Highlights of Northern Arizona Geology

Arizona Geological Survey
DOWN-TO-EARTH SERIES 7
About the Arizona Geological Survey...

Mission
To provide unbiased geologic information to the public to enhance understanding of the geologic framework and processes in Arizona and support prudent management and use of land, water, mineral, and energy resources.

Description
Arizona Geological Survey (AZGS) staff provide information, including geologic maps, reports, data, and related information, to interested citizens, service clubs, professional societies, governmental agencies, engineering geology firms, oil and gas exploration companies, mineral exploration companies, consultants, and many other types of businesses. To obtain the information they provide, geologists map and describe bedrock and surficial materials, metallic, nonmetallic, and energy resources, and geologic processes that may be hazardous to the public or limiting to land and resource management (e.g. earthquakes, land subsidence and earth fissures, flooding). They summarize the results of their studies in reports, which are released to the public. Staff also compile and maintain computer databases and other files, a geology library, and a repository of rock cuttings and cores.

The Arizona Oil and Gas Conservation Commission, which regulates the drilling for and production of oil, gas, helium, and geothermal resources, is administered by the AZGS, which also provides staff support. Staff issue permits to drill, monitor drilling, inspect completed wells, compile drilling and production data, and maintain files of well cuttings and related information about subsurface geology. They also prepare maps that show the distribution and thickness of bedrock formations present in the subsurface, describe the character of those formations, disseminate information, and encourage the responsible exploration for and development of oil, natural gas, helium, geothermal, and related resources.

Goals
To provide unbiased information about Arizona's geologic materials, processes, and resources in a timely, courteous manner.

To map and describe bedrock and surficial geologic units and geologic processes and materials, including those that can be hazardous to residents or limiting to the use of land, water, mineral, and energy resources in Arizona.

To provide administrative and staff support for the Arizona Oil and Gas Conservation Commission, which has responsibility to protect public health and safety relative to oil and gas drilling and production.

History
The AZGS and its predecessors have provided information and assistance to Arizonans since 1889. The Office of the Territorial Geologist was established in 1881, but was not funded until 1889. To keep pace with the times, its enabling legislation and duties were updated and the agency was renamed in 1915 (Arizona Bureau of Mines), 1977 (Arizona Bureau of Geology and Mineral Technology), and in 1988 (Arizona Geological Survey). In 1991 the Oil and Gas Conservation Commission, which regulates the drilling and production of oil, gas, helium, and geothermal resources, was attached administratively to the AZGS.

For more information
Additional information about the geology of Arizona, the Arizona Geological Survey, the Oil and Gas Conservation Commission, or publications that are available for purchase, please contact us at the following address:

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Highlights of Northern Arizona Geology

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Acknowledgments

The compilation and editing of a volume such as this is easy when one starts with such well-written, interesting, previously published articles. I therefore am grateful to all of the authors: Stephen J. Reynolds, Andre R. Potochnik, Evelyn VandenDolder, and Peter Kresan for their great work. In addition to authoring one of the articles, Evelyn VandenDolder edited most of the articles when they initially appeared in Fieldnotes and Arizona Geology, and to her I am especially grateful. Peter Corrao designed, formatted, and did the layout for the publication. Some photographs were provided by Peter Kresan, Larry Fellows, Steve Richard, Jon Spencer and Meteor Crater Enterprises, Inc. In addition, Jamie Gleason, Larry Fellows, Rose Ellen McDonnell, and Jon Spencer critically reviewed portions of the manuscript and offered helpful suggestions. I sincerely appreciate the contributions made by each individual to create an interesting, informative, accurate and high-quality work.

Robin Frisch-Gleason, Compiler and Editor
Arizona Geological Survey
For about 20 years the Arizona Geological Survey (AZGS) published a 12-page quarterly newsletter, first named Fieldnotes and then Arizona Geology. In 1993 we reduced the length of each issue to four pages and we no longer use it to provide multi-page general-interest articles. The Down-To-Earth (DTE) publication series serves that purpose.

A number of concise, informative, well written articles of general interest were published in the newsletter prior to 1993. Believing that some of them were just too good to be allowed to fade into obscurity, we decided to republish them in the DTE series. The first was "How geologists tell time," which became DTE 4. That was followed by "Things geologic, a collection of writings by H. Wesley Peirce," which was published as DTE 5. Several articles about the geology of northern Arizona are included in this volume, including the Grand Canyon, petrified wood, and some of those scenic features and areas that entice visitors from many states and countries.

The AZGS has much more information about these and many other aspects of Arizona geology in our library. We welcome you to call or stop at our office for information.

Larry D. Fellows, Director and State Geologist
Arizona Geological Survey
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Introduction

For those who appreciate geologic masterpieces, Arizona is a world apart. In a state graced with the snow-capped reaches of the San Francisco Peaks, the infinite majesty of the Grand Canyon, the erosional works of art displayed in Monument Valley, the antiquity of biologic past in Petrified Forest National Monument, the cosmic collisions evidenced at Meteor Crater, and so much more, the earth-science curious have an enormous playground. Geologic history is captured in these wondrous testimonials.

Arizona Geological Survey (AZGS) geologists and their predecessors have been amassing information about the geology of Arizona since 1889. The AZGS has had the great privilege and responsibility of studying, mapping, and making accessible information on the many geologic wonders of this spectacular state and providing information critical to land-use decisions. As part of our mission, we provide a quarterly newsletter, *Arizona Geology* (formerly *Fieldnotes*), which features articles on various geologic stories of our state. Though this newsletter has a wide national readership, we reach only a very small portion of the geologically interested, but non-technically oriented public. As a result, much of the public misses out on eye-opening and fascinating articles about Arizona’s geology.

The purpose of this book is to bring together some of the many interesting articles on geologic features and phenomena that so many of us see on weekend picnics and afternoon hikes throughout northern Arizona’s wildlands, which have not been readily accessible to the general public. Though these chapters touch on a mere handful of worthy discussions, they are a first step toward introducing the mountain of useful literature for the public. To understand the geological significance of some of these features is to fully appreciate their timeless and far-reaching beauty. We hope that the following compendium of articles will enhance your understanding and appreciation of Arizona’s geologic wonders.

Robin Frisch-Gleason, Compiler and Editor
*Arizona Geological Survey*
CHAPTER 1

Geologic Features of Northern Arizona

by Stephen J. Reynolds

Introduction

Northeastern Arizona has long been famous for its rich endowment of scenic beauty and natural wonders, such as the Grand Canyon, Monument Valley, and Meteor Crater (Figure 1). How did such features form? What is the geologic story behind the scenery? Geologists and park naturalists are often asked these and other questions. Most answers are not simple.

Behind every landscape are hundreds of subtle and not-so-subtle geologic controls. An entire geologic story exists within every pinnacle, canyon, and rock layer. What concerns us here is not the detailed script of the geologic story, but the overall plot.

This article contains a short summary of the geology of northeastern Arizona, followed by a "character sketch" of the area's best known...
HIGHLIGHTS OF NORTHERN ARIZONA'S GEOLOGY

San Rafael Group, Dakota Sandstone, and Mancos Shale
Glen Canyon Group
Moenkopi and Chinle Formations
Sedimentary rocks

Generalized Geologic Map of Northeastern Arizona

Figure 2. Geologic map (modified from Cooley, 1967).

Geologic features. A list of general references is included for those interested in learning more about the geology of this fascinating region.

Geologic History of Northeastern Arizona

Northeastern Arizona is part of the Colorado Plateau physiographic province, a region of wide-open spaces and breathtaking vistas. Landscapes of the Colorado Plateau are dominated by broad plains or plateaus that are interrupted by a series of mesas, cliffs, and deep canyons. The spectacular scenery of the region is mostly due to erosion of a sequence of flat-lying sedimentary formations. Differences in color and resistance to erosion between adjacent sedimentary layers create the colorful, stair-stepped appearance that is so typical of the region.

The geologic history of northeastern Arizona began in the Precambrian Era nearly two billion years ago (see Figures 2-4), when sediments and volcanic rocks were buried to great depths and converted into metamorphic rocks by high temperatures and pressures. They were intruded by magma (molten rock) that solidified into

Figure 3. Geologic cross-section from Grand Canyon to Chuska Mountains (modified from Oetking and others, 1967).
These ancient metamorphic and granitic rocks represent the first step in the long process of building the continental crust of Arizona. They have been buried by thousands of feet of younger sedimentary rocks and are presently exposed only in the bottom of the Grand Canyon and in small areas of the Defiance Plateau. Drill holes by oil companies indicate that Precambrian metamorphic and granitic rocks underlie essentially all of northeastern Arizona.

About 1.1 billion years ago, parts of the region were invaded by shallow seas, in which sedimentary rocks of the Grand Canyon Supergroup were deposited. Sedimentation was locally accompanied by emplacement of basaltic intrusions and by eruption of basaltic lavas. Episodes of faulting occurred during and after deposition of the Grand Canyon Supergroup.

After a prolonged period of erosion that lasted about 500 million years, early Paleozoic seas invaded most of Arizona and resulted in the deposition of limestone, shale, and beach sands. Within northeastern Arizona, these sedimentary rocks are exposed only in the lower walls of the Grand Canyon. However, they reappear from beneath their cover of younger rocks along the Mogollon Rim to the south and the Grand Wash Cliffs to the west.

In the latter half of the Paleozoic Era, about 300 million years (m.y.) ago, northeastern Arizona was the site of shallow seas, extensive mudflats, and large fields of sand dunes. The resulting sequences of limestone, shale, siltstone, and sandstone are exposed in
the upper walls of the Grand Canyon and are partially exposed in Monument Valley, Canyon de Chelly, the Defiance Plateau, and the Mogollon Slope.

In the early part of the Mesozoic Era (225 m.y. ago), the region consisted of a broad coastal plain on which the Triassic Moenkopi Formation was deposited. Subsequent mountain building and volcanism to the south contributed steam-carried debris and volcanic ash that were deposited as the Chinle Formation. The Chinle Formation is exposed in the Painted Desert and in brightly-colored lower slopes of the Vermillion Cliffs, Echo Cliffs, and Paria Canyon. The next sedimentary formations deposited, those of the Glen Canyon Group, consist of red, orange, and white sandstone and siltstone that represent ancient sand dunes and river deposits. They form the upper parts of the spectacular Vermillion Cliffs, Echo Cliffs, and Paria Canyon and are also widely exposed around Glen Canyon, Navajo National Monument, and the northern Chinle Valley. These formations locally contain numerous dinosaur footprints and bones.

During the middle part of the Mesozoic Era (180-110 m.y. ago), more sandstone, siltstone, and shale were deposited by streams, wind, and ocean currents. These rocks, assigned to the San Rafael Group, Dakota Sandstone, and Mancos Shale, are most widely exposed around the periphery of Black Mesa, such as in Coal Mine Canyon. In Black Mesa, they are overlain by late Mesozoic sandstone, siltstone, and shale of the Mesaverde Group, which contains important coal resources. These rocks were deposited in deltas and shallow, retreating seas.

Near the end of the Mesozoic, the Colorado Plateau and the rest of Arizona were subjected to stresses that folded the sedimentary layers and caused some areas to be uplifted relative to others. By the start of the Cenozoic Era (65 m.y. ago) the seas had completely retreated from northeastern Arizona, never to return. The oldest Cenozoic rocks are igneous intrusions and wind-deposited sandstones, found in and around the Chuska Mountains. Much younger lake beds, stream deposits, and volcanic rocks accumulated south of Black Mesa and the Defiance Plateau. In latest Cenozoic time, intense volcanism constructed the San Francisco Mountains near Flagstaff. Volcanism has continued until very recently, as evidenced by the formation of Sunset Crater in 1065 A.D. The present episode of canyon cutting probably started within the last 10 million years.
Grand Canyon

Any discussion of geologic features of northeastern Arizona should include the Grand Canyon (Figure 5). (See Chapter 2, this volume.) The canyon is perhaps the most magnificent erosional feature on earth. It is a remarkable 277 miles long, up to 18 miles wide, and approximately one mile deep. The canyon was carved by the Colorado River and its tributaries, and widened by landslides, rockfalls, and various other types of erosion. Within a geologist’s conception of time, the canyon is a relatively young feature formed within the last 5 to 10 m.y. However, rocks exposed in the canyon walls are much older, ranging in age from almost 2 billion years to less than 250 m.y. As in most geologic settings, the oldest rocks are at the bottom. The dark, inner gorge of the canyon has been incised into Precambrian metamorphic and granitic rocks that are nearly two billion years old, almost half as old as the earth itself. The metamorphic rocks represent sedimentary and volcanic rocks that were buried to great depths and metamorphosed by high temperatures and pressures. Some granitic rocks were probably formed when the metamorphic rocks were melted.

The top of the Precambrian rocks is marked by an unconformity, a surface that represents a period of erosion that, in this case, lasted up to 500 m.y. The unconformity is overlain by Paleozoic sedimentary rocks that form the conspicuous layering in the canyon walls. The sedimentary rocks were deposited between 600 m.y. and 250 m.y. ago in shallow seas, deserts, and meandering rivers. They consist of resistant sandstone and limestone that form major cliffs, and easily eroded siltstone and shale that form gentle slopes. This sequence of sedimentary rocks is not restricted to the Grand Canyon, but extends beneath most of the Colorado Plateau of northern Arizona. Rocks of similar age reappear at the surface along the Mogollon Rim, Monument Valley, and near Canyon de Chelly.

Monument Valley

Monument Valley is another of nature’s masterpieces of erosion (Figure 6). The trademarks of Monument Valley are spectacular, steep-sided mesas, buttes, and pinnacles that rise abruptly from a nearly featureless plain. The scenery of the valley is dominated by three main sedimentary layers that are similar in age to those exposed in the upper walls of the Grand Canyon.
The lowest layer is composed of easily eroded shales and mudstones that occur in the gently sloping pedestals around each monument. The middle and most prominent layer, referred to as De Chelly Sandstone, forms a brightly colored orange and red cliff. The sandstone was originally deposited as sand dunes approximately 270 m.y. ago. It is overlain by a thin, protective cap of Triassic Shinarump Conglomerate that represents ancient stream deposits. All three layers once extended continuously over the entire Monument Valley Region, but they were gradually removed from most areas by erosion within the last 10 m.y. The "monuments" are remnants of the layers that erosion left behind.

Canyon de Chelly

Beautiful Canyon de Chelly (pronounced de-shay) is the topographic opposite of Monument Valley. Whereas Monument Valley contains isolated monuments rising above a low-relief plain, Canyon de Chelly is a deep cleft within a gently inclined plain (Figure 7). The steep-sided canyon was formed as streams eroded down through a sequence of resistant rocks that are partly the same sedimentary formations that form Monument Valley. Canyon de Chelly contains a lower, slope-forming layer, a middle cliff of brightly colored De Chelly Sandstone, and an upper protective cap of tan and brown Shinarump Conglomerate. The middle sandstone formed as part of the same field of sand dunes as the middle sandstone of Monument Valley. The original forms of the sand dunes are preserved in the rocks as a series of gently sloping layers or cross-beds (Figure 8). The cross-beds represent the fronts of ancient sand dunes and can be used to determine which way the wind was blowing when the sand was deposited 275 m.y. ago.

The actual canyon was not formed until much more recently, probably within the last several million years. At famous Spider Rock (Figure 7) the canyon is over 1,000 feet deep and 3,000 feet wide. The canyon walls become progressively lower downstream to the west because the resistant cap rock and underlying layers gently slope in that direction. The pre-historic Anasazi Indians constructed White House and other dwellings within recesses and alcoves in the sheer vertical walls.

Figure 10. Mesaverde Group, Mancos Shale, and older strata on east flank of Black Mesa. Photograph by J. Dale Naitoms.

Figure 11. Coal Mine Canyon, west of Black Mesa. Badlands topography is developed in sedimentary strata of the San Rafael Group of Mesozoic age. Photograph by Susanne Gillatt.

Figure 12. Typical Hopi Butte. Dark-colored butte is composed of late Cenozoic volcanic rocks that overlie, and are flanked by Mesozoic sandstones of the Glen Canyon Group. Photograph by Stephen J. Reynolds.
Chuska and Lukachukai Mountains

The Chuska and Lukachukai Mountains, some of Arizona’s least publicized scenic attractions, are familiar to many geologists as the site of Arizona’s largest oil field. Both mountain ranges are located in northeastern Arizona, near the New Mexico border. The Chuska Mountains are an impressive, mesa-like range that reaches elevations of over 9,700 feet and affords excellent views of Shiprock and Canyon de Chelly. The rugged and colorful flanks of the range are composed of red- and orange-colored sandstone and siltstone of early Mesozoic age (see Figure 9). These strata are successively overlain by younger, light-colored sedimentary rocks and a dark-colored cap of Cenozoic volcanic flows. Rocks beneath the Lukachukai Mountains were found in 1967 to contain significant oil deposits. This oil field accounted for nearly 90 percent of Arizona’s total oil production. Since its discovery, it has yielded over 16 million barrels of oil, which is less petroleum than Arizona presently consumes in four months.

Black Mesa

Black Mesa is one of the largest geological entities of Arizona (Figure 2). It is a more-or-less circular feature approximately 60 miles in diameter, with an area of 3,200 square miles. The mesa is a saucer-like erosional remnant of sedimentary rocks of the Cretaceous Mesaverde Group that once covered much of northeastern Arizona (Figure 3). These rocks overlie and are significantly younger than the Paleozoic sedimentary layers of the Grand Canyon, Monument Valley, and Canyon de Chelly. In fact, drilling by oil companies indicates that Paleozoic rocks are buried nearly a mile below the surface of Black Mesa. Imagine the walls of the Grand Canyon with yet another mile of rocks on top!

Sedimentary rocks of the Mesaverde Group are not as brightly colored as the older rocks that surround Black Mesa. The Mesaverde Group is composed of tan and gray sandstone, siltstones, and shales that were deposited in shallow seas, along beaches, and by streams (Figure 10). These rocks contain Arizona’s largest known deposits of coal. The coal was formed from plants that accumulated in swampy or marshy environments. The plant-rich layers were buried by younger stream and beach deposits, and were gradually
Figure 15. Meteor Crater. Walls of crater are composed of limestone and sandstone of late Paleozoic age. Rocks below floor of crater are shattered. Photograph courtesy of Meteor Crater Enterprises, Inc.

Figure 16. Sunset Crater with Bonito Lava Flow in foreground. Photograph by Stephen J. Reynolds.
Figure 17. San Francisco Mountains from northeast. Photograph by Philip A. Pearthree.

Figure 18. Aerial photograph of S P Crater and lava flow. Photograph by Larry D. Fellows.
converted into coal. Black mesa coal was first used for fuel by prehistoric Indians and will be a major energy source for the southwest U.S. many years into the future.

Coal Mine Canyon

Some extremely beautiful landscapes occur in and around Coal Mine Canyon, west of Black Mesa. Scenic badlands topography has been formed in varicolored sandstone and siltstone of the Mesozoic San Rafael Group (Figure 11). A coal seam within the sedimentary layers was evidently ignited by lightning and burned to produce brightly colored rocks resembling slag from a furnace. Locally, shale layers directly above the coal seam display exotic colors and abundant oyster fossils. The somewhat eerie aspect of the landscape is accentuated by legends of a silvery ghost that haunts the area during full moons.

Hopi Buttes

Landscapes south of Black Mesa are dominated by dark-colored buttes that stand above a surrounding red- and tan-colored terrain (Figure 12). The oldest rocks exposed near the Hopi Buttes are red-colored sandstone and siltstone of Mesozoic age. These rocks are overlain by light colored layers of Late Cenozoic sandstone, siltstone, and mudstone that were deposited in ancient Lake Bidahochi approximately 5 m.y. ago. The lake beds locally contain fossil fish and larger vertebrates such as antelope, camels, and mastodons. These rocks are in turn overlain by dark-colored volcanic rocks that were erupted onto the floor of the lake. The volcanic rocks are mostly basaltic lava flows and pyroclastic deposits composed of ash, cinders, and larger fragments. Sedimentary layers derived from the volcanic rocks are relatively common. Some buttes are true volcanic vents, whereas others are simply capped by thin lava flows. The Hopi Buttes exist because the volcanic rocks are more resistant to erosion than are the surrounding and underlying sedimentary rocks.

Painted Desert - Petrified Forest

Colorful landscapes of the Painted Desert lie mostly south and west of Hopi Buttes and extend along the little Colorado River Valley from east of Holbrook to north of Cameron. This region is characterized by extensive, low-relief plains and a series of small cliffs, ledges, and rounded hills (Figure 13). Most of the Painted Desert is underlain by variably colored sandstone, siltstone, and shale of the early Mesozoic Chinle Formation. These sedimentary rocks were deposited by meandering streams that flowed north across the region some 200-250 m.y. ago. The red, orange, pink, and purple colors in the rocks are due to oxidized iron and manganese minerals. Many of the white and gray layers contain clays that were formed by the weathering and alteration of volcanic ash. The volcanic ash was evidently blown into the area from erupting volcanoes to the west.

The Chinle Formation locally contains brightly colored petrified wood (Figure 14). [See Chapter 3, this volume.] The Petrified Forest is one of the world’s greatest concentrations of large, petrified logs. The logs were originally transported northward into the area by flooding streams and were buried by successive layers of ash, mud, and sand. Ground water percolating through the sediments dissolved silica from the volcanic ash and redeposited it in the buried logs, turning them to stone. Impurities of iron, copper, and manganese in the silica give the petrified logs their splendid color.

Meteor Crater

The tranquil appearance of the Painted Desert and Little Colorado River Valley is interrupted west of Winslow by a large, circular crater (Figures 1 and 15). This feature, well known as Meteor Crater, is over 4,000 feet wide and 550 feet deep. It is one of the most spectacular meteorite impact craters in the world. The crater was formed approximately 20,000 years ago when a nickel-iron meteorite crashed onto the flat surface of the Colorado Plateau at over 30,000 miles per hour. The meteorite is calculated to have been over 80 feet in diameter and to have largely vaporized upon impact. Sedimentary layers along the rim of the crater were upturned by the force of impact and were covered by debris blasted out of the crater. Numerous fragments of the meteorite have been found below the floor of the crater and on the surrounding plateau surface.

Sunset Crater

A different type of crater lies east of the San Francisco Mountains, approximately 30 miles
GEOLOGIC FEATURES OF NORTHERN ARIZONA

northwest of Meteor Crater. Sunset crater was produced by a volcanic eruption a little more than 900 years ago. The eruption, which occurred around 1065 A.D., marks the most recent volcanic activity in the San Francisco volcanic field. The 1,000-foot-high crater was formed when hot volcanic cinders were blown into the air, and then settled around the vent (Figure 16). Formation of the main cinder cone was accompanied by eruption of a dark, basaltic lava flow that occurs in Bonito Canyon. At the end of the volcanic episode, hot springs and vapors escaped from the vent and deposited brightly colored minerals near the top of the crater. These yellow, red, and orange minerals give the crater its color of a perpetual sunset.

Needless to say, the volcanic eruption had a profound impact on the local Indians. Prior to the eruption, Indians, now referred to as the Sinagua, lived around the San Francisco Mountains in pithouses. The spectacular, but ominous eruption, prompted many Sinigua to flee the area. After the eruption, neighboring Indians, including the Anasazi, migrated into the area to farm on the moisture-retentive volcanic ash. Multi-room dwellings, such as those preserved at Wupatki National Monument, were constructed at this time. Relentless winds eventually stripped the soil of its beneficial volcanic ash, and the Indians abandoned Wupatki and neighboring villages.

San Francisco Mountains

The San Francisco Mountains (or Peaks) are Arizona's largest stratovolcano and highest mountains (Figure 17). Humphreys and Agassiz Peaks reach over 12,000 feet in elevation and stand approximately a mile above the surrounding Colorado Plateau. The San Francisco Mountains were formed by successive eruptions of lava and pyroclastic debris within the last two m.y. The top of the volcano, which may have once been as high as 15,000 feet above sea level, has been lowered substantially by volcanic collapse and subsequent glacial erosion. The glaciers probably extended from near the crest of the peaks to near the floor of the adjacent plateau.

Surrounding the main peaks are a number of smaller volcanic vents. Elden Mountain, O'Leary Peak, and Kendrick Peak are volcanic domes similar in origin to the one presently forming in the crater of Mount St. Helens in southwestern Washington state. Numerous cones are scattered around the higher peaks. Some of these, such as S P Crater, Sunset Crater, and Merriam Crater, are recent and well preserved. Photographs of S P Crater and its accompanying lava flow appear in most introductory geology textbooks (Figure 18).

Additional Reading


Geology of Side Canyons of the Colorado

by Andre R. Potochnik and Stephen J. Reynolds

The majesty of the Grand Canyon emanates from the magnitude of its impressive dimensions. The Colorado River has cut a mighty gorge; its tributaries are no less spectacular. Trails from the rim are few, the hike is lengthy, and access to much of the canyon from above is limited; however, a river trip through the Grand Canyon, with ample time for hiking, enables one to explore many side canyons with relative ease. Unlike a view from the rim, a view from the river gives one an inside-out perspective (Figure 1). The rim view paints an overall picture of the grand-scale geologic scene. In the side canyons, one can further examine the details of geologic features and relationships that tell a more complete story.

The sequence of rocks in the Grand Canyon can be divided into four groups, each separated by a major unconformity (time break) that indicates a significant erosional episode and thus a major gap in the geologic record (Figure 2). The two oldest groups consist of Precambrian igneous and metamorphic crystalline rocks [Vishnu Group, about 1.8 billion years (b.y.) old], overlain by a tilted sequence of sedimentary rocks (Grand Canyon Supergroup, 1.4 to 1.0 b.y. old). Extensive erosion of these Precambrian rocks formed a conspicuous planar surface on which the canyon's characteristic, horizontally stratified Paleozoic rocks were deposited 550 to 250 million years (m.y.) ago. The fourth group includes a veneer of late Cenozoic sediments and volcanic rocks that were deposited during and after the period of canyon cutting, mostly 6 m.y. ago to the present. The topographic signature of the Cenozoic Era is punctuated by Canyonlands and broad pediments, features sculpted by the agents of erosion that responded to the gentle uplifting of the region to about 2 miles above sea level.

Figure 1. The Colorado River within Marble Canyon, as seen from Saddle Canyon. Photograph by Stephen J. Reynolds.
From its source in northeastern Colorado to its mouth at the Gulf of California, the Colorado River crosses four major physiographic provinces: the Rocky Mountain region, the Colorado Plateau, the Transition Zone, and the Basin and Range Province. On the final leg of its long journey across the Colorado Plateau, the river follows a sinuous course in northern Arizona through the Grand Canyon. The Grand Canyon, Transition Zone, and Colorado Plateau end abruptly at the Grand Wash Cliffs, where the river flows into the Basin and Range Province near Lake Mead. The canyon is 277 miles long, up to 18 miles wide, and a mile deep through much of its length. It passes through five structural provinces of the Colorado Plateau, each bounded by a major fault or monoclinal fold. An unusual aspect of the Colorado River is that it actually follows these structural weaknesses only twice and for a mere one-fifth of its length. Elsewhere, it boldly crosscuts these structures and flows against the regional dip of the strata (Figure 3).

In contrast, side canyons are more strongly influenced by structural and geomorphic controls such as faults, regional dip of strata, and rock hardness. Fault-controlled canyons are recognized by distinct linear trends. Side canyons that flow down the regional dip tend to be longer than those that drain into the river against the dip. Many of the larger canyons drain source areas of higher elevation and thus greater rainfall. Canyons formed in softer shales and mudstones are generally wider than those confined to the harder sandstone, limestone, and crystalline rocks. The length of time over which these controls have operated contributes to the wide variety of side canyons. The unique architectural style and attractive features of each side canyon are thus determined by a combination of factors. The nine canyons shown in Figure 3 have been chosen for this discussion because a wide range of geologic features are clearly displayed in a variety of settings.

**North Canyon**

In the first 20 miles below Glen Canyon Dam, the Colorado River cuts down through the red-colored Mesozoic rocks of the Vermilion and Echo Cliffs into the underlying cream-colored Permian rocks that form the familiar rim of the Grand Canyon. By North Canyon (mile 20 from Lees Ferry), the river has also deeply incised the underlying, rust-colored, Permian Hermit Shale and Permian-Pennsylvanian Supai Group. A hike up North Canyon reveals sculptured formations of the Supai Group, including a gray conglomerate that marks the base of the Esplanade Sandstone. The canyon walls are steep and high, textures are soft and gentle, colors are warm and soothing, and the acoustics are those of a cathedral. Only minor vegetation survives on the scoured bedrock floor, but the sacred, night-blooming Datura bush grows in abundance near the mouth of the canyon. Nearly a mile of hiking leads to a sanctuary with smooth, concave walls formed by dramatic, curved fractures in the sandstone (Figure 4). A serene plunge pool cannot be passed without a swim, intentional or otherwise (Figure 5).

**Nautiloid Canyon**

Not far downstream from North Canyon, gray- and cream-colored strata form a small cliff along the river’s shores. Through the next 12 miles, the river’s course becomes confined within the towering walls of the canyon’s single most formidable barrier to river-rim hiking: the Redwall Limestone. This fossiliferous carbonate rock was deposited in a vast shallow sea that
inundated much of western North America during Mississippian time more than 300 m.y. ago. In 1869 John Wesley Powell named Marble Canyon for the beautiful marblelike polish of the Redwall Limestone flanking the river. The limestone’s true ivory and gray colors, exposed by running water or recent rockfalls, are usually concealed by a red iron-oxide stain derived from the overlying Supai Group and Hermit Shale.

The 500-foot vertical walls of nearly pure limestone and dolomite are highly resistant to erosion in the semiarid climate of the inner canyon. Numerous solution caverns, however, were dissolved by the ground water of a more humid climate during an earlier geologic period. Many large caverns developed along vertical joints or cracks in the limestone and are particularly conspicuous near mile 35, where a large set of joints bisects the canyon.

In this vicinity, a narrow cleft called Nautiloid Canyon enters from the east (Figure 6). A short, 100-yard climb into this canyon reveals numerous fossilized remains of the chambered nautiloid. Discovered by William Breed in 1969, these fossils were the first of their kind to be found in the Grand Canyon. The polished limestone floor of Nautiloid Canyon bears many cross sections of these ancient cone-shaped creatures, which can be

Figure 3. Simplified geologic map of the Grand Canyon region.

Figure 4. North Canyon. Curved fractures and bedding surfaces occur in the Permian Esplanade Sandstone of the Supai Group. Photograph by Andre R. Potochnik.
up to 20 inches in length. The tentacle-like appendages on some specimens may be preserved soft parts. These fossils, found in the Thunder Springs Member of the Redwall Limestone, are but one of several animals preserved in this cherry rock.

**Buck Farm Canyon**

Small rapids and riffles occasionally punctuate the shady serenity of Marble Canyon as the river cuts into older Paleozoic strata downstream from Nautiloid Canyon. Only the keenest observer will notice where the river intersects the inconspicuous horizontal contact between the Mississippian Redwall Limestone and underlying Cambrian Muav Limestone. The parallel layering and similar appearance of these two red-stained limestones belies the staggering difference in their ages. Rocks representing Late Cambrian through Early Mississippian time, nearly 200 m.y. of earth history, are missing at this stratigraphic boundary. A clue to these vanished pages of time is evident in the canyon walls upstream from Buck Farm Canyon, where purplish lenses of sandy limestone 50 feet high and hundreds of feet long are sandwiched between the Redwall and Muav Limestones (Figure 7). A hike in Buck Farm Canyon near mile 40 affords an opportunity to examine closely one of these Devonian Temple Butte Limestone lenses.

The bowl-shaped cross section of these lenses suggests the following scenario of events. After deposition of the Muav Limestone in Cambrian time, vertical forces uplifted the continent above sea level, and streams carved channels into the landscape. Subsequent transgression of a Devonian sea filled these channels with impure limestone, which accumulated to even greater thicknesses in the western Grand Canyon. Both Temple Butte Limestone and Muav Limestone were then eroded down to a peneplain as the landmass once again emerged from the sea in Late Devonian time. This second erosional period so thoroughly leveled the landscape that the Temple Butte Limestone in the eastern Grand Canyon was preserved only at the bottom of channels in which it had first accumulated. A third marine advance from the west blanketed the region with the Redwall Limestone in middle Mississippian time, preserving the channel infillings in the geologic record. The relatively recent cutting of the Grand

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*Figure 5. Plunge pool within North Canyon. Photograph by Andre R. Potocknik.*

*Figure 6. A pool and dry waterfall near the mouth of Nautiloid Canyon. Photograph by Susanne Gillatt.*
Canyon affords cross-sectional views of these channels, which were originally cut some 400 m.y. ago. How did the landscape appear during the erosional intervals and what lived in the Devonian sea? The flat-lying, undisturbed nature of the Paleozoic rocks tells us that dynamic crustal activity such as mountain building, faulting, and volcanism were absent. During the first erosional episode, one can imagine a bleak, featureless landscape of Muav Limestone incised by local stream channels. Probably no plants or animals lived on land, but early, bony-plated fishes first made their appearance in the Devonian sea that inundated this landscape. The landmass once again emerged from the sea and the earliest land plants took root. The subsequent inundation by the Mississippian sea brought a much greater abundance and diversity of marine life including corals, sponges, shellfish, echinoderms, and nautiloids.
bands that form graceful, curving patterns throughout the rock (Figure 8). These Liesegang bands or “picture sandstone” effects were caused by precipitation of iron oxides in the ground-water-saturated matrix of the porous sandstone.

Evidence of the forces that uplifted the Kaibab Plateau relative to areas to the east is dramatically displayed a short distance above a large rockfall that chokes the channel. The bedding planes in the Tapeats Sandstone become tilted gently upward as one walks upcanyon until, at one point, they are abruptly bent vertically (Figure 9). The narrow gorge opens into a wide valley of rolling hills with many small tributaries that drain the soft shales of the Precambrian Chuar Group. The Kaibab Plateau, underlain by the entire Paleozoic sequence, is seen on the western skyline some 5 miles distant and 2,000 feet higher than the elevation of the same formations along the river. The sharp upturn in the strata in Carbon Canyon is a local fold caused by the Butte fault. This fault parallels a broad structural upwarp called the East Kaibab monoclina, which forms the eastern boundary of the Kaibab Plateau. A structural weakness of great antiquity, the Butte fault was a normal fault (westside down) in the Precambrian but was reactivated as a reverse fault (west side up) in late Mesozoic or Cenozoic time during uplift of the Kaibab Plateau. Cenozoic erosion has breached the monocline, causing removal of the entire Paleozoic sequence and exposure of the underlying Chuar Group shales.

**Monument Creek**

Near mile 93, Monument Creek enters the Colorado River from the south side in the deepest section of the Grand Canyon and Inner Granite Gorge. Within the walls of this side canyon are exposures of older Precambrian metamorphic and granitic rocks, whose resistance to erosion is responsible for the steep-walled, "V" shape of the Inner Gorge (Figure 10). The steep metamorphic layering and numerous convoluted folds within
the rocks recall a time when the rocks flowed like warm asphalt, as high temperatures and large horizontal stresses accompanied the collision of crustal blocks some 100 kilometers wide (Figure 11). The mountains that formed during this collision were eroded away before the Cambrian sea encroached on the landscape and buried it beneath beach sand that later became lithified or compacted to form the Tapeats Sandstone. The unconformity between the steeply dipping metamorphic rocks and the overlying, gently inclined Tapeats Sandstone is well exposed within Monument Canyon. Called the Great Unconformity, this erosional surface represents the absence of more than 1 b.y. in the geologic record.

In the more recent geologic past, boulders carried down the present canyon of Monument Creek and deposited at its mouth have partially dammed the Colorado River, causing the major rapid of Granite Falls (Figure 12). Monument Canyon, which contains remnants of a mudflow deposited in 1984, has the characteristics that a side canyon needs to form a large rapid in the river. These include a steep stream gradient; a narrow canyon with a flat floor, a sufficient supply of large boulders, and a source of fine-grained material to generate mudflows or debris flows. (Large boulders are more easily transported in a medium that is thicker than water). Monument Creek does not have a large drainage area compared to other canyons; apparently this factor is of secondary importance in creating a large rapid.

Blacktail Canyon

Inner Granite Gorge ends near Blacktail Canyon, where the regional westward dip of the strata causes the Tapeats Sandstone to descend to river level. Blacktail Canyon near mile 120 is a narrow, somewhat tubelike notch cut along the Great Unconformity between the sandstone and underlying Precambrian Vishnu Schist (Figure 13). The details of the unconformity, which is exposed along the polished walls of the canyon, are incredibly clear (Figure 14). The vertical metamorphic layering in the schist is abruptly overlain by sandstone and conglomerate derived from weathering and erosion of the schist. Thin vertical quartz veins in the schist were resistant to weathering and were eroded into small quartz pebbles now found in the basal sandstone. One can easily imagine the waves of the Cambrian sea, 600 m.y. ago, crashing onto jagged hills of schist and churning the metamorphic rock into sandy beaches as the sea advanced across the barren landscape.
Tapeats Creek

A few miles downstream from Inner Granite Gorge near mile 134, a cold and clear-flowing perennial stream called Tapeats Creek enters the Grand Canyon. The lowest rock formations of the Precambrian Unkar Group are exposed near river level. The characteristic tilt of these rocks readily distinguishes them from the more flat-lying Paleozoic rocks. A creekside path through ancient ruins and garden sites of the Anasazi Indians leads to a trail along Tapeats Creek that traverses upward through these Precambrian strata into the Paleozoic rocks. Here, Thunder Springs bursts from a cavern high in the Muav Limestone wall.

The Bass Formation, the oldest unit in the Precambrian Grand Canyon Supergroup, contains wavy, fossilized algal mats, the oldest preserved evidence of life revealed in the Grand Canyon. Bright reddish-orange shales and siltstones of the overlying Hakatai Shale contain ripplemarks and mudcracks, features that suggest deposition in a tidal-flat environment. A gradational contact between these shales and the underlying Bass Limestone indicates that Hakatai mudflats gradually displaced the algal marine environment as the Bass sea retreated from the area. The tidal flats were in turn covered by a thick sequence of sand deposited near the shoreline of a sea. Consolidation of these sands formed the overlying Shinumo Quartzite, a cliff-forming unit that forms the steep-walled, narrow canyon of upper Tapeats Creek. A sill of dark-colored diabase was formed as molten rock intruded between layers of the Bass Formation more than 1 b.y. ago. The layers in the Bass Formation were forcibly pushed apart to accommodate these lavas and reacted with the magma to form thin layers of green serpentine and fibrous chrysotile asbestos.

An upcanyon view from high on the Thunder River switchbacks reveals the angular unconformity between the Shinumo Quartzite and overlying Cambrian rocks (Figure 15). The Tapeats Sandstone, a beach sand of the advancing Cambrian sea, was deposited on the shores of a Shinumo Quartzite island that stood as a large remnant of late Precambrian erosion. As the sea deepened, the island became submerged, and offshore muds of the Bright Angel Shale were deposited across the top of the former island.

Havasup Creek

Downstream from Tapeats Creek, the regional tilt of the rock layers causes the cliff forming Paleozoic limestones, once again, to appear at river level. The confluence of Havasu Creek with the Colorado River near mile 157 is easily missed. A narrow Muav Limestone gorge obscures the enormity of this large tributary, second only to the Little Colorado River in size. A well-beaten path and gentle stream gradient encourage a hike along the 8-mile trail to the Havasupai Indian village. Havasu Creek is known for its spectacular waterfalls, and the verdant banks of this perennial, aqua-blue stream are lined with velvet ash, cottonwood, and wild grape.

Travertine deposits are perhaps the most fascinating geologic feature of Havasu Creek (Figure 16). This peculiar rock is formed by the precipitation of calcium carbonate as the creek courses through the thick Paleozoic limestones. Precipitation is augmented by warming and evaporation during the long flow to the Colorado. The travertine thus tends to encrust and take the form of any object over which the creek passes.

Distinctive features of travertine cementation are the flat-topped and sinuous “dams” so commonly seen in the creek (Figure 17). These dams form by a self-enhancing process. An
obstruction tends to catch sticks and leaves, which become encrusted with calcium carbonate, thereby increasing the size of the obstruction. When the obstruction becomes large enough, mosses colonize it and provide an additional substrate that increases its width and size. Eventually a dam will form across the channel with perhaps one or two spillways through which the stream flows. The process becomes self-restricting in the spillways because water velocity is sufficient to prevent accumulation of debris, growth of moss, and precipitation of travertine.

Whitmore Wash

Near mile 188, below the notorious Lava Falls rapids, Whitmore Wash preserves evidence of a time even more tumultuous than that experienced by the river traveler while navigating the rapids. Whitmore Wash and the area around Lava Falls contain remnants of dark basalt lava flows that once filled the Grand Canyon to a depth of more than 1,500 feet (Figure 18). The lava erupted from volcanic vents, such as Vulcan’s Throne, that pierce the Esplanade, a widespread erosional surface approximately 3,000 feet above the canyon bottom. The Esplanade formed at the top of resistant red sandstones of the Supai Group as the overlying, less resistant Hermit Shale was removed by erosion.

Many vents occur near the Hurricane Fault, a major, recently active, north-south fault that may have served as a conduit for the ascending lavas.

Figure 16. Travertine along the canyon walls of Havasu Creek. Photograph by Susanne Gillatt.

Figure 17. Travertine terraces in Havasu Creek show sinuous character and spillways. Photograph by Stephen J. Reynolds.
Upon eruption, the flows of molten lava cascaded over the walls of the Grand Canyon into the Colorado River 3,000 feet below, creating enormous clouds of steam and filling tributary canyons that drained into the Grand Canyon prior to volcanism. The lava-filled canyon of "old" Whitmore Wash is visible from river level where the main Whitmore trail climbs the north wall of the Grand Canyon into Toroweap Valley. Less than one-half mile downstream from the trail is the new Whitmore Wash, a narrow side canyon that drains the same extensive watershed as the former wash. The new wash, however, has cut into the Paleozoic limestones instead of excavating the more erosionally resistant lava that fills the old channel. In the main Grand Canyon, the dams formed by lava flows were more transient, probably surviving less than 10,000 years.

Final Comments

The canyons described above represent just a small sample of the geologic wonders and natural beauty found within side canyons of the Colorado River. Each canyon is unique, both in scenery and in the array of exposed geologic features. Short hikes within these canyons complement the river-running, which alternates between the relaxing tranquility of long, slow-moving stretches and the bursts of apprehension, excitement, and chaos within the rapids. The entire experience is difficult to describe, but impossible to forget.

Additional Reading


CHAPTER 3

Petrified Wood: Legacy from a Late Triassic Landscape

by Evelyn M. VandenDolder

The broad, lowlying flood plain is part jungle, part marsh. It is crossed by numerous meandering streams and rivers; ponds, swamps, and oxbow lakes dot the landscape. The climate is warm and moist, the vegetation lush. The thick growth includes an abundance of ferns, giant rushes, horsetails with diameters as large as 1 foot, and 1- to 4-foot-tall cycads that look like large pineapples capped by coarse leaves. Clams, snails, horseshoe crabs, and crayfish scavenge the lake and river bottoms and muddy banks. Freshwater sharks stalk the waters. Plentiful fish, some as long as 5 feet and weighing as much as 150 pounds, fall prey to giant 10-foot-long, 1,000 pound amphibians that resemble salamanders. Crocodile-like reptiles, up to 1 ton and 30 feet long, snatch fish and unwary animals that venture too close to the water.

In the distant mountains toward the south, near the headwaters of the rivers and streams, 200-foot-tall pinelike trees dominate the scene. Some are carried downstream toward the north after they are killed by insects, lightening, high winds, floods, disease, or old age. A few of these become lodged in shallow areas along the stream bottoms or on sandbars within the flood plain and are eventually covered with successive layers of sand, silt, mud, and volcanic ash.

Although the flood plain resembles the equatorial Amazon or marshy Everglades, the scene actually depicts Arizona and surrounding areas, as they were about 225 million years (m.y.) ago (Dietz and others, 1987). At that time, the landmass now called “Arizona” was part of the supercontinent Pangaea 1,700 miles toward the south near the Equator, and Arizona’s petrified logs were still living trees.

Chinle Formation

Paleontologists have pieced together this panorama of Late Triassic (208 to 230 m.y. ago) life from fossils embedded in the sedimentary layers of the Chinle Formation. This formation, one of the most widely distributed Late Triassic deposits in the world, blankets most of the Colorado Plateau, including parts of Utah, Colorado, New Mexico, and Arizona (Stewart and others, 1972). It derives its name from Chinle Valley in northeastern Arizona, where outcrops are extensive. The Navajo term chinli, which means “it flows out,” probably describes the stream that flows from Canyon de Chelly into Chinle Valley (Gillette and others, 1986).

The formation’s stream deposits of conglomerate, sandstone, siltstone, mudstone, and claystone impart the colorful tints to the Painted Desert of northeastern Arizona (Figure 1). The rainbow hues of the rounded hills were created in a warm, wet, oxidizing environment during the Late Triassic (Ash and May, 1969; Dietz and others, 1987). Faunal differences in units of the Chinle Formation suggest that it was deposited over a long period of time, during which environmental changes occurred (Gillette and others, 1986). In the Petrified Forest, where the Chinle Formation is about 932 feet thick, researchers have discovered 200 genera of fossil plants, as well as 30 species of fossil vertebrates, including dinosaurs (Gillette and others, 1986; Meyer, 1986; Ash, 1987). For this reason, some paleontologists believe that the Petrified Forest is the best place on Earth to study life as it was during the Late Triassic.

The Late Triassic age of the Chinle Formation and fossils embedded within it has been deter
however, are within the Chinle Formation in Petrified Forest National Park (Phillips and Bloyd, 1988). The park contains the largest known accumulation of petrified logs in the world (National Park Service, undated; Figure 2). Early American Indians revered the petrified logs. The navajos called the logs *Yei bitsin*, the “the bones of Yeiito.” In Navajo mythology, Yeiito was a monster whose congealing blood formed lava flows. The Paiutes believed the logs were the spears of the wolf god Sinaway that were broken during a terrible battle among the gods (Deitz and others, 1987).

About 90 percent of the petrified wood in the national park is of the species *Araucarioxylon arizonicum*, which is distantly related to the Araucarias that currently grow in South America, Australia, and New Zealand. These include the Norfolk Island pine, the monkey puzzle tree, and the bunya-bunya (Ash and May, 1969; Dietz and others, 1987). Petrified wood from two other trees, *Woodworthia arizonica* and *Schilderia adamannica*, is also present in the park, but is less common.

Some of the petrified logs measure more than 28 inches in diameter and up to 203 feet in length (Ash, 1987). Because the majority of the logs lack branches, roots, and bark and are nearly horizontal in position, researchers believe that most of the original trees did not grow in the area encompassed by the park, but were transported long distances from forested areas by north-flowing streams (Ash and May, 1969; National Park Service, undated). The giant conifers probably thrived in ancestral highlands that may have existed in what is now southern Arizona and Mexico (Peirce and others, 1985; Peirce, 1986). In-situ stumps in growing position, however, are present in the northern part of the park, which suggests that some trees also grew on the flood plain (Ash, 1987).

After the trees were transported downstream and became trapped in shallow waters, fluvial deposits of silt, mud, and volcanic ash from volcanoes to the south or west buried the logs and cut off the supply of oxygen; decay was thus retarded. Ground water percolating through the sediments dissolved silica from the volcanic ash. As the silica filtered through the logs, it precipitated from solution as microscopic quartz crystals in the woody tissues where air, water, and sap were originally present in the living tree (National Park Service, undated). In some logs, cell structure remained intact, albeit entombed.

Where the logs were hollow, woody tissue did not limit crystal growth; large crystals of rosewood are common. The cores of the logs are completely crystalline; the outer areas are more compact and resinous. Early American Indians used some of the petrified wood to make bows, and it was also used in Navajo ceremonies. Today it is used as a material for furniture, jewelry, and decorative items.

Figure 1. The variegated layers of the Late Triassic Chinle Formation are due to the presence of oxidized iron and manganese minerals (dark bands) and volcanic ash altered to clay (light bands). Photograph by Evelyn M. VandenDolder.
quartz, smoky quartz, amethyst, and other gemstones or large masses of amorphous (noncrystalline) chalcedony and chert lined the cavity walls (Ash and May, 1969). Originally, researchers believed that minerals replaced the wood fibers. In recent experiments, however, after acid was used to dissolve the minerals, the original woody tissue was visible under a microscope (National Park Service, undated).

As the silica petrified the wood, other elements in the water, such as iron, copper, manganese, and carbon, added tints of red, yellow, orange, brown, blue, green, purple, and black to the fossilized tissues. In some logs, tunnels and galleries are visible, the remains of ancient excavations dug by Triassic insects (Ash, 1987). The high degree of preservation of the logs and other fossils in the Chinle Formation is due to favorable conditions, such as warm temperatures, high moisture, and little or no oxygen, during and after deposition of the sediments (Ash and May, 1969).

Post-Triassic Geologic History

At the time the logs were swept downstream and buried beneath fluvial deposits, the area was flanked by the ancestral Rocky Mountains on the east, ancestral highlands on the south, and a volcanic arc on the west and southwest (Peirce, 1986; Ash, 1987). Pangaea (a Greek word meaning “all earth”), the supercontinent, was still intact at this time.

About 205 m.y. ago, in the Early Jurassic, Pangaea began to break up and Arizona, as part of the North American continent, slowly drifted northward. Sediments accumulated intermittently throughout the Mesozoic Era (up to about 90 m.y. ago). Some were fluvial deposits left by streams and rivers; others were marine deposits that settled in a shallow, inland sea, which inundated the area. The Chinle Formation became buried beneath 2,000 to 3,000 feet of younger sediments (Ash and May, 1969; National Park Service, undated).

Beginning about 80 m.y. ago, the entire Four Corners area was gradually uplifted, the sea retreated, and erosion began to cut down into the sedimentary layers. The stress of earth movements and the weight of overlying rocks cracked the now petrified logs. Wind and water scoured the sedimentary layers for millions of years.

About 6 m.y. ago, a large lake was created, called Lake Bidahochi or Hopi Lake, on the bottom of which sand, silt, and clay accumulated (Gillette and others, 1986). Lake Bidahochi was later drained to the west and the sculpting of the Grand Canyon began. Volcanoes in the area erupted, depositing lava and volcanic ash within and on top of the Bidahochi Formation (Shafiqullah and Damon, 1986).

Erosion removed the last rocks overlying the Chinle Formation and exposed the petrified logs and other fossils. About 300 feet of fossil-bearing strata remain buried in Petrified Forest National Park (National Park Service, undated). Erosion,
PETRIFIED WOOD: LEGACY FROM A LATE TRIASSIC LANDSCAPE

Figure 3. Governor Rose Mofford (center) signs into law Senate bill 1435 in May, 1988, naming petrified wood (Araucarioxyylon arizonicum) the official State fossil of Arizona. Proponents of the bill were, from left to right, Dr. Robert S. Dietz, Senator Doug Todd (sponsor of the bill), Mitchell Woodhouse, and Dr. Troy L. Pévé. Dietz, Woodhouse, and Pévé were from the Department of Geology, Arizona State University. Photograph courtesy of the Governor's Office.

However, continues to reveal treasures from a past life, including more petrified wood. An estimated 1/4 inch of soil is removed from the steeper slopes of the Painted Desert each year (Ash and May, 1969).

Other Petrified Forests

Petrified Forest National Monument was established in 1906 by President Theodore Roosevelt to protect this resource from exploitation by commercial interests. The Painted Desert region was added in 1932 and the monument was made into a national park in 1962. The park now encompasses 93,492 acres (National Park Service, undated).

Although the Petrified Forest of Arizona is the most famous, petrified wood has been found in all 50 States and in many foreign countries (Dietz and others, 1987; National Park Service, undated). The most notable localities are Yellowstone National Park in Wyoming; the Black Hills and Badlands in South Dakota; Florissant Fossil Beds National Monument in Colorado; central and eastern Washington and Oregon; southern Utah; western Nevada; the Catskills in New York; New Albany Forest, Indiana; Red Deer Valley near Calgary, Canada; Joggins, Nova Scotia; Patagonia, Argentina; and Cairo, Egypt (Dietz and others, 1987; National Park Service, undated).

Most of these deposits are small and scattered. What distinguishes the Petrified Forest of Arizona from other localities is the large size of the deposits and the spectacular colors in the wood. The Petrified Forest of Arizona is also older than most other petrified forests in the western United States, which are Cretaceous to Tertiary in age (younger than 144 m.y. old; National Park Service, undated).

Arizona’s State Fossil

Petrified wood probably ranks third in value as an Arizona gemstone, after turquoise and peridot (Phillips and Bloyd, 1988). Because of its relative abundance in the State, its scientific significance, and its value as a semiprecious stone, petrified wood was made the official State fossil of Arizona in May 1988 (Figure 3). Arizona joins three other States - North Dakota, Washington, and Louisiana - in revering petrified wood as a State fossil or gem (Dietz and others, 1987). Araucarioxyylon Arizonicum, once the giant of a Late Triassic landscape, is now the giant among Arizona’s fossils.

Additional Reading


CHAPTER 4

Arizona Geology: An Aerial Tour of Northern Arizona

by Peter L. Kresan

From the air, the geologic fabric of Arizona is visible as "landprints" woven into beautiful and impressive designs. Patterns reflect structure, rock type, and the geologic history written in stone. This photo essay takes you on an annotated journey over Arizona's diverse landscapes. It is by no means a complete tour, but it will introduce you to the incredibly rich geologic heritage of this region, as revealed from above.

Figure 1. An index map that identifies areas depicted in the photographs; numbers on the map correspond to figure numbers.

Figure 2. In Marble Canyon, the Colorado River cuts into the ledgy Supai Formation beneath the slope-forming Hermit Shale and overlying massive cliffs of Coconino Sandstone, Toroweap Formation, and Kaibab Limestone. Sheer Wall Rapids (river mile 14.4 from Lee's Ferry) lie at the mouth of Tanner Wash, which merges with the Colorado River (left, center). The view is to the south across the Marble platform.
Figure 3. Many of the following photographic descriptions refer to geologic eras, periods or epochs, such as Paleozoic, Triassic, or Pleistocene. These time periods have specific meaning to geologists. This geologic time scale shows the age range for each of the geologic time periods. Numbers in middle column are ages in millions of years before present (B.P).

Figures 4a and 4b. The western edge of the Colorado Plateau in northwestern Arizona is shown in this U.S. Air Force, high-angle U-2 view looking to the north northeast. The Colorado Plateau extends to the east (right side of photograph) and is comprised of nearly horizontal layers, or strata, of rock mostly from the Paleozoic era. These strata are cut by a series of near-vertical faults, called normal faults, along which there is mostly vertical (up and down) movement of the crust.

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**Geologic Time Scale**

<table>
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<tr>
<th>ERA</th>
<th>PERIOD</th>
<th>MILLION YEARS B.P.</th>
<th>EPOCH</th>
<th>Distinctive Life Forms</th>
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<td>JURASSIC</td>
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<tr>
<td>CRETACEOUS</td>
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<tr>
<td>CENozoic</td>
<td>QUATERNARY</td>
<td>0.01-1.6</td>
<td>HOLOCENE (Recent)</td>
<td>First birds and abundant dinosaurs.</td>
</tr>
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<td></td>
<td></td>
<td>3</td>
<td>PLEISTOCENE</td>
<td>First mammals; conifers and cycads abundant; first dinosaurs; rapid development of reptiles.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>24</td>
<td>MIOCENE</td>
<td>Widespread extinction of life; Spread of the reptiles; development of conifers.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>37</td>
<td>OLIGOCENE</td>
<td>Earliest reptiles; abundant insects; Coal-forming swamps are widespread.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50</td>
<td>EOCENE</td>
<td>Echinoderm abundant; diversification of fish. (Climax of bryozoans and crinoids.)</td>
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<td></td>
<td>66</td>
<td>PALEOCENE</td>
<td>First forests-gymnosperms; first amphibians; Abundant shads and fishes; abundant brachiopods.</td>
</tr>
</tbody>
</table>

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*Figure 3.*  
*Figure 4a.* Photograph courtesy of U.S. Air Force.  
*Figure 4b.* Photograph courtesy of U.S. Air Force.
as much as 2,000 feet (6,000 meters) in the Red Lake area to the south (Lucchitta and Young, 1986). The Basin and Range lies west (left) of the Grand Wash Cliffs and is characterized by a more complex array of alternating mountains (ranges) and valleys (basins) formed over the last 15 million years by extension. As the crust in the Basin and Range was pulled apart (extended) the basins differentially subsided and/or tilted.

**Figure 5.** A Pleistocene basalt flow from the SP cinder cone spilled into a series of grabens, depressions caused by the dropping of crust between two high-angle normal faults. This graben was already partially filled with an older basalt flow from Crater 160, south of SP Crater. The overall thickness of the SP flow ranges from 15-60 meters. Crater 160 is a cone of cinder, tuff and spatter, noted for its abundance and variety of xenoliths (relic pieces of country rock found embedded in volcanic deposits). (Moore and others, 1974).

**Figures 6a and 6b.** The Mesa Butte fault, SP Crater and flow, and much of the San Francisco Volcanic Field near Flagstaff are shown in this U.S. Air Force, high-altitude, U-2 photo. The view is to the south. Bill Williams Mountain, Sitgreaves Mountain, and Kendrick Peak are silicic to intermediate volcanic centers along or near the Mesa Butte fault. Red Mountain, Mesa Butte, and Shadow Mountain (not shown on this
HIGHLIGHTS OF NORTHERN ARIZONA’S GEOLOGY

photo) are prominent basaltic volcanic centers along the fault (Shoemaker and others, 1974). The San Francisco volcanic field on the southern margin of the Colorado Plateau is composed of Quaternary and late Tertiary basaltic rocks erupted from the vents marked by cinder cones, like SP and Sunset Craters. A series of intermediate to silicic eruptive centers also produced volcanoes of considerable elevation. The highest of these composite volcanoes is the 12,670-foot Humphreys Peak, the highest peak in Arizona.

Figures 7a and 7b. The Painted Desert, Moenkopi Plateau and Black Mesa are shown on this U.S. Air Force, high-altitude, U-2 image looking toward the northeast. In contrast to the Grand Canyon area where mostly Paleozoic rocks are exposed, Mesozoic sedimentary rocks predominate in this view across northeastern Arizona from Cameron. Lying at the north end of the Mesa Butte fault, the isolated Shadow Mountain cinder cone is the northernmost eruptive center of the San Francisco volcanic field. One of its basalt flows has been dated by K-Ar at 0.62 ±0.23 m.y. B.P. Flows from Shadow Mountain are approximately contemporaneous with faulting in the underlying Chinle Formation, the varicolored Triassic mudstone that forms the Painted Desert (Condit, 1974).

Unobstructed by topographic barriers and driven by strong, year-round, west-southwest wind, sand climbs the Red Rock Cliffs and forms a pattern of linear dunes, which streak across the Moenkopi Plateau (Breed and others, 1984). The entire Glen Canyon Group is exposed in the Echo Cliffs. Coal Canyon is cut in rock layers of the Jurassic San Rafael Group and Upper Cretaceous coal-bearing Dakota Sandstone. Dakota Sandstone, Mancos Shale, and Mesa Verde Group (all Cretaceous age) are widely exposed in Black Mesa, the location of Arizona’s major coal resources.

Figure 8. About 200 meters of erosion exposed the plumbing of the approximately 30-m.y.-old Agathla Peak diatreme (volcanic pipe formed by gaseous explosion) near Kayenta in northeastern Arizona. The volcanic pipe chiefly consists of breccia (a coarse-grained rock composed of angular broken rock fragments held together by a mineral cement in a fine-grained matrix) with branching dikes and sills of igneous rock. There are several hundred well-exposed diatremes in Arizona, most of which are in the Navajo and Hopi volcanic fields. The edge of the Black Mesa cuts across the horizon in this
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low-altitude, aerial oblique view to the south (Fitzsimmons, 1973; Sheridan, 1984).

**Figure 9.** Sculptured from mostly Permian sedimentary rocks involved in the Monument upwarp, these spires, buttes, and mesas constitute Monument Valley north of Kayenta in northeastern Arizona. This low-altitude, aerial oblique view pans north across the Totem Poles and Spearhead Mesa to the Mittens area. De Chelly Sandstone forms the magnificent cliffs. The slopes beneath the massive cliffs are Organ Rock Shale. The very uppermost caps of many of the buttes north of the Totem Poles are composed of thin remnants of Moenkopi Formation overlain by the Shinarump Member of the Chinle Formation; both are of Triassic age (Baars, 1973).

**Figure 10.** Entrenched meanders of the Little Colorado River form a spectacular gorge west of Cameron. Arizona State Highway 64 and the slope of the Grand View monocline cut across the upper right (west) corner of this aerial view to the south. Permian Kaibab Limestone is the rimrock, underlain by Toroweap Formation and Coconino Sandstone deep in the gorge.

**Figure 11.** The erosionally embayed Mogollon Rim at Oak Creek Canyon near Sedona marks the southern edge of the Colorado Plateau. Oak Creek Canyon in the upper left (west) corner extends north toward San Francisco Mountain near Flagstaff. The light-colored cliffs in the foreground are Permian sedimentary rocks of the

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Figure 8. Photograph by Peter L. Kresan

Figure 9. Photograph by Peter L. Kresan

Figure 10. Photograph by Peter L. Kresan

Figure 11. Photograph by Peter L. Kresan

Coconino Plateau stands out. Darker areas are either forested ground at high elevation or volcanic centers covered with black lava. The dark area in the upper right is the Shivwits Plateau. Lake Mead is just beyond but is not in view.

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Additional Reading


Figure 12. Photograph courtesy of U.S. Air Force.
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