of the Chinle Formation (table 2); the Owl Rock and Mesa Redondo members are fossiliferous elsewhere. In addition, Quaternary deposits in the area have yielded proboscidean (e.g., mammoths) remains, although not within the park (Tweet et al. 2009).

The fossils preserved at Petrified Forest National Park represent entire ecosystems. Hundreds of fossil sites are known: 125 sites with plant megafossils, 152 sites with fossil invertebrates, 365 sites with fossil vertebrates, and 10 sites with trace fossils (Bill Parker, Petrified Forest National Park, written communication, September 3, 2009). The Chinle Formation has yielded more than 200 different fossil plants, including lycopods, horsetails, ferns and fernlike foliage (fig. 10), cycads, cycadeoids, ginkgoes, cordaites, conifers in the form of silicified wood, compressed leaves, stems, cones, amber, pollen, and spores. Fossils of Triassic fauna in the park include invertebrates such as bivalves, gastropods, and crayfish; and vertebrates such as freshwater fish (e.g., sharks, coelacanth, and lungfish), amphibians, archosaurs, and therapsids. Archosaurs are a specialized group of animals that includes birds and crocodiles. In the Upper Triassic, archosaurs were represented by aetosaurs, phytosaurs, rauisuchians, and dinosaurs. Therapsids were large reptiles that possessed many mammalian characters, including a "cheek" bone, enlarged canine teeth, a pelvis, and a specialized attachment of the skull to the spine (fig. 11). Phytosaurs (fig. 12) and metoposaurs (a type of amphibian) dominate the vertebrate remains at the park (Parrish 1989). Trace fossils, which show the presence or evidence of behavior but not the actual remains of an organism, include insect nests, trails left by horseshoe crabs, vertebrate tracks, coprolites (fossil dung), and channels and tunnels burrowed into fossilized wood.

The petrified logs that made the park famous are part of the Chinle Formation. The Sonsela Member of the Chinle Formation is the primary source of petrified wood, and hosts the Crystal, Jasper, and Rainbow forests in the park. The Blue Mesa Member, which contains the majority of fossil-leaf localities, also yields abundant petrified wood, as does the Petrified Forest Member. The petrifaction process was sometimes so exact that the resulting fossils show many details of the logs' original surfaces and occasionally internal cell structures. Many of the logs are from an extinct tree called *Araucarioxylon arizonicum*. Two others—*Woodworthia* and *Schilderia*—occur in small quantities in the northern part of the park. During the petrifaction process, iron and other minerals combined with silica (quartz) to create the rainbow-colored wood (fig. 13). In addition, clear quartz, purple amethyst, yellow citrine, and smoky quartz grew in cracks in the logs that formed as a result of crushing or decay. These minerals enhance the "multicolored profusion" and "thousands of random facets" of the petrified wood at the park (Schullery 2001, p. 372).

Since 1989, investigators have touted Petrified Forest National Park as preserving the "dawn of dinosaurs" (Lucas and Hunt 1989). In 1984, when Bryan Small discovered "Gertie"—Petrified Forest's most famous fossil (*Chindesaurus*)—the public fascination with dinosaurs was rekindled. In 1995, Long and Murry formally described *Chindesaurus bryansmalli*, named in honor of its discoverer and the location of the find (Chinde Point). The remains of Triassic dinosaurs such as *Coelophysis* together with *Chindesaurus bryansmalli*—actually a dinosaur ancestor—has earned Petrified Forest National Park the prestige of being a birthplace of the world's most famous fossils and covering the "dawn" of their origin.

Chinle Formation and Badlands Topography

Named for the Chinle Valley north of the park (Gregory and Stone 1917), the Chinle Formation comprises most of the colorful hills, flat-topped mesas, and sculptured buttes of the park's badlands (fig. 14). The overlying Bidahochi Formation also provides some color and topographic variety to the badlands terrain. Various combinations of minerals in beds of clay and sandstone provide the "paint" of the Painted Desert and other badlands areas (fig. 15).

The colorful layers in the Chinle Formation represent ancient soil horizons (paleosols). The red and blue layers generally contain the same amount of iron and manganese, so differences in color depend on the position of the groundwater as the ancient soils were forming. In soils where the water table was high, a lack of oxygen in the sediments resulted in a reducing environment, giving the iron minerals in the soil a grayish or bluish hue. Reddish soils formed where the water table was consistently lower, allowing the iron minerals to oxidize (rust). A fluctuating water table caused the mottled (gleyed) paleosols in bluish beds.

Rapid erosion is a notable characteristic of the badlands terrain, and is easily observable because of the lack of vegetative cover. Rugged badlands topography results from differential erosion—the effect of weathering and erosion on alternating layers of fine-grained, relatively soft material and coarser grained, more resistant rock. Sandstone, conglomerate, and lava resist erosion, forming cliffs that result in the development of mesas. Some of the more resistant units form cap rocks on the buttes and mesas of the landscape (Harris and Tuttle 1990). The underlying beds of softer material erode much more rapidly and tend to produce sloping hillsides. When the cap rock is removed, these softer layers often form conical mounds (National Park Service 1986). On a smaller scale, differential erosion forms hoodoos—tall thin columns of soft sedimentary rock topped by a piece of harder, less easily eroded rock (fig. 16).

In addition to hoodoos, the multicolored rocks of the Chinle Formation comprise many other landforms—arroyos, washes, and gullies; plateaus; mesas, buttes, monuments, and spires; cuestas; and escarpments.

Arroyo, Wash, and Gully

Depending on geography (physical and human), either the term "arroyo," "wash," or "gully" becomes the vernacular. According to Stokes (1969), the word "arroyo" is used in areas with Spanish influence. Arroyos are steep-walled, flat-bottomed desert drainages. "Wash," an English word, has the connotation of wave action. During the short rainy period, dry washes can be suddenly flooded, but they generally become dry again within a few hours (Seff 1962). The term "gully" seems to apply to something smaller and shallower than an arroyo or wash; it also brings to mind many closely spaced tributaries.

Plateau

A plateau is a large, comparatively flat area with much of its surface at summit level. Many other landforms can exist on plateaus (Ham 2008); deep valleys often dissect and high hills often surmount plateaus (Neuendorf et al. 2005). Plateaus are considerably elevated above the adjacent terrain, generally more than 150 m (490 ft) in elevation. Plateaus are higher and more extensive than mesas (Neuendorf et al. 2005), which also stand distinctly above the surrounding country.

Mesa, Butte, Monument, and Spire

Mesas, buttes, monuments, and spires can be geomorphically grouped. They are all isolated conspicuous landforms with steep slopes and flat tops that stand distinctly above the surrounding landscape. Each is created by erosion, as explained by Stokes (1969): "a mesa…becomes a butte…becomes a spire…and disappears" (p. 26). According to Neuendorf et al. (2005), however, a spire is not a defined geomorphic form, but would likely come under the definition of "monument"—an isolated pinnacle, column, or pillar of rock resulting from erosion and resembling a manufactured monument or obelisk, usually extremely regular in form and of grand dimensions. Mesas are bounded by abrupt or steeply sloping erosion scarps on all sides and capped by layers of resistant, nearly horizontal rock (often lava). A mesa is similar to but has a more extensive summit than a butte. Like mesas, buttes are often capped with a resistant layer of rock and bordered by talus. Both represent an erosional remnant carved from flat-lying rocks.

Cuesta

Like mesas and buttes, cuestas are isolated conspicuous landforms that stand distinctly above the surrounding landscape. They, too, have steep slopes, but only on one side. Unlike mesas and buttes, cuestas do not have flat-lying summits; they are asymmetric. Confusingly, Agate Mesa in the park is actually a cuesta (Bill Park, Petrified Forest National Park, written communication, June 2009). Differential erosion controls the asymmetry of the slopes, with one slope long and gently dipping, and the opposite "scarp slope" steep or even clifflike.

Escarpment

When the steep slopes of plateaus, mesas, and cuestas are continuous, the term "escarpment" applies. An escarpment is a long, more or less continuous cliff or relatively steep slope facing in one general direction. Escarpments break the continuity of the land by separating two level or gently sloping surfaces. They are produced by erosion or faulting. In some parts of the world (e.g., Great Britain), "cuesta" and "escarpment" are synonymous, especially as they refer to the face. However, in the southwestern United States, the term escarpment is best applied to long continuous features, while cuestas are generally more longitudinally limited.

Unconformities

An unconformity is a surface in the rock record that represents a time from which no rocks are preserved in an area; that is, either no rocks formed or they formed but then eroded away. These surfaces depict "missing" rock and "missing" time, often a significant portion of "lost" geologic history. Because unconformities are often widespread across a region, they are useful for correlating rocks of various ages for long distances.

The surface between the Bidahochi Formation and Chinle Formation in Petrified Forest National Park is an unconformity. Conspicuous for its shape and color, this unconformity is nearly horizontal and separates the black basalt and yellowish-gray sandstone of the Bidahochi Formation (above) from the red mudstone of the Chinle Formation (below) (fig. 17). This surface marks a time gap of about 200 million years. The underlying mudstone belongs in the Upper Triassic (approximately 228.7 to 199.6 million years ago); the overlying volcanic and sedimentary rocks belong to the

Miocene and Pliocene epochs (23 to 2.6 million years ago). Based on the large interval of missing time, this unconformity likely represents sediments that were deposited and later removed by erosion (Bezy and Trevena 2000). Comparison to other rocks in the region indicates that more than 305 m (1,000 ft) of strata were stripped from this surface (Bezy and Trevena 2000).

Structural Geology and Features

Rocks in the region of Petrified Forest National Park tilt to the northeast at an angle of 1° to 2°. Geologists have not mapped any significant faults within Petrified Forest National Park (Blakey and Raucci 2006), but gently warping strata occurs throughout the park. Conspicuous examples of this warping are the sharp syncline of the Sinking Ship near Blue Mesa and the broad dome that elevates the Newspaper Rock area (Blakey and Raucci 2006). The colorful sandstone and mudstone layers of the Chinle Formation, which were originally deposited in the horizontal position during the Triassic Period, emphasize the up-warped (anticline) and down-warped (syncline) features. Other areas of significant structural deformation include a broad upwarp in the Devil's Playground area north of I-40, the subtle synclines of the Flattops and Rainbow Forest areas, and Blue Mesa sink (see Subsidence section under "Geologic Issues"). The Pennsylvanian–Permian Holbrook Basin underlies the Petrified Forest region, and mobile salts within this basin are the likely cause of warping (Akers 1964) (see Potash section under "Geologic Issues").

Sedimentary Structures

Sedimentary structures are features of sedimentary rocks such as bedding, ripples, and mud cracks; they are generally best seen in the field and on the outcrop rather than in hand specimen. These structures are generated by a variety of sedimentary processes, including fluid flow, sedimentary gravity flow, soft-sediment deformation, and biogenic activity (Boggs 1995). Because they reflect environmental conditions that prevailed at or very shortly after deposition, they are of special interest to geologists as a tool for interpreting ancient depositional environments.

The most common sedimentary structure in the rocks at Petrified Forest National Park is cross-bedding—the layering of sediment at an angle to the horizontal. Seff (1962) noted that both trough and planer cross-bedding are abundant in the thick sandstone units. In some of the finer siltstones, cross-bedding exists at very low angles and often extends laterally for 30 m (100 ft) or more (Seff 1962). All members of the Chinle Formation and nearly all major sandstone bodies within these members host cross-bedding (Blakey and Raucci 2006).

Geomorphologists use cross-bedding to determine the strength and direction of ancient wind and water currents and to estimate minimum water depth or dune height. In the case of the cross-bedding at Petrified Forest National Park, these sediments were deposited in a fluvial environment (Bezy and Trevena 2000). As sand grains moved from upstream to downstream in stream channels and on sand bars, various sedimentary structures formed. Trough cross-beds generally formed in the longitudinal bars of braided rivers and in the thalweg (deepest point) of meandering rivers. Lateral accretion beds are gently dipping planar cross-beds that formed on the point bars of meandering rivers, perpendicular to flow direction. Ripple cross-lamination is a finer, smaller-scale structure that formed under gentler flow conditions with finer grained sediments such as silt; sediments settled into horizontal layers and water later reworked the sediments into undulating ripples. Under higher velocity flow conditions, sand can also form horizontal bedding and laminations.

Various investigators (e.g., Seff 1962; Heckert and Lucas 2002; Blakey and Raucci 2006; Woody 2006) have noted other sedimentary structures preserved in the rocks at Petrified Forest National Park:

- Lenticular (lens-shaped) bedding—lenses in mud and rippled cross-laminated sand where the ripples or lenses are discontinuous, not only in the vertical but also more or less in the horizontal direction (Reineck and Wunderlich 1968).
- Cut-and-fill scours and deposits—sedimentary structures consisting of a small erosional channel that is subsequently filled with sediment.
- Mudstone rip-ups—flat clasts of mud that have been "ripped up" by currents from a semi-consolidated deposit of mud and transported to a new depositional site.
- Mud cracks—cracks in clay, silt, or mud that formed via shrinkage during subaerial dehydration.
- Raindrop and hailstone impressions (or prints)—small, shallow, craterlike pits surrounded by a slightly raised rim. These impressions form in soft, fine sand, silt, or clay by the impact of a falling raindrop or hailstone. They are rare features preserved on the bedding planes of sedimentary rocks or as casts on the underside of overlying sandstone beds.

Eolian Features and Processes

The persistence of the wind is an undeniable part of Petrified Forest National Park, and the windblown landscape of dunes attests to this fact. According to Bezy and Trevena (2000), distinctive forms at the park include the following types: (1) barchans (crescent-shaped) dunes with the "horns" pointing downwind; (2) transverse dunes with steep downwind but gentle upwind slopes that form perpendicular to the prevailing wind; and (3) longitudinal dunes—long, narrow, symmetrical ridges of sand that form parallel to the prevailing wind. Dunes may also be a component of other landforms (Ham 2008).

Smaller-scale eolian features in the park include desert pavement and ventifacts. Desert pavement is a residual surface of wind-polished, closely packed cobbles, pebbles, and fragments of petrified wood left behind after winds have swept away the fine material. Desert pavement is often cemented with mineral matter such as calcium carbonate (Bezy and Trevena 2000), which protects the finer material underneath from wind erosion and further deflation. A good example of desert pavement occurs 0.8 km (0.5 mi) southwest of the Tepees parking area (fig. 1). At this location, sparse vegetation, abundant sand, and persistently strong winds create perfect conditions for shaping ventifacts (Bezy and Trevena 2000). Wind erosion (abrasion/sandblasting) shapes, wears, cuts, and polishes pebbles and stones into ventifacts.

Investigators have noted three major drainage basins in the park as having eolian landforms: Lithodendron Wash, Dry Wash, and Jim Camp Wash (Ellwein 1997; see fig. 1). Eolian deposits are thin and uncommon in Lithodendron Wash, which is principally underlain by easily erodible mudstone; however, a thick mantle of eolian material covers the surrounding area. Although generally characterized by mesas and buttes (see Chinle Formation and Badlands Topography section), Dry Wash contains wide alluvial valleys with abundant eolian deposits. Finally, eolian deposits are common on the drainage divides of Jim Camp Wash.

In 1977, participants in an environmental management workshop for Petrified Forest National Park surmised that most of the dunes in Lithodendron Wash were a result of severe overgrazing at the turn of the 20th century (Shenk 1977). Since that time, however, investigations have revealed a long history of eolian development starting in the Pleistocene that includes two modes of development. First, linear dunes are present only on low-relief surface remnants that formed before the development of badlands. Well-developed soils reflect the continued geomorphic stability of this surface since eolian deposition. Second, superimposed on the existing badland landscape are small, constructional Holocene dunes. Buried soils identified in middle-Holocene deposits suggest multiple episodes of deposition followed by periods of stability sufficient to enable soil development. The Holocene dunes and soil stratigraphy likely reflect the impacts of late Quaternary climate changes on the rapidly evolving badlands in Petrified Forest National Park (Ellwein et al. 1997). Vegetation has stabilized most dunes in the area (Ham 2008).

Investigators primarily used soil development, but also stratigraphic relationships and landforms (e.g., fans and pediments), to estimate the ages of eolian deposits (Ellwein 1997). The older the dunes, the more well-developed the soils associated with them. Ellwein et al. (1997) interpreted the oldest dunes as middle Pleistocene (75,000 to 200,000 years old). “Middle-aged” dunes—e.g., those in Lithodendron Wash—are middle Holocene (2,000 to 8,000 years old); “young” late-Holocene dunes (less than 1,000 years old) occur throughout the park. Blakey and Raucci (2006) mapped larger-scale (1:24,000) Quaternary (Pleistocene and Holocene) eolian dunes and sand sheets; they also noted that eolian processes have modified many undifferentiated surficial deposits.

In a 2002 study, visitors frequently responded that the wind was what they “liked least” about their experience in the park (Lee et al. 2002). Management concerns associated with eolian processes are high erosion rates and the associated loss of major archaeological and fossil resources (National Park Service 1997). In addition, Petrified Forest National Park is very close to the threshold for eolian activity in the modern climate (Ellwein 1997). Shenk (1977) suggested a variety of research questions associated with eolian features and processes: (1) What physical processes create the dunes? (2) Where are the dunes moving? and (3) Is any material coming from outside Petrified Forest National Park? In addition, Shenk (1977) recommended that investigators study the dunes as an ecosystem.

Volcanic Features

During the late Miocene and early Pliocene (23 to 2.6 million years ago), a large basin with ephemeral lakes (playas) covered much of northeastern Arizona. Volcanoes nearby, and as far away as southwestern Nevada, spewed ash and lava into the basin. Many of the volcanoes at this time were phreatomagmatic (i.e., groundwater and surface water mingled with magma). Ascending magma mixed explosively with water-saturated mud and volcaniclastic sediments. Fine-grained ash landed in the lakes and was deposited within the sediments. Volcanic deposits of this age in the park are part of the Bidahochi Formation.

After a few million years of erosion, most of the Bidahochi Formation has been removed from Petrified Forest National Park, but three small volcanic structures—Pintado Point, Pilot Rock, and Black Knoll—exist within the park. The erosion-resistant lava flows such as Pilot Rock protect the softer lakebed deposits beneath. These structures are most likely outliers of the Hopi Buttes volcanic field to the northwest (fig. 18); however, the San Francisco–Mormon Mountain volcanic field to the west and the Springerville–White Mountains volcanic field to the southeast are also contenders. Plymate et al. (2001) reported that argon-40/argon-39 dating of a massive flow unit from each of these three structures yielded ages of 4.67 ± 0.66 million years for the Pintado Point structure, 5.0 ± 1.4 million years for the Pilot Rock structure, and 5.0 ± 1.5 million years for the Black Knoll structure. Although these ages do not preclude these features from being part of the San Francisco–Mormon Mountain or Springerville–White Mountains volcanic fields, they are most consistent with the timing of the major volcanic activity in the Hopi Buttes field (Plymate et al. 2001).

The Hopi Buttes volcanic field, which extends northwest from the northern overlooks of the park, is one of the largest concentrations of maar landforms in the world, covering about 2,500 km^2 (965 mi^2) and containing more than 300 maar–tuff ring volcanoes (fig. 18) (White 1991). Maars are flat-bottom, roughly circular volcanic cones that form from phreatomagmatic explosions near the surface. The vent from one of these maars is exposed on the rim of the Painted Desert across the park road to the east of Pintado Point (see fig. 1). Most of the maars and associated diatremes at Hopi Buttes formed between 8.5 and 6 million years ago. Diatremes—subvolcanic roots or subsurface pipes—of individual Hopi Buttes volcanoes fed the maars and were filled by volcanic material at the time of the eruption. They are now exposed because of lowering of the land surface by erosion. The youngest volcanoes are 4.2 million years old.

The volcanoes of the Hopi Buttes volcanic field are also notable for being monogenetic. By definition, monogenetic volcanic fields have only one short eruptive event at each volcano, as opposed to several eruptions from the same vent over a long period in their history. Monogenetic fields occur only where the magma supply to the volcano is low or where vents are not close enough or large enough to develop plumbing systems for continuous feeding of magma (Wood and Kienle 1990). Monogenetic volcanic fields can provide snapshots of the region beneath the surface and can be useful in studying the generation of magma and the composition of the mantle because the single eruption would match that of the chamber from which it erupted.

Smaller volcanic features at the park include basaltic agglomerate—boulder-, cobble-, and pebble-sized fragments of basalt, which violently ejected from nearby volcanic vents and cemented with similarly ejected finer-grained volcanic ash (Bezy and Trevena 2000). Boulders of volcanic agglomerate at Petrified Forest National Park are as large as 1.2 m (4 ft) in diameter; such large fragments suggest that the source (vent) was not far away (Bezy and Trevena 2000). Additionally, angular fragments of agglomerate ejected out of the vent in the solid state; ellipsoidal or football-shaped fragments started as blobs of molten rock that molded via rotation during flight. These ellipsoidal objects are called "volcanic bombs." Their shapes are determined primarily by the viscosity of the molten rock (Bezy and Trevena 2000).

Stream Terraces

Cut into the north flank of the Puerco River valley are two large steplike surfaces. These are stream terraces—erosional remnants of the active floodplain that existed during the late Pleistocene to Holocene epochs. The terraces stand hundreds of feet about the Puerco River, but dip in the same general direction as the floodplain. During at least two episodes of erosion, the Puerco River cut down its channel and by shifting from one side of the valley to the over, removed all but these vestiges of the former valley floors (Bezy and Trevena 2000).

Stream terraces at lower levels can be subject to flooding during unusual weather events. The terraces are composed of stratified sandy, gravelly, loamy, silty, or clayey sediments and, in some cases, by buried paleosols. The parent material is alluvium (Ham 2008).

Tinajas

Natural potholes, called "tinajas," are a significant source of surface water in the arid Southwest. Tinajas form over time through fluvial processes that scour out the massive, homogeneous, non-fractured bedrock. They appear to form along mathematically predictable spacing, although no formal studies that look at distribution have been conducted (GRI scoping notes, Organ Pipe Cactus National Monument, January 25, 2006). Tinajas primarily occur in areas where bedrock is exposed at the surface, such as the Upper Triassic sandstone of the Chinle Formation.

Past investigators mistakenly identified tinajas in the park as reptile nests, but recent studies have clarified the features as "inorganic weathering pits" lacking evidence for positive identification as a tetrapod nest (Lucas and Hunt 2006).

Desert Varnish

Also called "rock varnish," desert varnish coats many rocks in Petrified Forest National Park. Varnish forms on all types of surfaces, from flat-lying desert pavement (see Eolian Features and Processes section) to mesa walls, but it seems to form best on harder rocks with high silica content (Stokes 1969). The often lustrous staining ranges in color from light brown to black, depending on how much has accumulated. Varnishes are complex combinations of clays and birnessite (manganese oxide) or iron oxides such as magnetite, maghemite, and hematite (Probst et al. 2001). Varnished rocks in the Southwest have special archaeological significance because of the prehistoric petroglyphs pecked through the mineral skin to the fresh rock below (fig. 19) (Bezy and Trevena 2000). Geomorphologists use desert varnish as a relative age indicator of the geomorphic surfaces upon which the varnish developed (Quade 2001). Because varnish forms at variable rates, however, it cannot be used reliably to date the human inscriptions (Bezy and Trevena 2000).

Rock varnish also provides evidence for deciphering past climate in the western United States. According to Liu and Broecker (2008), rock varnish provided evidence of nine millennial-scale wet events between 18,000 and 11,500 calendar years before present. Preliminary radiometric age calibration indicates that these events are broadly coeval with millennial-scale cooling events identified in the ice core record of the Greenland Ice Sheet Project 2 (Liu and Broecker 2008). These results, combined with previous documentation of millennial-scale wet events in the Holocene varnish record for the same region, indicate that such wet oscillations in the western United States may be part of regionally widespread manifestation of the North Atlantic climate (Liu and Broecker 2008).

Scientists and observers of nature have long debated two questions about desert varnish: (1) Is it microbially mediated? and (2) What is its genesis? Perry et al. (2003) addressed the first question by analyzing scrapings of desert varnish from the Sonoran Desert in Arizona and the Mojave Desert in California. These investigators found 13 amino acids, indicating a biogenic component of these varnishes, which may play a role in their formation. As for the second question, many observers have suggested that varnish is splashed or dripped onto rocks during storms and, as the water evaporates, the mineral matter stays behind, gradually forming a smooth coat. Now that manganese-oxidizing microorganisms have been implicated in the formation of desert varnish, the evaporation theory is outdated. Furthermore, scientists (e.g., Flood et al. 2001) have confirmed that the most likely elemental source for desert varnish is windblown dust.

Finally, desert varnish may preserve yet another paleontological resource in Petrified Forest National Park. Probst et al. (2001) investigated whether desert varnish can preserve a fossil record of the organisms that created the coatings. Scientists examined manganese- and iron-rich varnishes on granitic substrates from the Sonoran Desert in Arizona. The varnishes appear as toroidal-shaped and honeycomb-textured chains and cells—"biofabrics"—composed of clay minerals, in which single and colonial microorganisms in various stages of decay and fossilization are embedded. The study concluded that these features are suitable media for the preservation of microfossils (Probst et al. 2001). Furthermore, Krinsley (1998) determined that small coccoid and granular structures within the varnish matrix have a much higher concentration of iron and manganese than the surrounding matrix, and may in fact be bacterial casts, hyphae, buds, or bacterial precipitates.

Caliche

Petrified Forest National Park is located on the border of Navajo and Apache counties, Arizona. A typical soil profile in these counties contains as much as 36% calcium carbonate (Ham 2008). Silt and dust from the atmosphere are an important source of this carbonate. Under semi-arid conditions, soils with such notable amounts of calcium carbonate often form layers of caliche—a general term for concentrations of soluble calcium salts (e.g., calcium carbonate) that precipitate from soil moisture at or near the ground surface. Caliche occurs at Petrified Forest National Park because rainfall is insufficient to flush calcium salts from the soil. Some buried caliche zones may have formed during past periods of greater rainfall or increased accumulation of carbonate from the atmosphere (Bezy and Trevena 2000).

Ham (2008) noted calcium carbonate pendants and thick coatings on gravel in the soils in the area. Additionally calcium carbonate sometimes forms a "hardpan" layer, nodules, or tubes. A hardpan is an impervious layer of soil lying at or just below the surface. It is a result of cementation of soil particles, in this case with calcium carbonate. Nodules form when calcium carbonate precipitates from downward percolation of water, or less commonly, from moisture brought up from below by evaporation and capillary rise. Tubes occur when calcium carbonate coats and eventually replaces plant roots (Bezy and Trevena 2000).

Table 3. Types of fossils in the Chinle Formation at Petrified Forest National Park

Member	Petrified Wood	Leaves and Other Plant Remains	Fungi	Invertebrate Remains	Invertebrate Trace Fossils	Vertebrate Remains	Vertebrate Trace Fossils
Petrified Forest	X	X		X	X	X	X
Sonsela	X	X		X	X	X	X
Blue Mesa	X	X	X	X	X	X	X

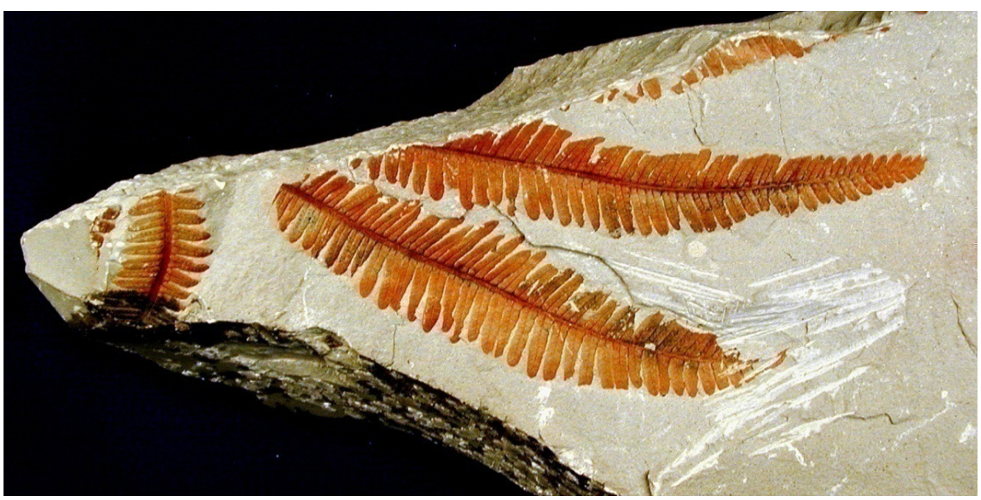

Figure 10. Fern fossil. While the petrified logs are the most well known plant fossils from the park, many other taxonomic groups and plant structures are represented. The fern *Phlebopteris smithii* is shown here. National Park Service photograph.

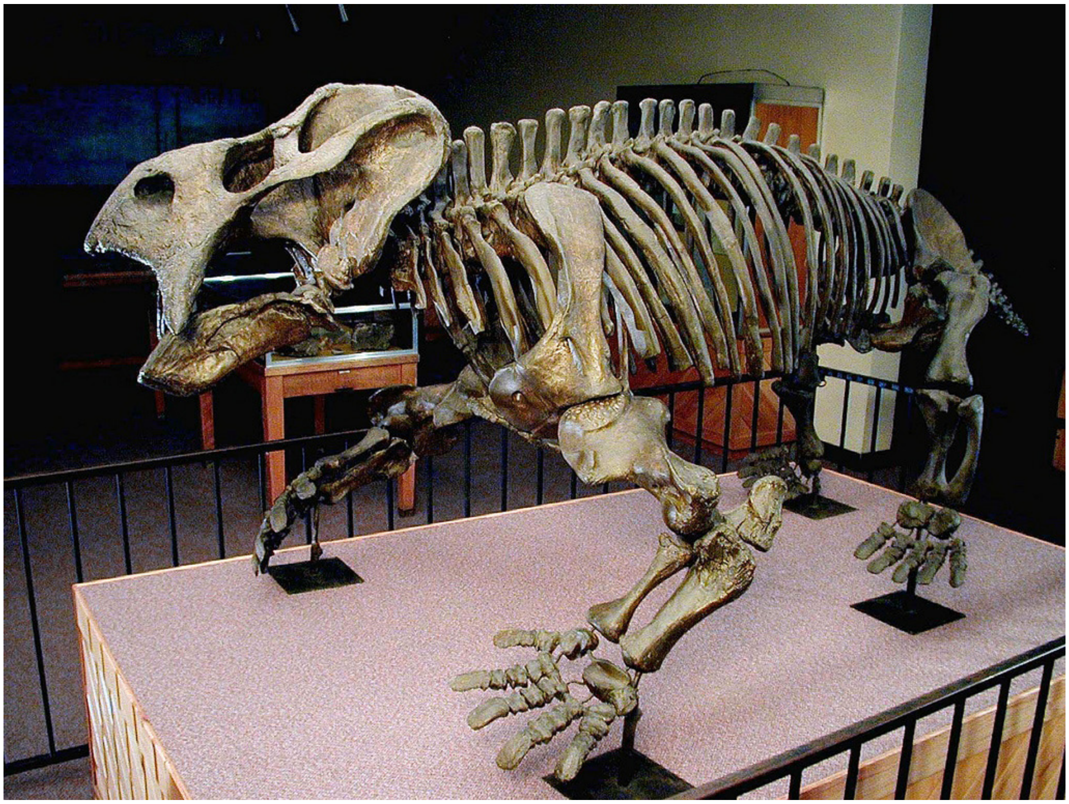

Figure 11. ***Placerias*** **skeleton.** ***Placerias*** **was a large therapsid, colloquially known as a "mammal-like reptile." Therapsid fossils are not common within Petrified Forest National Park, but are well known from other parts of Arizona. National Park Service photograph.**

Figure 12. Phytosaur skull. Phytosaurs are distantly related to crocodiles (note the elongated snout) and are the most common fossil animal found within Petrified Forest National Park. National Park Service photograph.

Figure 13. Rainbow-colored petrified wood. Most of the petrified wood in the park is from *Araucarioxylon arizonicum*, an extinct tree of Triassic age. Two others types of wood, *Woodworthia* and *Schilderia,* occur in small quantities in the northern part of the park. Iron and other minerals combined with silica created the rainbow colors. All types of quartz crystals—clear quartz, purple amethyst, yellow citrine, and smoky quartz—add to the colorful display. National Park Service photograph by T. Scott Williams.

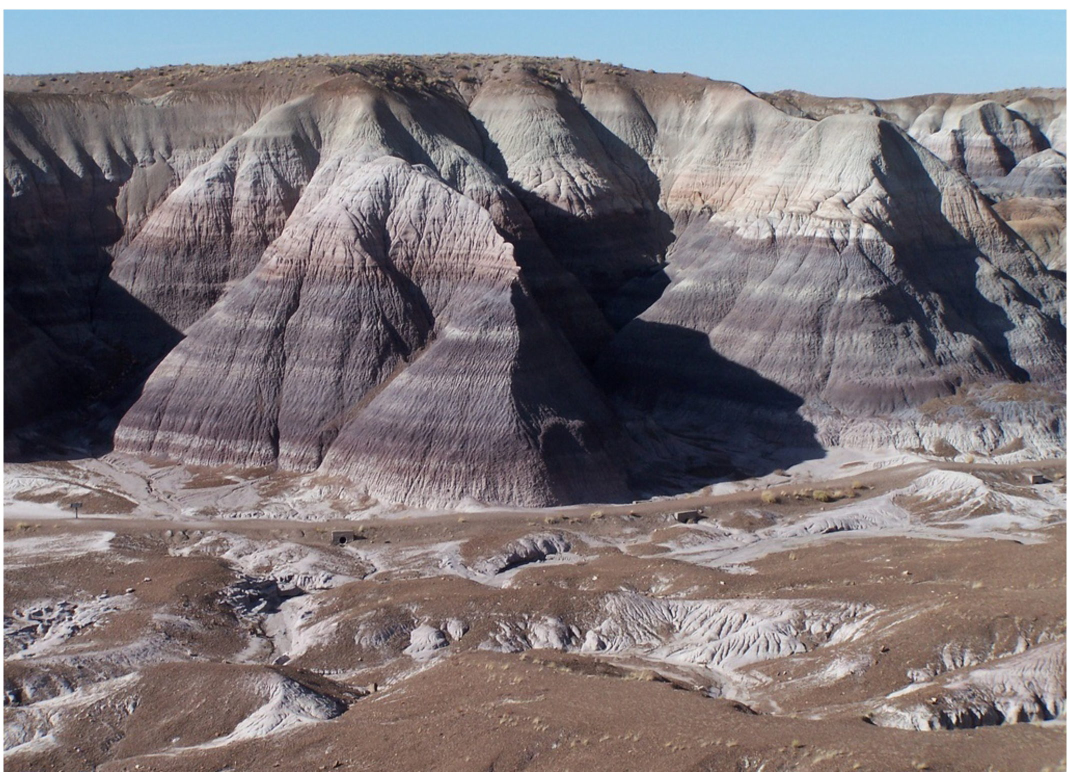

Figure 14. Badlands topography. The colorful hills, flat-topped mesas, and sculptured buttes of the park's badlands (this photo is from the Blue Mesa area) are composed of the Upper Triassic Chinle Formation, named for the Chinle Valley north of the park. The horizontal colored bands represent paleosols (ancient soil layers). National Park Service photograph by Marge Post.

Figure 15. Painted Desert. Colorful badlands of the Chinle Formation comprise the Painted Desert in Petrified Forest National Park. National Park Service photograph by T. Scott Williams.

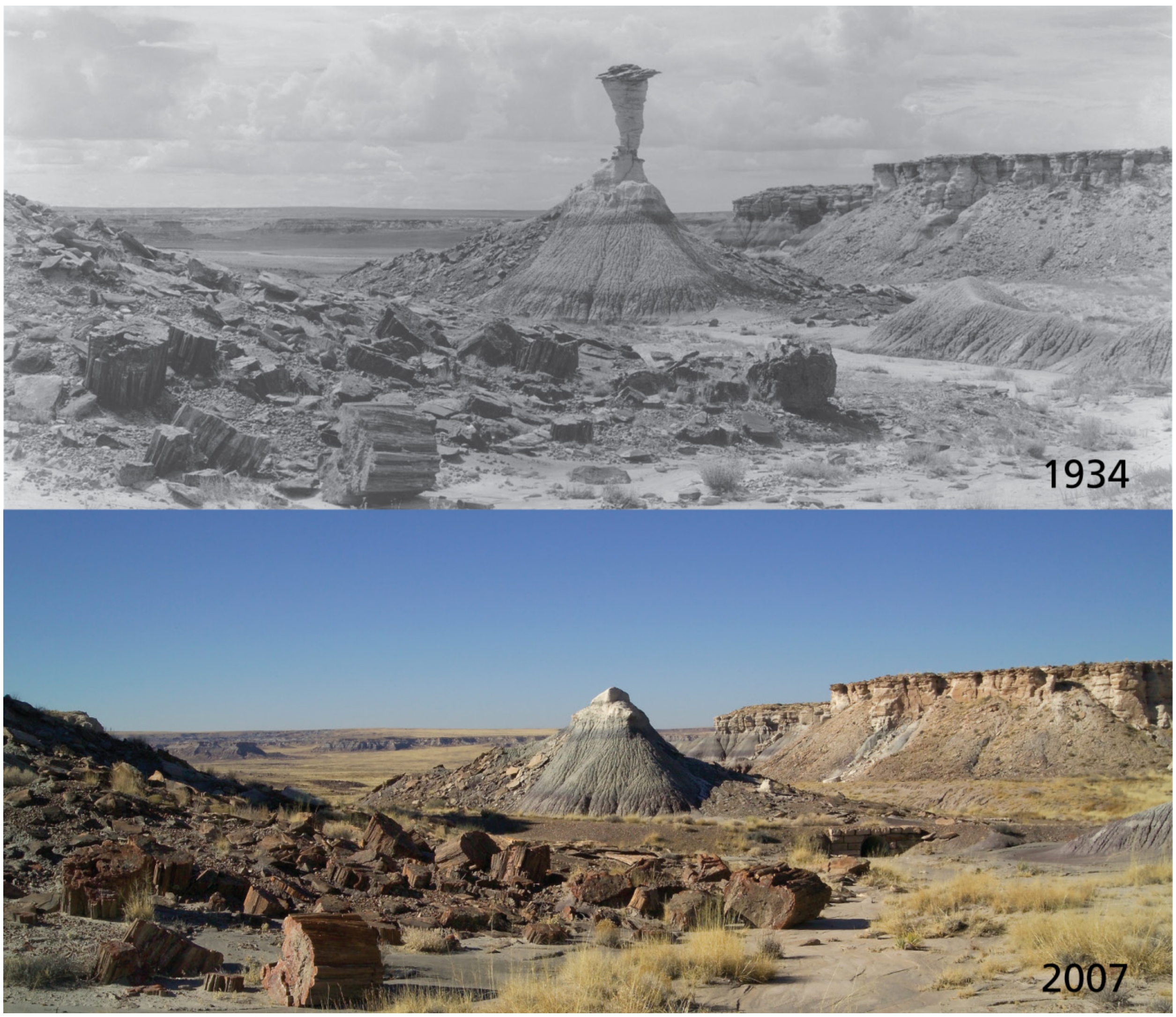

Figure 16. Erosion. Eagle Nest Rock was a prominent 5 m (15 ft) pillar (hoodoo) in the Jasper Forest bed of the Sonsela Member, and a popular attraction for early visitors to the park. Shaped by erosion, the feature also succumbed to erosive forces following a period of high rainfall and high winds in January 1941. National Park Service photographs by George Grant (1934) and T. Scott Williams (2007).

Figure 17. Unconformity. The arrow points to the contact between the yellow-gray sandstones and black basalts of the Miocene-aged Bidahochi formation (above) and the red mudstones of the Triassic-aged Chinle Formation (below). This unconformity represents about 200 million years of missing time. Arizona Geological Survey photograph by Larry Fellows in Bezy and Trevena (2000).

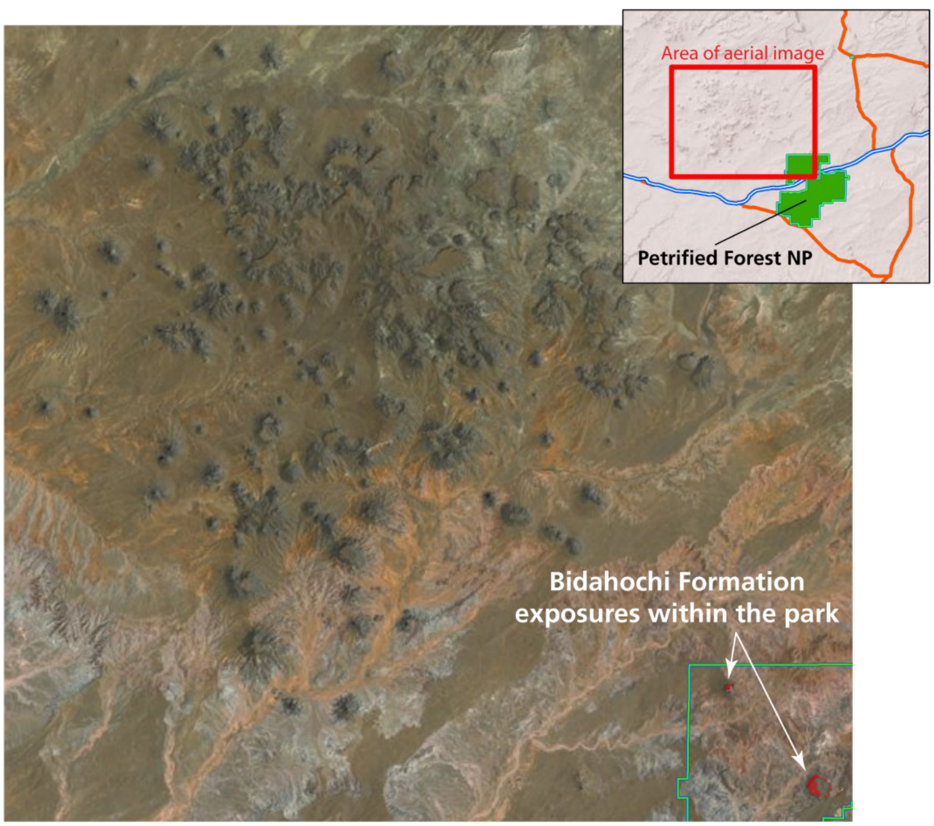

Figure 18. Hopi Buttes volcanic field. Within Petrified Forest National Park, rocks of the Bidahochi Formation are most likely outliers from the large Hopi Buttes volcanic field. This volcanic field is one of the world's largest concentrations of maar landforms (note the dark-colored cones in the image above). The volcanic field is approximately 80 km (50 mi) across. Aerial imagery compiled by Phil Reiker (NPS Geologic Resources Division) from ESRI ArcImage Service; USA Prime Imagery.

Figure 19. Petroglyphs. Prehistoric peoples etched petroglyphs into desert varnish throughout the Southwest. Petrified Forest National Park contains many examples. National Park Service photograph by T. Scott Williams.

Map Unit Properties

This section identifies characteristics of map units that appear on the Geologic Resources Inventory digital geologic map of Petrified Forest National Park. The accompanying table is highly generalized and for background purposes only. Ground-disturbing activities should not be permitted or denied on the basis of information in this table.

Geologic maps facilitate an understanding of Earth, its processes, and the geologic history responsible for its formation. Hence, the geologic map for Petrified Forest National park provided information for the "Geologic Issues," "Geologic Features and Processes," and "Geologic History" sections of this report. Geologic maps are two-dimensional representations of complex three-dimensional relationships; their color coding illustrates the distribution of rocks and unconsolidated deposits. Bold lines that cross or separate the color patterns mark structures such as faults and folds. Point symbols indicate features such as dipping strata, sample localities, mines, wells, and cave openings.

Incorporation of geologic data into a Geographic Information System (GIS) increases the usefulness of geologic maps by revealing the spatial relationships among geologic features, other natural resources, and anthropogenic features. Geologic maps are indicators of water resources because they show which rock units are potential aquifers and are useful for finding seeps and springs. Geologic maps are not soil maps, and do not show soil types, but they do show parent material—a key factor in soil formation. Furthermore, resource managers have used geologic maps to make connections between geology and biology; for instance, geologic maps have served as tools for locating sensitive, threatened, and endangered plant species, which may prefer a particular rock unit.

Although geologic maps do not show where earthquakes will occur, the presence of a fault indicates past movement and possible future seismic activity. Similarly, map units show areas that have been susceptible to hazards such as landslides, rockfalls, and volcanic eruptions. Geologic maps do not show archaeological or cultural resources, but past peoples may have inhabited or been influenced by depicted geomorphic features. For example, alluvial terraces may have been preferred use areas and formerly inhabited alcoves may occur at the contact between two rock units.

The geologic units listed in the following table correspond to the accompanying digital geologic data. Map units are listed in the table from youngest to oldest. Please refer to the geologic timescale (fig. 20) for the age associated with each time period. The table highlights characteristics of map units such as: susceptibility to erosion and hazards; the occurrence of paleontological resources (fossils), cultural resources, mineral resources, and caves or karst; and suitability as habitat or for recreational use. Some information on the table is conjectural and meant to serve as suggestions for further investigation.

The GRI digital geologic maps reproduce essential elements of the source maps including the unit descriptions, legend, map notes, graphics, and report. The following references are the sources for the GRI digital geologic data for Petrified Forest National Park, which covers the pre-2004 boundary:

Blakey, R., and Raucci, J. 2006. Geologic map of Petrified Forest National Park, Arizona. Scale 1:24,000. Unpublished data. Flagstaff, AZ: Northern Arizona University.

This publication incorporated new mapping and the following sources:

Billingsley, G. H. 1985a. Geologic map of Petrified Forest National Park, Arizona. Scale 1:48,000. Unpublished data. Petrified Forest, AZ: Petrified Forest Museum Association.

Johns, M. E. 1988. Architectural element analysis and depositional history of the upper Petrified Forest Member of the Chinle Formation, Petrified Forest National Park, Arizona. MS thesis, Northern Arizona University.

Woody, D. 2003. Revised geological assessment of the Sonsela Member, Chinle Formation, Petrified Forest National Park, Arizona. MS thesis, Northern Arizona University.

The GRI team implements a geology-GIS data model that standardizes map deliverables. This data model dictates GIS data structure including data layer architecture, feature attribution, and data relationships within ESRI ArcGIS software, and increases the overall utility of the data. GRI digital geologic map products include data in ESRI personal geodatabase, shapefile, and coverage GIS formats, layer files with feature symbology, Federal Geographic Data Committee (FGDC)-compliant metadata, a Windows help file that contains all of the ancillary map information and graphics, and an ESRI ArcMap map document file that easily displays the map.

GRI digital geologic data are included on the attached CD and are available through the NPS Natural Resource Information Portal at
http://science.nature.nps.gov/nrdata/

Map Unit Properties Table: Petrified Forest National Park

Age	Map Unit (Symbol)		Description	Exposure and Thickness	Paleontological, Mineral, and Cultural Resources	Suitability for Infrastructure and Recreation	Correlation
QUATERNARY		Surficial deposits, undifferentiated (Qsu)	Unconsolidated sand, silt, mud, and gravel: Includes alluvial surfaces (slopewash and sheet-flow deposits), active stream channels (ephemeral and perennial), colluvium, floodplain deposits, in situ soil development, and deposits of indeterminate origin; may be superficially modified by eolian processes	Alluvium is up to 60 m (200 ft) thick (Martin 2004)		Alluvium produces sufficient water, but would require treatment (Martin 2004); colluvium-covered slopes indicate potential for mass movement	
QUATERNARY		Eolian dunes and sand sheets (Qd)	Unconsolidated sand: Deposited in dunes by eolian processes or in extensive sand sheets by mixed alluvial and eolian processes; commonly heavily vegetated	200,000- to 75,000-year-old dunes at higher elevations in north part of the park; 8,000- to 2,000-year-old dunes in drainages (e.g., Lithodendron Wash); <1,000-year-old dunes throughout the park (Ellwein et al. 1997)			
MIOCENE/ PLIOCENE	Bidahochi Formation	Volcanic rocks (Mbv)	Basaltic lava and tephra deposits: Likely part of the Hopi Buttes volcanic field	Restricted to north portion of park (e.g., Headquarters Mesa)	Landmark features (e.g., Pilot Rock and Black Knoll)		Equivalent to the informal Member 5 of the Bidahochi Formation (Dallege 1999)
MIOCENE	Bidahochi Formation	Sedimentary rocks (Mbs)	Mudstone and minor siltstone: Deposited in freshwater lake or basin with shallow ephemeral lakes; outcrops generally medium tan to yellow, and locally difficult to distinguish from overlying Quaternary deposits; present as cut-and-fill deposits atop the Petrified Forest Member (TRcpf); usually preserved by volcanic cap rock	Limited outcrops near and south of Headquarters Mesa, on Pilot Rock, and in the northeast corner of the park			Likely equivalent to Members 1 and 2 of Dallege (1999)
			unconformity				
TRIASSIC	Chinle Formation	Owl Rock Member (TRco)	Sandstone and mudstone with minor limestone and siltstone: Lacustrine; mudstones—generally lighter in color than the underlying Petrified Forest Member (TRcpf); sandstones—pale reddish brown, fine-grained, well-sorted litharenites with common trough cross-strata; limestones—generally light-colored, mottled, pisolithic, and massive, locally brecciated and re-cemented; approximately 205 million years old (Bill Parker, Petrified Forest National Park, written communication, June 2009)	Exposed only on Chinde Mesa in the far north part of park, where 80 m (260 ft) are present (Ash 1992)	Limestone with secondary silica in dissolution zones (Dubiel 1993; Tanner 2000); selenite-gypsum lenses and chalcedony nodules; caliche	Bentonite; dissolution zones	
TRIASSIC	Chinle Formation	Petrified Forest Member[1] (TRcpf)	Mudstone with minor sandstone and siltstone: Deposited in vast, muddy floodplain; primarily pale red to purple mudstone with common thin sandstone interbeds; commonly bright reddish orange north of I-40; commonly light-green mottling in mudstones and large-scale scours in the upper part of the unit; approximately 210 million years old (Bill Parker, Petrified Forest National Park, written communication, June 2009)	Approximately 255 m (840 ft) thick (Ash 1992); exposed in Flattops and Painted Desert areas	Petrified wood; fossil leaves and other plant remains; invertebrate and vertebrate remains and trace fossils; gypsum	Bentonite	Called the Painted Desert Member (Petrified Forest Formation, Chinle Group) by Heckert and Lucas (2002)
TRIASSIC	Chinle Formation	Black Forest Bed (TRcpfbf)	Calcrete-nodule conglomerate and reworked tuffaceous material with sandstone and mudstone interbeds: Black silicified wood gives bed its name; dated isotopically at 213 ± 1.7 million years old (Riggs et al. 2003) and 211 ± 0.7 million years old (Heckert et al. 2009)	Conglomerate up to 13 m (4 ft); sandstone and mudstone (0.1 to 0.2 m [0.3 to 0.7 ft] thick); only exposed in north part of park	Known for permineralized black wood; invertebrate and vertebrate remains		
TRIASSIC	Chinle Formation	Lithodendron Wash Bed (TRcpflw)	Sandstone, conglomerate, and mudstone: Generally fine-grained sandstone with minor conglomerate, coarse-grained sandstone and interbedded mudstone; sandstones pale gray to tan on fresh surfaces, but commonly weather to medium brown; internal cross-stratification is ubiquitous, including trough and planar cross-sets, lateral accretion sets, and rare channel forms; multi-storied or single sets	Present throughout south part of the Petrified Forest Wilderness; total thickness up to 11 m (36 ft); many mesas and buttes of Painted Desert developed in this bed (Heckert and Lucas 2002)		Bentonite	Called Painted Desert Sandstone 3 by Billingsley (1985a) and Johns (1988)
TRIASSIC	Chinle Formation	Goblin Sandstone (TRcpfg)	Sandstone and minor conglomerate: Pale yellowish gray to pale red, fine-grained, well-sorted; planar and trough cross-bedding are common, as are small-scale scours and rip-up conglomerates at the base of coarse-grained beds	Present west of Chinde Point (forms the floor of washes); prominent ledge-former in the Devil's Playground area			May be equivalent to Painted Desert Sandstone 1 of Billingsley (1985a) and Johns (1988)
TRIASSIC	Chinle Formation	Flattops Beds 2–4 (TRcpff)	Sandstone: Generally fine- to medium-grained, moderately to well-sorted brownish gray sandstone; commonly planar and trough cross-strata are common and horizontal and ripple laminae	Flattops Bed 2 laterally extensive; Flattops Beds 3 and 4 restricted to the Flattops Mesa area along the main park road; unit thicknesses laterally variable but typically <10 m (33 ft); Flattops Bed 2 is the thickest (>10 m [33 ft] in some locations)	Unionid bivalves in Flattops Beds 2 and 3		

Age	Map Unit (Symbol)	Description	Exposure and Thickness	Paleontological, Mineral, and Cultural Resources	Suitability for Infrastructure and Recreation	Correlation
TRIASSIC — Chinle Formation	Sonsela Member / Petrified Forest Member undifferentiated (TRcspf)	Mudstone and sandstone: Pale greenish gray to bluish gray mudstone with minor to significant sandstone interbeds; commonly tabular bedding and cut-and-fill scours; lateral variation in lithology, becoming generally finer grained to the north	Informal unit mapped only in the Devil's Playground area north of I-40 (Blakey and Raucci 2006)		Bentonite	Transitional interval between the Sonsela and Petrified Forest members (Blakey and Raucci 2006)
	Sonsela Member[3]	Deposited in large gravelly river; entirely within Norian Stage (216.5 to 203.6 million years ago), approximately 216 million years ago (Bill Parker, Petrified Forest National Park, written communication, June 2009)	Includes the majority of strata in the central and southern portion of the park as well as the Devils Playground area	Primary source of petrified wood in the park; other plant, invertebrate, and vertebrate remains and trace fossils		
	Flattops 1 Bed (TRcsft1)	Sandstone and conglomerate: Medium- to coarse-grained, moderately to well-sorted, yellow brown to dark brown sandstone; compositionally immature and commonly multi-storied with thin mudstone interbeds; conglomerates comprise calcrete-nodule lags at the base of sandstone beds and discrete lenses of pebble-size clasts; volcanic clasts and intra-formational rip-ups	Individual beds 3 to 5 m (10 to 16 ft) thick; maximum thickness 25 m (80 ft), but appears to pinch out in the southeast and west edges of the south part of the park	Petrified wood and unionid bivalves; chert		Top of the Sonsela Member in Woody (2003); called Agate Bridge Bed by Heckert and Lucas (2002)
	Brown Sandstone (TRcsb)	Sandstone and minor conglomerate: Sandstones generally fine- to medium-grained, but coarse intervals common, especially near the base of scours; pale tan or gray on fresh surfaces, weathers to medium brown; internal structure—massive or weakly laminated to complex cross-stratification; may comprise either multiple stories or a single thick bed; forms prominent blocky ledges	Mapped only in the Devil's Playground area north of I-40 (Blakey and Raucci 2006); total unit thickness up to 6 m (20 ft), but lateral changes in thickness can be abrupt, especially near the northern pinch-out			
	Jasper Forest Bed (TRcsjf)	Sandstone, mudstone, and conglomerate	Caps bluffs at Blue Mesa, Jasper Forest, and Crystal Forest	Main petrified wood-bearing horizon in the central portion of the park; vertebrate remains occur locally		Called the Agate Bridge Bed by Heckert and Lucas (2002); may be analogous to one or more significant, medial sandstones within the Jim Camp Wash Beds in the Rainbow Forest area
	Jim Camp Wash Beds (TRcsjc)	Sandstone, siltstone, and mudstone: Pale gray, purple, and less commonly red mudstone; fine- to medium-grained and poorly sorted sandstone; sandstones—generally not laterally continuous, ribbon architecture common; thicker, more laterally continuous sandstone beds are locally present that are coarser grained, richer in volcanic clasts, and similar to Rainbow or Flattops sandstones from which they may be difficult to distinguish	Total thickness 30 to 45 m (100 to 150 ft), may locally thinner	Unionid bivalve fragments; vertebrate fossils; minor amounts of petrified wood; chert and calcareous nodules	Bentonite	
	Rainbow Forest Beds (TRcsrf)	Sandstone and conglomerate: Fine- to medium-grained, moderately well-sorted, pale gray sandstone; locally trough and planar cross-stratified	Individual beds are generally 1 to 4 m (3 to 13 ft) thick; total thickness up to 15 m (50 ft)	Main wood-bearing horizon in southern end of park, contains nearly all the more colorful specimens; andesite, rhyolite, chert, and quartzite in conglomerate		Basal bed of the Sonsela Member; tentatively includes the Camp Butte sandstone (Murry 1990)
	Blue Mesa Member (TRcbm)	Mudstone with minor siltstone and sandstone: Deposited in muddy floodplain, ancient soils; banded dark blue, gray, yellow, and red; structureless beds; base is approximately 219 million years old (Irmis and Mundi 2008)	Individual beds generally >2 m (7 ft) thick; total thickness 80 m (260 ft); base rarely exposed in park, best exposed in the Tepees area	Contains majority of fossil-leaf localities, as well as abundant petrified wood, including stumps in growth position, amber, pollen, and spores; vertebrate remains common in some horizons	Bentonite	
	Newspaper Rock Bed (TRcbmn)	Sandstone, shales, mudstone, and conglomerate: Deposited in meandering fluvial system; complex internal geometry, including trough cross-strata, stacked ripple laminations, and lenticular bedding	Up to 20 m (66 ft) thick, and includes prominent red paleosol horizon in the Tepees and Blue Mesa areas; lowest persistent ledge-forming sandstone in the park	Contains majority of fossil-leaf localities; fossil plants and fungi; vertebrate tracks	Sandstone facies prone to cliff retreat	Prominent bed in the Blue Mesa Member
	Lower sandstone unit[4] (TRcls)	Sandstone: Coarse-grained quartoze with significant quartz overgrowths; irregular and lenticular bedding and trough cross-strata	Exposed in a single isolated outcrop east of the Haystacks; total thickness up to 2 m (7 ft); individual beds 0.5 to 1 m (2 to 3 ft) thick, cross-bedding in 20- to 40-cm (8- to 16-in) sets			
	Mesa Redondo Member (TRclrm)	Pale-red mudstone: Deposited in a combination of fluvial environments; >219 million years ago (Bill Parker, Petrified Forest National Park, written communication, June 2009)	Uncertain thickness; only the top of the unit is exposed in the park			

[1]Since mapping by Blakey and Raucci (2006), Martz and Parker (2010) have reinterpreted the Petrified Forest Member as (from oldest to youngest) Flattops Bed 2, Flattops Bed 3, and Flattops Bed 4.
[2]Mapped by Blakey and Raucci (2006) as an informal unit only in the Devil's Playground area north of I-40.
[3]Since mapping by Blakey and Raucci (2006), Martz and Parker (2010) revised the Sonsela Member into the following beds (from oldest to youngest): Camp Butte beds, Lot's Wife beds, Jasper Forest bed / Rainbow Forest Bed, Jim Camp beds, and Martha's Butte beds.
[4]Lower sandstone unit mapped by Blakey and Raucci (2006) is probably within the lower part of the Blue Mesa Member (Bill Parker, Petrified Forest National Park, written communication, September 3, 2009).

Geologic History

This section describes the rocks and unconsolidated deposits that appear on the digital geologic map of Petrified Forest National Park, the environment in which those units were deposited, and the timing of geologic events that created the present landscape.

During the Upper Triassic Period, about 220 million years ago, Petrified Forest National Park was located just north of the equator on the southwestern edge of the supercontinent Pangaea, which spread from pole to pole. Much of Earth's surface was covered by a large ocean called Panthalassa. Pangaea was shaped like a huge letter "C" facing eastward (fig. 21). The open part of the "C" cupped the Tethys Ocean. The spine of the "C" ran adjacent to a long subduction zone, which formed the eastern margin of the ocean basin. Pangaea began to break apart during the Triassic Period, but dispersed mostly during the Jurassic. Just as the formation of Pangaea influenced geologic and biologic events during the Paleozoic Era, the breakup of this supercontinent profoundly affected geologic and biologic events during the Mesozoic Era. The movement of continents affected ocean circulation and climatic regimes. Populations became isolated and were brought into contact with other populations, leading to evolutionary changes in the biota.

Ancient soils and fossil plants and animals indicate that the climate was humid and subtropical during Upper Triassic time. However, the rocks of Petrified Forest National Park show evidence of an increasingly arid climate and a transition from low-sinuosity perennial streams to mostly ephemeral streams and small lakes in younger rocks (Johns 1988; Tanner 2000; Woody 2003).

The regional setting of Petrified Forest National Park was a single depositional basin or closely interconnected array of sub-basins (Stewart et al. 1972a, b; Lucas 1993). The Chinle Formation is a sequence of nonmarine strata of Upper Triassic age that was deposited into this vast basin, which extended north-south from Wyoming to Texas, and east-west from western Oklahoma to southeastern Nevada—an area of about 2.3 million km^2 (0.9 million mi^2) (Lucas 1992).

Triassic (refer to fig. 20 for a geologic timescale) volcanism resulted in the deposition of ash in the park, which weathered to form bentonitic clay. Investigators have identified the volcanic source material as coming from far and near. Dubiel (1994) suggested that a magmatic-volcanic arc on part of the western edge of Pangaea likely provided volcanic ash, as well as clastic detritus to the Chinle deposition basin. Harris (1977) extrapolated that the volcanic ash may have been transported by the wind from volcanic fields in Nevada. Some have suggested more local source areas—the Mogollon Highlands to the south of the park and the Uncompahgre Highlands to the north (Smiley 1985). These areas also provided clastic sediments (Dubiel 1994). The deposited ash, whatever its source(s), leached the silica responsible for the petrifaction of the park's famous logs (National Park Service 2003).

The sedimentary layers of the Chinle Formation—the principal fossil-bearing strata in the park—consist of sandstone, siltstone, mudstone, conglomerate (i.e., silica and limestone pebbles and calcrete nodules), and minor limestone beds (in the Owl Rock Member). These rocks preserve a suite of lowland terrestrial environments, including river channels, floodplains, swamps, and small lakes (Dubiel 1994; Blakey and Raucci 2006). Each member details the stratigraphy, sedimentology, and paleontology of a particular depositional setting.

Mesa Redondo Member

The Mesa Redondo Member records a combination of fluvial environments: fast through-flowing streams carried considerable runoff (represented by highly cross-bedded conglomerate) and slowly moving streams in broad floodplains deposited fine-grained sediments (represented by mudstone and siltstone) (Cooley 1958). The Mesa Redondo Member is not well exposed in the park, but limited outcrops of rocks underlying the Blue Mesa Member are present near the Haystacks in the southern part of the park (fig. 1).

Blue Mesa Member

The lowest (oldest) well-defined rock unit in Petrified Forest National Park is the Blue Mesa Member of the Chinle Formation. Approximately 219 million years ago, streams deposited the strata of the Blue Mesa Member, which are best exposed at the Tepees area in the southern part of the park (Lucas 1993; Heckert and Lucas 1995b; Irmis and Mundil 2008). These rocks represent part of a vast muddy tropical floodplain (Dubiel 1989; Demko 1995a, b). Plants growing at this time included conifer trees, cycadeoids, cycads, and ferns (Ash 2005). Small rivers meandered across the landscape, heading northwestward toward the Panthalassa shoreline located near the Utah-Nevada border. Large plant eaters such as the cow-sized mammal-like reptile *Placerias* browsed along the river banks (Lucas 2001).

Sonsela Member

About 216 million years ago, large gravelly rivers deposited the Sonsela Member of the Chinle Formation in a wide fluvial plain (Dubiel 1989). These rivers carried heavier bedloads than either earlier or later Triassic river channels preserved at Petrified Forest National Park (Blakey and Gubitosa 1984). The change from a muddy floodplain of the Blue Mesa Member likely resulted from a slowing of the rate at which the crust was subsiding in western North America at this time (Blakey and Gubitosa

1984). Large conifer trees grew along the rivers, and their fossilized stumps and logs became the park's renowned petrified forests (Heckert and Lucas 1995a). Plant-eating reptiles, such as the heavily armored *Paratypothorax*, foraged on the forest floors (Lucas 2001).

Petrified Forest Member

About 210 million years ago, when the red-bed mudstones and sandstones in the Painted Desert formed, the Triassic river system was once again a vast muddy floodplain (Blakey and Gubitosa 1984; Dubiel 1989). Unlike the floodplain of the older Blue Mesa Member, however, huge rivers meandered across the Petrified-Forest-Member floodplain, and tall trees lined the watercourses. These trees became the logs of the Black Forest near Kachina Point. Crocodile-like phytosaurs, some as long as 7 m (23 ft), hunted along the river banks (Lucas 2001).

Owl Rock Member

Sediments settled in a lake and formed the Owl Rock Member 205 million years ago. This member represents the southern extension of a lacustrine system that was centered on the Four Corners area of the Colorado Plateau (see fig. 4). Gastropods at the base of the Owl Rock Member attest to the original lacustrine setting for some of the beds, though many of the strata were subsequently altered by pedogenesis (soil formation) while exposed under drier conditions and lowered lake levels (Dubiel 1993; Tanner 2000). Lucas (1992) referred to these deposits as "soil caliches" (see Caliche section under "Geologic Features and Processes"). The lateral extent of the Owl Rock Member's limestone beds (some of which are laminated), as well as invertebrate burrows and gastropods in the intervening siltstones, add credence to a lacustrine interpretation for the Owl Rock Member (Dubiel 1993).

Jurassic and Cretaceous Rocks

Since deposition of the Triassic rocks, tectonic forces have uplifted northeastern Arizona by at least one vertical mile. Working in concert, uplift and erosion removed any Jurassic and Cretaceous (between 200 and 65.5 million years ago) rocks that may have been present.

Miocene-Pliocene and Quaternary Units

Although the Upper Triassic Chinle Formation dominates the geologic setting of Petrified Forest National Park, rocks and unconsolidated deposits from two other geologic time intervals are part of the park's landscape: Miocene–Pliocene Bidahochi Formation and Quaternary deposits.

Bidahochi Formation

Sedimentary and volcanic rocks of the Bidahochi Formation cap higher mesas in the Painted Desert area. Bidahochi sediments settled in a freshwater-lake environment and became mudstone and siltstone. This lake—called Lake Bidahochi by Smiley (1985) and Lake Hopi by Dallegge (1999) and Blakey and Raucci (2006)—was regionally extensive and persisted until late Miocene or early Pliocene time. The section at Petrified Forest National Park represents only the early phases of deposition in the Bidahochi basin (Dallegge 1999). Alternatively, the Bidahochi setting may have been a basin that contained many ephemeral lakes (Dallegge et al. 2000). Vents of the Hopi Buttes volcanic field erupted lava and ash into the lake of the lower Bidahochi Formation, creating a series of maar deposits and lava flows. Basaltic rocks also formed landmark features such as Pilot Rock and Black Knolls in the park. The Bidahochi Formation spans about 5 million years from approximately 9 to 4 million years ago (Love 1989). Erosion has removed much of the Bidahochi Formation from the park area.

Quaternary Deposits

Sediments of the Quaternary Period (the past 2. 6 million years) consist of fluvial (river-deposited) mud, silt, sand, and gravel, and eolian (wind-deposited) sand that form extensive dunes and sand sheets. These sediments cover the Miocene-Pliocene and Triassic rocks throughout much of the park.

Presently, synchronous forces of deposition and erosion are creating new sedimentary layers and landforms such as sand dunes and stream channels while stripping away older rocks and exposing fossil flora and fauna.

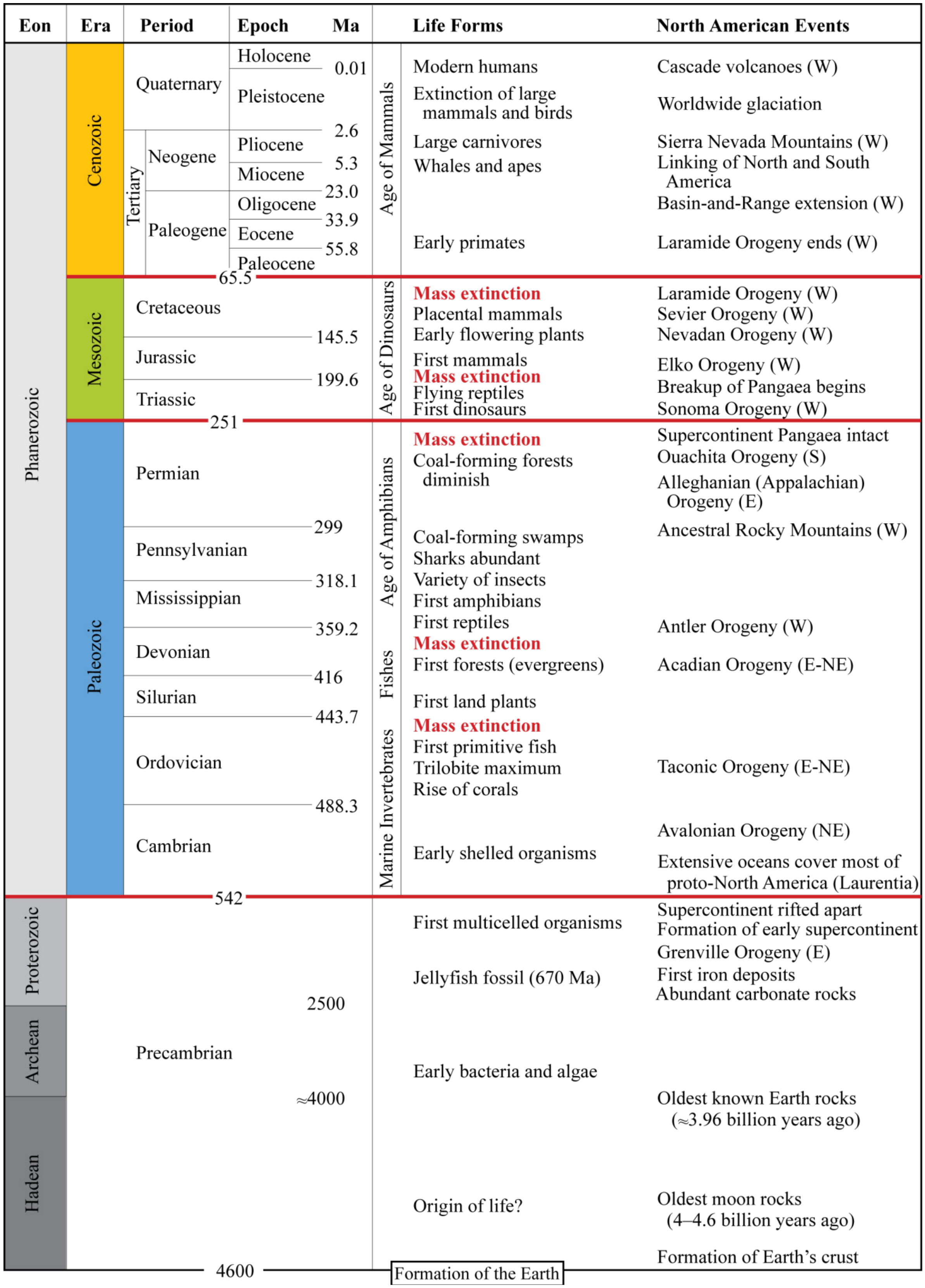

Figure 20. Geologic timescale. Included are major life history and tectonic events occurring on the North American continent. Red lines indicate major unconformities between eras. Isotopic ages shown are in millions of years (Ma). Compass directions in parentheses indicate the regional location of individual geologic events. Adapted by Trista Thornberry-Ehrlich (Colorado State University) from the U.S. Geological Survey, http://pubs.usgs.gov/fs/2007/3015/ with additional information from the International Commission on Stratigraphy http://www.stratigraphy.org/view.php?id=25.

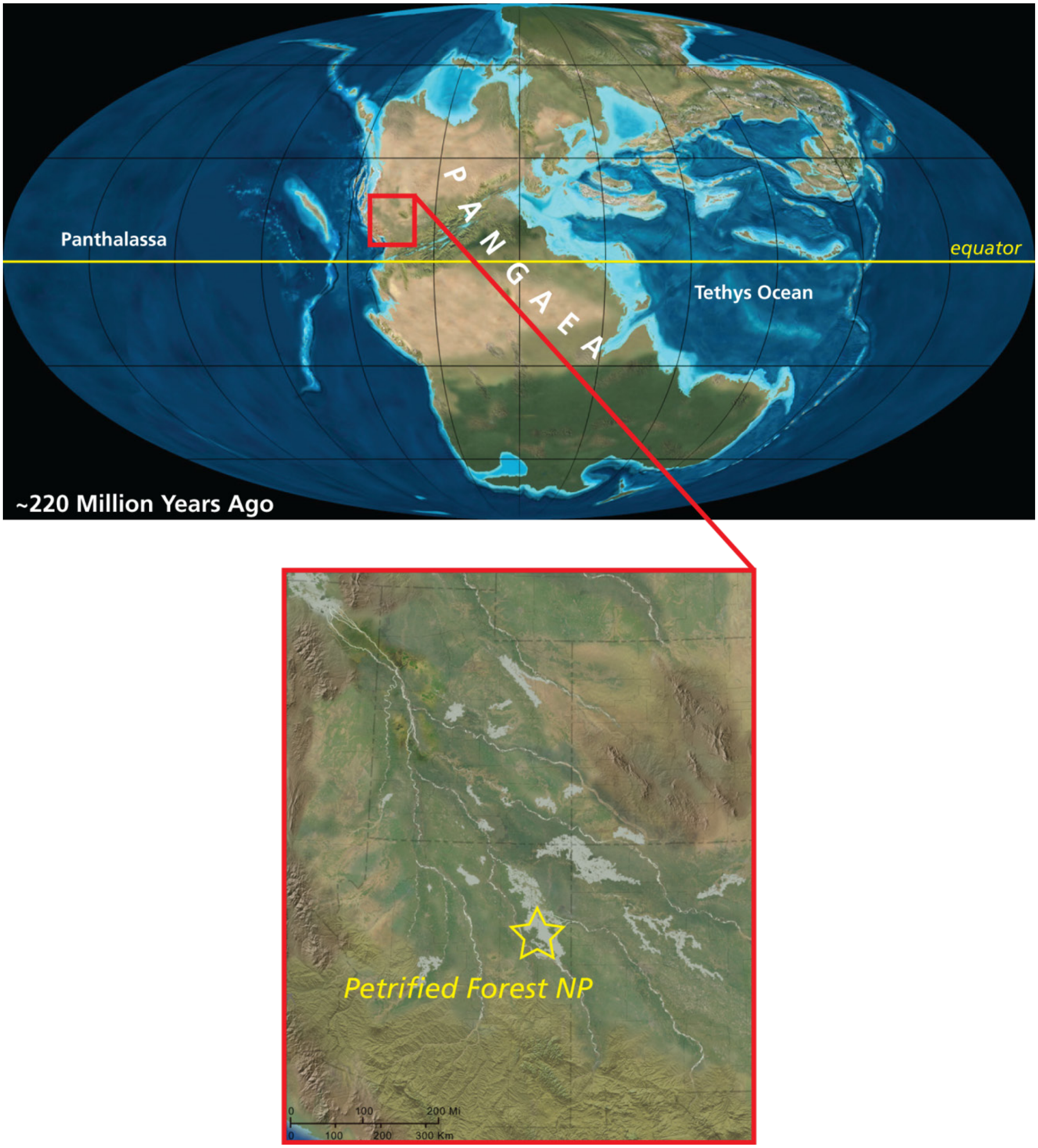

Figure 21. Pangaea. During the Upper Triassic Period, Petrified Forest National Park was located just north of the equator on the western edge of the supercontinent Pangaea. The west coast of Pangaea was situated along a subduction zone; the eastern shoreline cups the Tethys Ocean. At the time, much of Earth's surface was covered by a large ocean called Panthalassa. Base paleogeographic images by Ron Blakey (Northern Arizona University Department of Geology); available at http://jan.ucc.nau.edu/~rcb7/index.html (accessed May 2010).

Glossary

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

alluvium. Stream-deposited sediment.
anticline. A convex-upward ("A" shaped) fold. Older rocks are found in the center.
aquifer. A rock or sedimentary unit that is sufficiently porous that it has a capacity to hold water, sufficiently permeable to allow water to move through it, and currently saturated to some level.
arroyo. A small, deep, flat-floored channel or gully of an ephemeral or intermittent stream in the arid and semiarid regions of the southwestern United States.
ash (volcanic). Fine pyroclastic material ejected from a volcano (also see "tuff").
barchan dune. A crescent-shaped dune with arms or horns of the crescent pointing downwind. The crescent or barchan type is most characteristic of inland desert regions.
basin (structural). A doubly plunging syncline in which rocks dip inward from all sides.
basin (sedimentary). Any depression, from continental to local scales, into which sediments are deposited.
bed. The smallest sedimentary strata unit, commonly ranging in thickness from one centimeter to a meter or two and distinguishable from beds above and below.
bedding. Depositional layering or stratification of sediments.
bedrock. A general term for the rock that underlies soil or other unconsolidated, surficial material.
calcareous. Describes rock or sediment that contains the mineral calcium carbonate ($CaCO_3$).
cementation. Chemical precipitation of material into pores between grains that bind the grains into rock.
chalcedony. A variety of quartz that is commonly fibrous on a microscopic level, may be translucent or semitransparent, and has a nearly wax-like luster.
chemical sediment. A sediment precipitated directly from solution (also called nonclastic).
chemical weathering. Chemical breakdown of minerals at Earth's surface via reaction with water, air, or dissolved substances; commonly results in a change in chemical composition more stable in the current environment.
clast. An individual grain or rock fragment in a sedimentary rock, produced by the physical disintegration of a larger rock mass.
clastic. Describes rock or sediment made of fragments of pre-existing rocks (clasts).
clay. Can be used to refer to clay minerals or as a sedimentary fragment size classification (less than 1/256 mm [0.00015 in]).
claystone. Lithified clay having the texture and composition of shale but lacking shale's fine layering and fissility (characteristic splitting into thin layers).
conglomerate. A coarse-grained, generally unsorted, sedimentary rock consisting of cemented, rounded clasts larger than 2 mm (0.08 in).
cross-bedding. Uniform to highly varied sets of inclined sedimentary beds deposited by wind or water that indicate flow conditions such as water flow direction and depth.
cuesta. An asymmetric landform with one gently sloping side and one steeply sloping side. Results from erosion of gently dipping rock strata.
deformation. A general term for the process of faulting, folding, and shearing of rocks as a result of various Earth forces such as compression (pushing together) and extension (pulling apart).
dip. The angle between a bed or other geologic surface and horizontal.
dome. General term for any smoothly rounded landform or rock mass. More specifically refers to an elliptical uplift in which rocks dip gently away in all directions.
drainage basin. The total area from which a stream system receives or drains precipitation runoff.
dune. A low mound or ridge of sediment, usually sand, deposited by wind. Common dune types include "barchan," "longitudinal," "parabolic," and "transverse" (see respective listings).
eolian. Describes materials formed, eroded, or deposited by or related to the action of the wind. Also spelled "Aeolian."
ephemeral stream. A stream that flows briefly only in direct response to precipitation in the immediate locality and whose channel is at all times above the water table.
escarpment. A steep cliff or topographic step resulting from vertical displacement on a fault or by mass movement. Also called a "scarp."
fault. A break in rock along which relative movement has occurred between the two sides.
formation. Fundamental rock-stratigraphic unit that is mappable, lithologically distinct from adjoining strata, and has definable upper and lower contacts.
fracture. Irregular breakage of a mineral. Any break in a rock (e.g., crack, joint, fault).
geology. The study of Earth including its origin, history, physical processes, components, and morphology.
gully. A small channel produced by running water in earth or unconsolidated material (e.g., soil or a bare slope).
hoodoo. A pillar of rock developed by erosion of horizontal strata of varying hardness. Typically found in climatic zones where most rainfall is concentrated during a short period of the year.
isotopic age. An age expressed in years and calculated from the quantitative determination of radioactive

elements and their decay products; “absolute age” and “radiometric age” are often used in place of isotopic age but are less precise terms.

lamination. Very thin, parallel layers.

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

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

litharenite. Short for “lithic arenite.” Describes sandstone containing >25% fine-grained rock fragments; <10% feldspar; and <75% quartz, quartzite, and chert.

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

maar. A low-relief, broad volcanic crater formed by multiple shallow explosive eruptions; it may contain a lake.

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

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

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

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

mud cracks. Cracks formed in clay, silt, or mud by shrinkage during dehydration at Earth’s surface.

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

overburden. Rock and sediment, not of economic value, and often unconsolidated, that overlies an ore, fuel, or sedimentary deposit.

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

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

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

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

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

pisolite. A sedimentary rock, commonly limestone, made up chiefly of rounded, pea-sized grains called pisoliths.

plastic. Capable of being deformed permanently without rupture.

plateau. A broad, flat-topped topographic high (both terrestrial and 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.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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.

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

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

system (stratigraphy). The group of rocks formed during a period of geologic time.

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

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

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

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

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

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

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

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

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

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

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

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

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

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Additional References

This section lists additional references, resources, and web sites that may be of use to resource managers. Web addresses are current as of June 2010.

General Geology and Paleontology

Paleobiology Database: http://paleodb.org/cgi-bin/bridge.pl

Ron Blakey (Northern Arizona University) paleogeographic reconstructions: http://jan.ucc.nau.edu/~rcb7/index.html

Geology of National Park Service Areas

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

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

U.S. Geological Survey Geology of National Parks (includes 3D photographs). http://3dparks.wr.usgs.gov/

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

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

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

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

Resource Management/Legislation Documents

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

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

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

Geologic Monitoring Manual
R. Young and L. Norby, editors. Geological Monitoring. Geological Society of America, Boulder, Colorado.
[Website under development]. Contact the Geologic Resources Division to obtain a copy.

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

Geological Survey Websites

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

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

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

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

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

Other Geology/Resource Management Tools

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

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

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

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

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

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

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

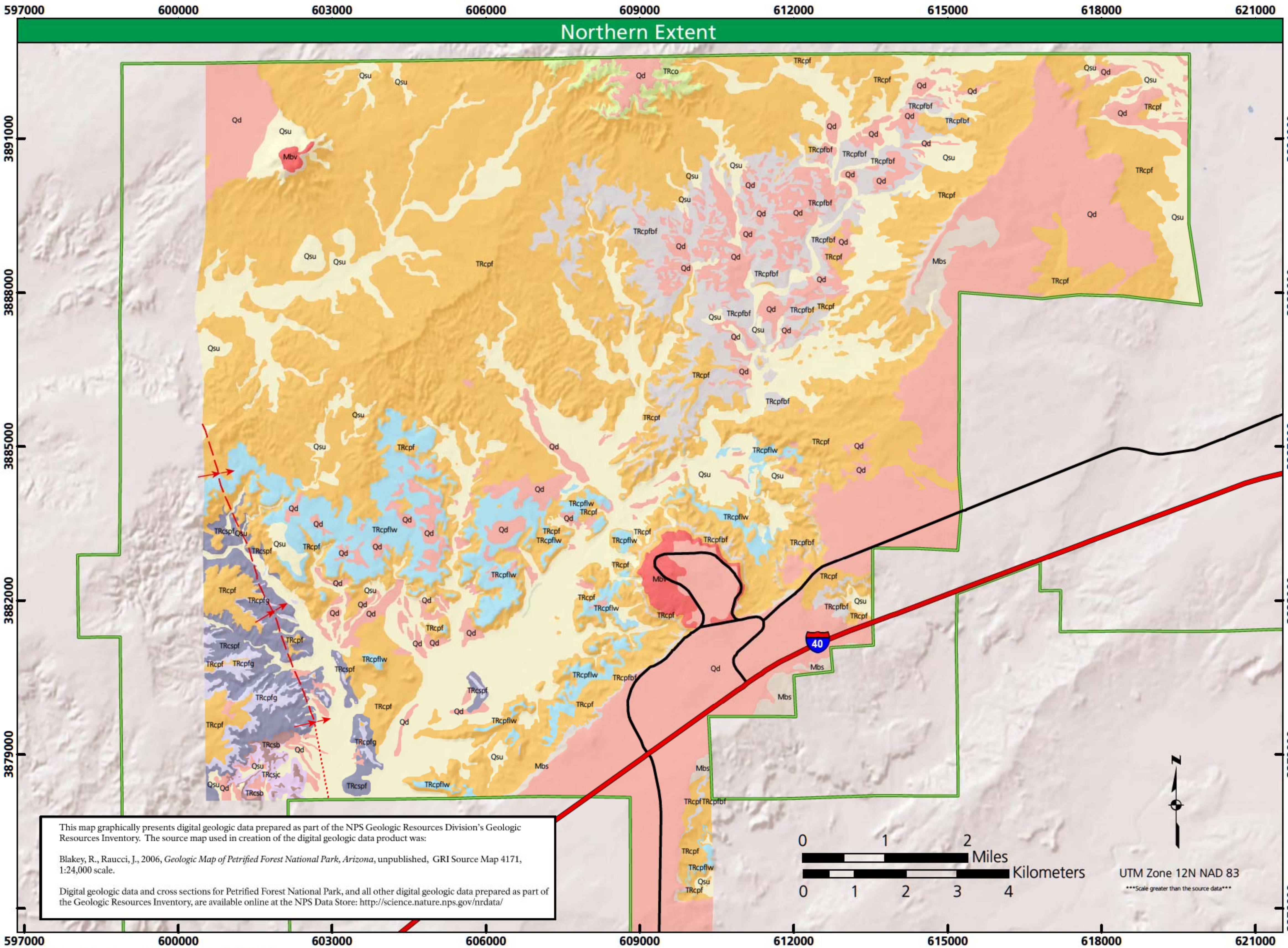
Appendix A: Overview of Digital Geologic Data

The following pages are an overview of the digital geologic data for Petrified Forest National Park. For poster-size PDFs of these overviews and complete digital data, please see the included CD or visit the Geologic Resources Inventory publications web site: http://www.nature.nps.gov/geology/inventory/gre_publications.cfm.

Note: Digital geologic data was produced prior to the park's expansion in 2004.

National Park Service
U.S. Department of the Interior

Overview of Digital Geologic Data for Petrified Forest NP



This map graphically presents digital geologic data prepared as part of the NPS Geologic Resources Division's Geologic Resources Inventory. The source map used in creation of the digital geologic data product was:

Blakey, R., Raucci, J., 2006, *Geologic Map of Petrified Forest National Park, Arizona*, unpublished, GRI Source Map 4171, 1:24,000 scale.

Digital geologic data and cross sections for Petrified Forest National Park, and all other digital geologic data prepared as part of the Geologic Resources Inventory, are available online at the NPS Data Store: http://science.nature.nps.gov/nrdata/

NPS Boundary

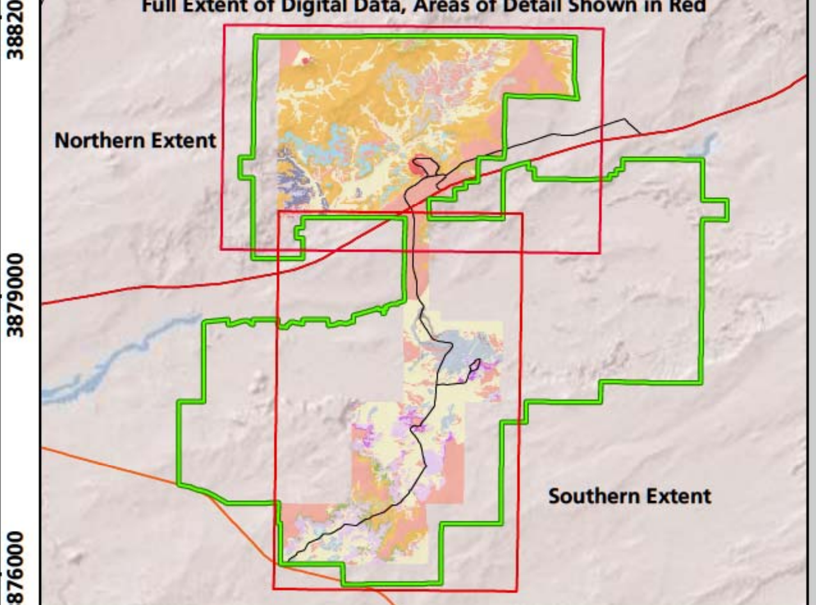
Folds

- monocline, approximate
- monocline, concealed

Geologic Units

- Qsu - Surficial deposits, undivided
- Qd - Eolian deposits
- Mbv - Bidahochi Fm. - Monchiquite lava flows
- Mbs - Bidahochi Fm. - Sedimentary member
- TRco - Chinle Fm. - Owl Rock member
- TRcpfbf - Chinle Fm. - Black Forest Tuff
- TRcpflw - Chinle Fm. - Lithodendron Wash
- TRcpfg - Chinle Fm. - Goblin Sandstone
- TRcpf - Chinle Fm. - Petrified Forest member
- TRcspf - Chinle Fm. - Sonsela/Petrified Forest transitional beds
- TRcsb - Chinle Fm. - Brown Sandstone
- TRcsjc - Chinle Fm. - Jim Camp Wash

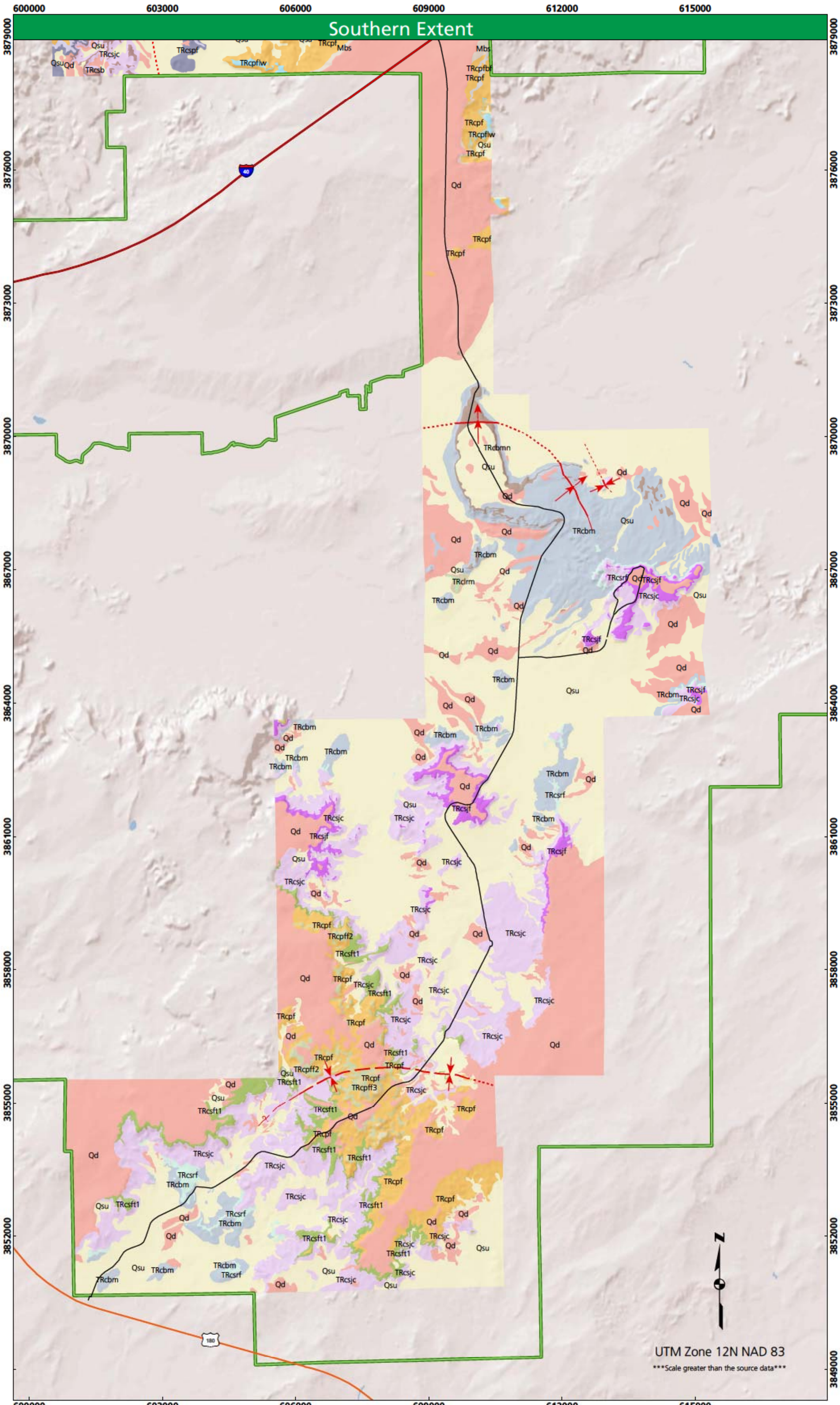
Full Extent of Digital Data, Areas of Detail Shown in Red



Produced by the Geologic Resources Inventory

June 2010

Overview of Digital Geologic Data for Petrified Forest NP



NPS Boundary

Folds

- syncline, known or certain
- syncline, approximate
- syncline, concealed
- syncline, approximate and queried
- syncline, concealed and queried
- monocline, known or certain
- monocline, concealed
- monocline, approximate and queried

Geologic Units

- Qsu - Surficial deposits, undivided
- Qd - Eolian deposits
- Mbs - Bidahochi Fm. - Sedimentary member
- TRcpfbf - Chinle Fm. - Black Forest Tuff
- TRcpflw - Chinle Fm. - Lithodendron Wash
- TRcpfg - Chinle Fm. - Goblin Sandstone
- TRcpff4 - Chinle Fm. - Flattops Bed 4
- TRcpff3 - Chinle Fm. - Flattops Bed 3
- TRcpff2 - Chinle Fm. - Flattops Bed 2
- TRcpf - Chinle Fm. - Petrified Forest member
- TRcspf - Chinle Fm. - Sonsela/Petrified Forest transitional beds
- TRcsft1 - Chinle Fm. - Flattops Bed 1
- TRcsb - Chinle Fm. - Brown Sandstone
- TRcsjf - Chinle Fm. - Jasper Forest
- TRcsjc - Chinle Fm. - Jim Camp Wash
- TRcsrf - Chinle Fm. - Rainbow Sandstone
- TRcbm - Chinle Fm. - Blue Mesa member
- TRcbmn - Chinle Fm. - Newspaper Sandstone
- TRcls - Chinle Fm. - Lower sandstone unit
- TRclrm - Chinle Fm. - Lower red member

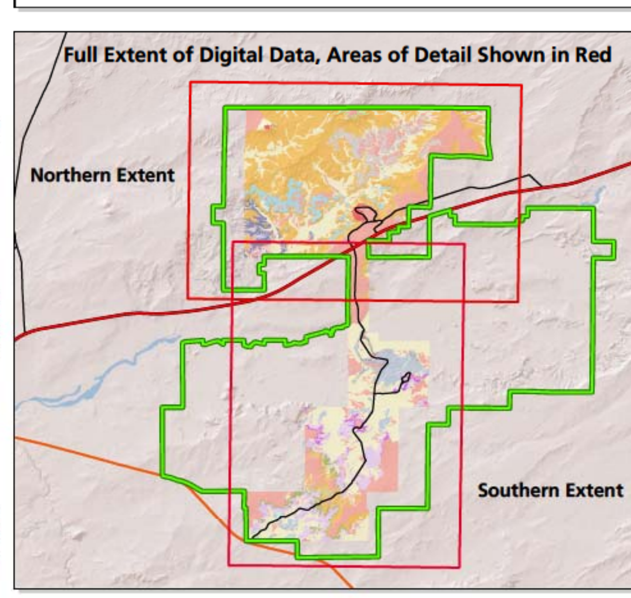
0 1 2 3 4 Miles

0 1 2 3 4 Kilometers

This map graphically presents digital geologic data prepared as part of the NPS Geologic Resources Division's Geologic Resources Inventory. The source map used in creation of the digital geologic data product was:

Blakey, R., Raucci, J., 2006, *Geologic Map of Petrified Forest National Park, Arizona*, unpublished, GRI Source Map 4171, 1:24,000 scale.

Digital geologic data and cross sections for Petrified Forest National Park, and all other digital geologic data prepared as part of the Geologic Resources Inventory, are available online at the NPS Data Store: http://science.nature.nps.gov/nrdata/



Appendix B: Scoping Session Participants

The following is a list of participants from the GRI scoping session for Petrified Forest National Park, held on June 27–28, 2001. The contact information and email addresses in this appendix may be outdated; please contact the Geologic Resources Division for current information. The scoping meeting summary was used as the foundation for this GRI report. The original scoping summary document is available on the GRI web site: http://www.nature.nps.gov/geology/inventory/gre_publications.cfm.

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