National Park Service
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Natural Resource Stewardship and Science

Telling Time at Grand Canyon National Park

2020 Update

Natural Resource Report NPS/GRCA/NRR—2021/2246

ON THE COVER

Grand Canyon National Park. View from the South Rim showing the canyon’s three sets of rock.
Photo Credit: Chappell Aerial, courtesy NPS

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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 formal peer review by subject-matter experts who were not directly involved in the collection, analysis, or reporting of the data, and whose background and expertise put them on par technically and scientifically with the authors of the information.

Views, statements, findings, conclusions, recommendations, and data in this report do not necessarily reflect views and policies of the National Park Service, U.S. Department of the Interior. Mention of trade names or commercial products does not constitute endorsement or recommendation for use by the U.S. Government.

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Glossary

Absolute age: a numeric age in years. Numeric age is the preferred term.

Accuracy: measure of how close a numeric date is to the rock's real age

Angular unconformity: a type of unconformity or a gap in the rock record where horizontal sedimentary layers (above) were deposited on tilted layers (below). At Grand Canyon, horizontal layers of the Layered Paleozoic Rocks lie on top of the tilted rocks of the Grand Canyon Supergroup.

Basalt: a dark, fine-grained volcanic (extrusive igneous) rock with low silica (SiO_2) content

Biochron: length of time represented by a fossil biozone

Carbonate: sedimentary rock such as limestone or dolostone largely composed of minerals containing carbonate (CO_3^{-2}) ions

Contact: boundary between two bodies of rock or strata

Daughter isotope: the product of decay of a radioactive parent isotope

Detrital: pertaining to grains eroded from a rock that were transported and redeposited in another

Dike: a wall-like (planar) igneous intrusion that cuts across pre-existing layering

Diabase: a dark igneous rock similar in composition to basalt but with coarser (larger) grain size

Disconformity: a type of unconformity or gap in the rock record between two sedimentary layers caused by erosion or nondeposition where the layers are parallel to one another

Dolomite: the mineral calcium magnesium carbonate $CaMg(CO_3)_2$ that usually forms when magnesium-rich water alters calcium carbonate ($CaCO_3$)

Dolostone: a rock predominantly made of dolomite

Eon: longest subdivision of geologic time in the Geologic Timescale; for example, the Proterozoic Eon

Era: second-longest subdivision of geologic time below eon in the Geologic Timescale; for example, the Paleozoic Era

Epoch: fourth-longest subdivision of geologic time, shorter than a period and longer than a stage in the Geologic Timescale; for example, the Pleistocene Epoch

Faunal succession: the change in fossil assemblages through time which has a specific, reliable order

Foliation: tectonic layering in metamorphic rocks caused by parallel alignment of minerals due to compression

Formation: the fundamental unit in stratigraphy and geologic mapping that consists of a set of strata with distinctive rock characteristics. Formations may consist of a single rock type (e.g., Tapeats Sandstone or Redwall Limestone), or a mixture of rock types (e.g. Hermit Formation, which includes sandstone, mudstone, and shale).

Fossil: evidence of life in a geologic context usually consisting of the remains or traces of ancient life

Fossil biozone: stratigraphic unit defined by a distinctive assemblage of fossils

Ga: giga annum: billion years; in this paper, our usage implies billion years before present (or ago) when used for numeric ages

Gneiss: a high-grade metamorphic rock with strong foliation and light and dark bands of minerals

Granite: a high silica (SiO_2) pink to white intrusive igneous rock composed mainly of feldspar and quartz

Granodiorite: a gray intrusive igneous rock composed of feldspar, quartz, biotite, and hornblende with less silica (SiO_2) than granite

Group: a sequence of two or more related formations, with a stratigraphic rank higher than formation; for example, the Chuar Group is made up of the Nankoweap, Galeros, and Kwagunt formations

Igneous rock: a rock that solidified from molten material (magma or lava), either within the Earth (as an intrusive or plutonic rock) or after eruption onto the Earth's surface (as an extrusive or volcanic rock)

Inclusion: a fragment of an older rock within a younger rock

Index fossil: a fossil or assemblage of fossils that is diagnostic of a particular time in Earth history

Intrusion: an igneous rock body that crystallized underground. Intrusions may have any size or shape; large ones are known as plutons, thin ones parallel to layering are known as sills, and thin ones that cut across layering are called dikes.

Isotope: one of the forms of a chemical element (with the same atomic number) that contains a different number of neutrons

Lateral continuity: a geologic principle that sedimentary rocks extend laterally, and that if they are now separated due to erosion, they were once laterally continuous; for example, the Kaibab Formation on the South Rim is laterally continuous with the Kaibab Formation on the North Rim

Lava: molten rock erupted onto the Earth's surface

Ma: mega annum: million years; in this paper, our usage implies million years before present (or ago) when used for numeric ages

Magma: molten or partially molten rock material formed within the Earth

Member: a subdivision of a formation, usually on the basis of a different rock type or fossil content; for example, the Hotauta Conglomerate is a member of the Bass Formation

Metamorphic rock: a rock formed by recrystallization under intense heat and/or pressure, generally in the deep crust

Monadnock: a bedrock island that sticks above the general erosion level

Nonconformity: an unconformity or gap in the rock record where sedimentary layers directly overlie older and eroded igneous or metamorphic rocks

Numeric age: age of a rock in years (sometimes called absolute age)

Numeric age determination: measurement of the age of a rock in years, often through the use of radiometric-dating techniques

Orogeny: mountain building event, usually in a collisional tectonic environment

Parent isotope: the radioactive isotope that decays to a daughter isotope

Pegmatite: a type of intrusive igneous rock usually of granitic composition with large crystal size

Period: third-longest subdivision of geologic time shorter than an era and longer than an epoch in the Geologic Timescale; for example, the Permian Period

Plate tectonics: theory that describes the Earth's outer shell as being composed of rigid plates that move relative to each other causing earthquakes, volcanism, and mountain building at their boundaries

Pluton: large intrusion of magma that solidified beneath the Earth's surface

Precambrian: the period of time before the Cambrian Period that includes the Proterozoic, Archean, and Hadean eons and represents approximately 88% of geologic time

Precision: measure of the analytical uncertainty or reproducibility of an age determination

Proterozoic: geologic eon dominated by single-celled life extending from 2,500 to 541 million years ago; divided into the Paleoproterozoic (1,600–2,500 Ma), Mesoproterozoic (1,000–1,600 Ma), and Neoproterozoic (541–1,000 Ma) eras

Radioactive decay: the process by which the nuclei of an unstable (radioactive) isotope lose energy (or decay) by spontaneous changes in their composition which occurs at a known rate for each isotope (expressed as a half life); for example, the parent uranium (^{238}U) isotope decays to the daughter lead (^{206}Pb) isotope with a half life of 4.5 billion years

Radiometric dating: age determination method that uses the decay rate of radioactive isotopes and compares the ratio of parent and daughter isotopes within a mineral or rock to calculate when the rock or mineral formed

Regression: geologic process that occurs when the sea level drops relative to the land level; for example, by sea level fall and/or uplift of the land, causing the withdrawal of a seaway from a land area

Relative time: the chronological ordering of a series of events

Rift basin: a basin formed by stretching (extension) of the Earth's crust. Rift basins are linear, fault-bounded basins that can become filled with sediments and/or volcanic rocks.

Rodinia: a Neoproterozoic supercontinent that was assembled about 1.0 Ga (during Unkar Group time) and rifted about 750 Ma (during Chuar Group time)

Sedimentary rock: a rock composed of sediments such as fragments of pre-existing rock (such as sand grains), fossils, and/or chemical precipitates such as calcium carbonate ($CaCO_3$)

Schist: a metamorphic rock with platy minerals such as micas that have a strong layering known as foliation or schistosity

Silica: silicon dioxide (SiO_2), a common chemical "building block" of most major rock-forming minerals, either alone (i.e., as quartz) or in combination with other elements (in clays, feldspars, micas, etc.)

Sill: a sheet-like igneous intrusion that is parallel to pre-existing layering

Snowball Earth: a hypothesis that the Earth's surface became completely or mostly frozen between 717 and 635 million years ago

Stage: a short subdivision of geologic time in the Geologic Timescale often corresponding to the duration of a fossil assemblage

Stratigraphic age: the era, period, epoch, or stage a rock is assigned to based on its fossil biozones or numeric age

Stratigraphy: the study of layered rocks (strata), which usually consist of sedimentary rock layers, but may also include lava flows and other layered deposits

Stromatolite: a fossil form constructed of alternating layers (mats) of microbes (algal or bacterial) and fine-grained sediment

Subduction zone: a plate boundary where two plates converge and one sinks (subducts) beneath the other

Supergroup: a sequence of related groups, with a higher stratigraphic rank than group; for example, the Grand Canyon Supergroup consists of the Unkar and Chuar groups

Superposition: principle of geology that the oldest layer in a stratigraphic sequence is at the bottom, and the layers get progressively younger upwards

Tectonics: large-scale processes of rock deformation that determine the structure of Earth's crust and mantle

Trace fossil: a sign or evidence of past life, commonly consisting of fossil trackways or burrows

Transgression: a movement of the seaway across a land area, flooding that land area because of a relative sea level rise and/or land subsidence

Travertine: calcium carbonate ($CaCO_3$) precipitated by a spring; most travertine deposits also contain some silica

Unconformity: a rock contact across which there is a time gap in the rock record formed by periods of erosion and/or nondeposition

Volcanic ash: small particles of rock, minerals, and volcanic glass expelled from a volcano during explosive eruptions. Volcanic ash may be deposited great distances (even hundreds of miles or kilometers) from the volcano in especially large eruptions.

Yavapai orogeny: mountain building period that occurred approximately 1,700 million years ago when the Yavapai volcanic island arc collided with proto-North America

Zircon: a silicate mineral ($ZrSiO_4$) that often forms in granite and other igneous rocks and incorporates uranium atoms, making it useful for radiometric dating

Executive Summary

Grand Canyon National Park is all about *time* and *timescales*. Time is the currency of our daily life, of history, and of biological evolution. Grand Canyon's beauty has inspired explorers, artists, and poets. Behind it all, Grand Canyon's geology and sense of timelessness are among its most prominent and important resources.

Grand Canyon has an exceptionally complete and well-exposed rock record of Earth's history. It is an ideal place to gain a sense of geologic (or *deep*) time. A visit to the South or North rims, a hike into the canyon of any length, or a trip through the 277-mile (446-km) length of Grand Canyon are awe-inspiring experiences for many reasons, and they often motivate us to look deeper to understand how our human timescales of hundreds and thousands of years overlap with Earth's many timescales reaching back millions and billions of years.

This report summarizes how geologists tell time at Grand Canyon, and the resultant "best" numeric ages for the canyon's strata based on recent scientific research. By best, we mean the most accurate and precise ages available, given the dating techniques used, geologic constraints, the availability of datable material, and the fossil record of Grand Canyon rock units. This paper updates a previously-published compilation of best numeric ages (Mathis and Bowman 2005a; 2005b; 2007) to incorporate recent revisions in the canyon's stratigraphic nomenclature and additional numeric age determinations published in the scientific literature.

From bottom to top, Grand Canyon's rocks can be ordered into three "sets" (or primary packages), each with an overarching story. The Vishnu Basement Rocks were once tens of miles deep as North America's crust formed via collisions of volcanic island chains with the pre-existing continent between 1,840 and 1,375 million years ago. The Grand Canyon Supergroup contains evidence for early single-celled life and represents basins that record the assembly and breakup of an early supercontinent between 729 and 1,255 million years ago. The Layered Paleozoic Rocks encode stories, layer by layer, of dramatic geologic changes and the evolution of animal life during the Paleozoic Era (period of ancient life) between 270 and 530 million years ago.

In addition to characterizing the ages and geology of the three sets of rocks, we provide numeric ages for all the groups and formations within each set. Nine tables list the best ages along with information on each unit's tectonic or depositional environment, and specific information explaining why revisions were made to previously published numeric ages. Photographs, line drawings, and diagrams of the different rock formations are included, as well as an extensive glossary of geologic terms to help define important scientific concepts.

The three sets of rocks are separated by rock contacts called unconformities formed during long periods of erosion. This report unravels the Great Unconformity, named by John Wesley Powell 150 years ago, and shows that it is made up of several distinct erosion surfaces. The Great Nonconformity is between the Vishnu Basement Rocks and the Grand Canyon Supergroup. The Great Angular Unconformity is between the Grand Canyon Supergroup and the Layered Paleozoic Rocks. Powell's term, the Great Unconformity, is used for contacts where the Vishnu Basement Rocks are directly overlain by the Layered Paleozoic Rocks. The time missing at these and other unconformities within the sets is also summarized in this paper—a topic that can be as interesting as the time recorded.

Our goal is to provide a single up-to-date reference that summarizes the main facets of when the rocks exposed in the canyon's walls were formed and their geologic history. This authoritative and readable summary of the age of Grand Canyon rocks will hopefully be helpful to National Park Service staff including resource managers and park interpreters at many levels of geologic understanding; the glossary helps explain geoscience terms and the references cited section provides up-to-date peer reviewed resources for deeper inquiry.

Acknowledgments

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AM would like to thank Andy Hubbard, acting Program Manager for the Chihuahuan Desert I&M Network and Program Manager for the Sonoran Desert I&M Network, for his support of this report.

We all thank the staff of Grand Canyon National Park. For over 100 years, they have protected this magnificent landscape for past, present, and future enjoyment, inspiration, and investigation. Many staff members led or participated in research to understand the canyon. Every year, NPS staff educate hundreds of thousands of visitors and students about Grand Canyon and its rich geologic history, through publications, exhibits, programs, and personal contacts.

Foreword: Once Upon A Time at Grand Canyon

Vincent L. Santucci, Senior Paleontologist. National Park Service

Given the many ways to view the Grand Canyon, the temporal perspective of "time" represents one of the most unfathomable intellectual concepts associated with the ancient landscape. The Grand Canyon is a place where Father Time converged with Mother Earth to create one of the most recognizable geologic features on Earth. Our views of the canyon are measured in hours, days, weeks, years, and human lifetimes. However, the canyon's extensive pre-human history involves more than 1.8 billion rotations around the sun, including at least 647 billion cycles of sunrises and sunsets.

Attempts at telling the "science behind the scenery" at Grand Canyon collectively involve the research, field work, experimentation, and reporting by many thousands of geologists and other scientists. The first scientific publication known to mention Grand Canyon was published by Edward Hitchcock in 1857. According to archivist and historian Earle Spamer, the largest category of scientific publications dedicated to the Grand Canyon focus on the geology and paleontology, totaling more than 7800 dedicated articles (E. Spamer, pers. comm., October 2020).

Despite the tens of thousands of publications devoted to Grand Canyon, new scientific investigations and research continue to expand our understandings and shape our interpretations. *Telling Time at Grand Canyon National Park* by Karl Karlstrom, Laura Crossey, Allyson Mathis and Carl Bowman, presents a comprehensive and well-written synthesis of past and current geologic research and interpretations of "deep time" at Grand Canyon. The authors present essential details of the park's long geologic history in order to highlight the principle events and processes that originally formed and then reshaped the canyon over time. This contribution will be an important new resource for a wide audience of students, scientists, park staff, and the public, while also serving to inspire future inquiry and discovery within the Grand Canyon!

1 Introduction

This paper is about *time* and about telling time at Grand Canyon National Park (NP). It is designed as a *one-stop* summary for resource managers, park interpreters, and others to obtain up-to-date numeric ages for Grand Canyon rocks and geologic events based on current (2020) research. One portrayal of geologic time is shown in Figure 1. *Rock Captures Time* refers to the depth of geologic time, measured in billions of years, and the stories told by different rock units. *Time Carves Canyon* reminds us of the millions of years it took for the river and erosion to carve through rock to shape canyons and landscapes. *Canyon Reveals Rock* summarizes multiple time scales – the very old rocks exposed by the actively carving Colorado River in the walls of the relatively young Grand Canyon.

With one of the clearest exposures of the rock record and a long, diverse geologic history, Grand Canyon NP is an ideal place to gain a sense of geologic (or *deep*) time, especially given the great antiquity of those rocks. The oldest basement rocks exposed in the canyon (Figure 2) are ancient; 1,840 million years old. The Kaibab Formation, the youngest of Grand Canyon's strata, holds up both the North and South rims. The Kaibab is 270 million years old, and was deposited prior to the age of the dinosaurs. Today's canyon is geologically quite young, having been carved in the past 5–6 million years. Younger deposits within Grand Canyon, including Ice Age fossils in caves, 1,000 year-old lava flows that cascaded into the western canyon (Figure 3), recently-deposited debris flows, and river sediments that record oscillating climates and human influences, bring Grand Canyon's geologic record to the present.

The geology of Grand Canyon and the long time frames encoded by its rocks can be hard to comprehend. One prominent effort to make the geologic history of Grand Canyon and the age of the rocks exposed within it more relevant to the public is the Trail of Time, a geologic timeline exhibit near Grand Canyon Village (Figures 4 and 5). The Trail of Time follows the Rim Trail between Yavapai Geology Museum and Grand Canyon Village and affords spectacular vistas, interpretive panels, and has samples of Grand Canyon rocks to see and touch. Also, it is a memorable and accessible family hike.

Grand Canyon NP was established in 1919 and has been enlarged to encompass most of the physiographic Grand Canyon in northern Arizona (Figure 6). It is one of the most famous and highly visited parks in the National Park System, attracting visitors for many reasons. It has diverse animals and plants in ecosystems that span desert to mountain life zones. Its human history traces cultures back to more than 10,000 years ago. Its beauty has inspired artists and poets. Its societal importance involves all of these aspects and more. Behind it all, geology is its most prominent and important resource.

Figure 1. The icon for the Trail of Time exhibit at the South Rim of Grand Canyon reflects a cyclic view of the interactions between time, rock, and erosion.

The first geologists who explored and studied Grand Canyon included John Strong Newberry, who was part of the Lieutenant Joseph Christmas Ives expedition of 1857–1858, and John Wesley Powell, who led the famous 1869 expedition down the Colorado River. They classified and correlated the canyon's rock units based on fossils and the geologic knowledge that was available at the time. Early studies of Grand Canyon geology could only describe the age of Grand Canyon rocks in the broadest of parameters. With the later development and refinement of techniques that determine the numeric ages of rocks, geologists developed the ability to know the ages of rocks exposed in Grand Canyon with greater accuracy and precision. Advancements in geologic dating techniques are part of a renaissance of geologic research in the canyon that accelerated in the late 1990s.

Mathis and Bowman (2005a; 2005b) recognized the need for a list of numeric ages that would be broadly available to nontechnical audiences and produced the first compilation of "best" numeric ages of Grand Canyon rocks, with best meaning the most accurate and precise ages available. The constraints on determining the best ages for each rock unit include the inherent limitations of the dating techniques used, the availability of datable material and/or fossils present in each rock unit, and the quality and quantity of relevant geological observations. In turn, scientific understanding of Grand Canyon geology and how dating techniques are used to obtain the age of rocks are part of the expert opinion also needed to ascertain the best numeric values.

Scientific research since 2005, as well as the opening of the Grand Canyon Trail of Time on the South Rim in 2010, has resulted in numerous refinements in Grand Canyon's stratigraphy and improved dates for many of the canyon's rock layers. After 15 years, a revision and expansion of the original publication is needed. This report provides a 2020 update on the best ages geologists have determined for Grand Canyon rocks.

Park Significance

Grand Canyon is one of the planet's most iconic geologic landscapes. The purpose of Grand Canyon National Park is to preserve and protect its natural and cultural resources, and the ecological and physical processes of Grand Canyon along with its scenic, aesthetic, and scientific values for the benefit and enjoyment of the public (NPS 2017). Geology has always been recognized as central to the canyon's significance, from its description as "the

Figure 2. Earth history revealed: Vishnu Basement Rocks at the canyon's bottom are nearly 2 billion years old. The youngest of the Grand Canyon strata on the South Rim skyline was deposited about 270 million years ago. The canyon landscape has been carved in only the past 5–6 million years (CHAPPELL AERIAL PHOTO/COURTESY NPS).

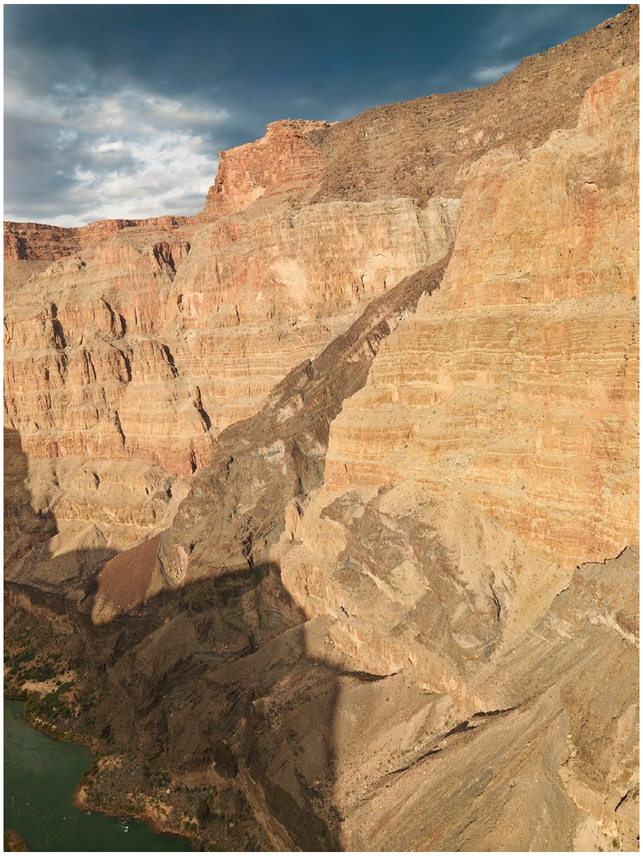

Figure 3. Lava flowed into the western Grand Canyon during the past 600,000 years. This cascade is called Devils Slide. The age of these younger surficial deposits help researchers understand modern landscape evolution (CHAPPELL AERIAL PHOTO/COURTESY NPS).

greatest eroded canyon in the United States" (1908 proclamation of Grand Canyon National Monument by Theodore Roosevelt) to its designation as a UNESCO World Heritage site for being "among the Earth's greatest ongoing geological spectacles."

Grand Canyon is probably the single location on the planet that provides the best opportunities for both researchers and students to learn about geology (Spamer 1989). The canyon remains an important field laboratory for active researchers. It also provides great opportunities for informal and formal science education via promotion of national and global geoscience literacy, both on site and remote learning. One of the goals of this paper is to help lower barriers that can separate active research from education efforts and park management.

The national park contains most of the 277-river-mile (446-km) long canyon from Lees Ferry to the Grand Wash Cliffs, and covers 1,217,403.3 acres (487,350 hectares) or 1,904 square miles (4,950 square kilometers). Rocks exposed in Grand Canyon's walls record approximately one third of the planet's history, from the Precambrian (Proterozoic Eon) to the Permian Period of the Paleozoic Era, and contain important information about the evolution and history of life (Santucci and Tweet 2020). These strata, along with younger deposits within the canyon, illustrate much of the tectonics, evolution, and geologic history of the western United States.

All of the park's natural and cultural resources are intertwined with its geology and geologic history. Therefore, telling geologic time and the challenge of helping visitors relate human and geologic timescales are important parts of the resource management and interpretive efforts at Grand Canyon NP. Geologic time also provides the framework for understanding much more than bedrock geology, such as water supply for the park's 6.5 million annual visitors, the waxing and waning of flow in the Colorado River, the history and future of mining in the Grand Canyon region, analysis of geologic hazards, and the nature and interaction of Grand Canyon's ecosystems under changing climate regimes.

A full understanding of geologic time encompasses diverse geologic topics including plate tectonics, stratigraphy, historical geology, paleontology, and geomorphology. Advances in understanding the history of our planet often begin in a well-exposed and well-known location like Grand Canyon, but quickly extend to include other areas. Grand Canyon is connected to other national parks on the Colorado Plateau, such as Arches, Bryce Canyon, and Zion that share an overall geologic history, and has a common erosional history with other parks located along the Colorado River and its tributaries, such as Black Canyon of the Gunnison NP, Colorado National Monument (NM), and Lake Mead National Recreation Area. On an even broader scale, Grand Canyon's rock record provides important information about the tectonic history of North America as it contains data about the formation of new continental crust early in its history and has been influenced by current tectonic environments. Grand Canyon is one of many park areas that has had an outsized role in the development of the science of geology in North America and an important locale for increasing geoscience literacy in the public. Many such park areas have been formed by dramatic events in planet's history (Lillie 2005).

The Need for Numeric Ages

When someone's objective is simply to learn how old a rock layer is, sorting through the technical geologic literature, the subdivisions of geologic periods, and the scientific names of microscopic index fossils, can be confusing. Most non-geoscientists will find a description of the Kaibab Formation as from the Permian Period not particularly meaningful, much less a description that involves a more specific fossil stage. Moreover, the intricacies of how geologists tell time by using both relative and radiometric dating techniques can add to the complexity.

Nevertheless, people generally understand a numeric age, such as the Kaibab Formation being 270 million years old. Therefore, numeric ages are essential when resource managers, park interpreters, educators, and guides communicate geology to the public and to one another. But finding such numbers in the scientific literature is not always easy. Some studies report only the stratigraphic age or the broad geologic era or period of a rock unit and do not use numeric ages (see Geologic Timescale and Geologic Dating Techniques). Moreover, scientific papers that do publish radiometric age determinations are not always clear about the geologic significance of these dates. For example, a radiometric date on zircon crystals found in an igneous rock measures the time when the rock (and the zircons within it) crystallized. But dates on zircon grains found within a sedimentary rock only provide a maximum age for the sedimentary rock since the grains themselves crystallized in an older igneous rock that was eroded to become a sediment source. Grains within a sedimentary rock inherently must be older than the rock itself.

Unfortunately, telling geologic time seems mysterious to many people without backgrounds in Earth science. Naturally, a non-geoscientist may wonder, “How do you know that?” when a geologist or park interpreter says, “That rock formed 270 million years ago.” To add to the confusion, both technical and popular

Figure 4. Visitors ponder geology, rock exhibits, and the views near the “time zero” portal on the main Trail of Time (NPS/MICHAEL QUINN).

literatures report a wide variety of numeric ages for Grand Canyon rocks. Further, popular accounts may not always utilize the most current research. For example, one publication may say that the Kaibab Formation is 270 million years old, while another says 255 million years old. The same inconsistencies arise for the other rock units in the park. Audiences may be left wondering which are the correct (or best) ages and why. At worst, they may discount the scientific methods used to measure deep time. Geologists know that these changes reflect the scientific process itself. Scientists continually apply new research, dating methods, and critical analysis of previously published works to refine the understanding of the age of rock units.

Previous Compilations of Numeric Ages

Nature Notes 2005

The first systematic compilation of best numeric ages was issued in 2005 in the then-Grand Canyon NP publication *Nature Notes* (Mathis and Bowman 2005a; 2005b). While they did not conduct geologic research themselves, these authors extensively consulted with geoscientists investigating Grand Canyon's geology and reviewed the technical literature in order to prepare their compendium. The *Nature Notes* compilation did not include specific ages for every rock unit exposed in Grand Canyon, but provided numeric ages or range of numeric ages for most of the canyon's prominent units.

These numeric ages were also published in *Park Science* (Mathis and Bowman 2007) and *Boatman's Quarterly Review*, a publication of the Grand Canyon River Guides (Mathis and Bowman 2006a; 2006b; 2006c). They were also presented to the public in park-produced publications and in ranger interpretive programs, and used elsewhere such as in the *Yardstick of Geologic Time* (Mathis 2006).

The Trail of Time 2010

The Trail of Time on the South Rim is a geology timeline installed along the spectacular Rim Trail (Figures 3 and 4). Bronze markers set every meter (a long step) along the trail represent one million years of Earth's history. The 2,000 steps between Yavapai Geology Museum and Grand Canyon Village cover the last 2,000 million (2 billion) years, encompassing Grand Canyon's rock record. Rock specimens were collected along the river and brought up to be placed at their age (their "birthday") along the timeline. The Early Earth Trail extends beyond the village to Maricopa Point and the age of the Earth at 4,560 million years ago. The Trail of Time was funded by the National Science Foundation with in-kind support from Grand Canyon NP. It opened in 2010 (Karlstrom et al. 2008). The Trail of Time project was the culmination of 25 years of research on the geology of Grand Canyon and the age of its rocks by the Trail of Time team, and is still an active bridge between research advances and geoscience education.

One of the challenges of the exhibit development was determining the proper age for each rock. Because the Trail of Time is a timeline and includes samples of all the major named units in Grand Canyon, it

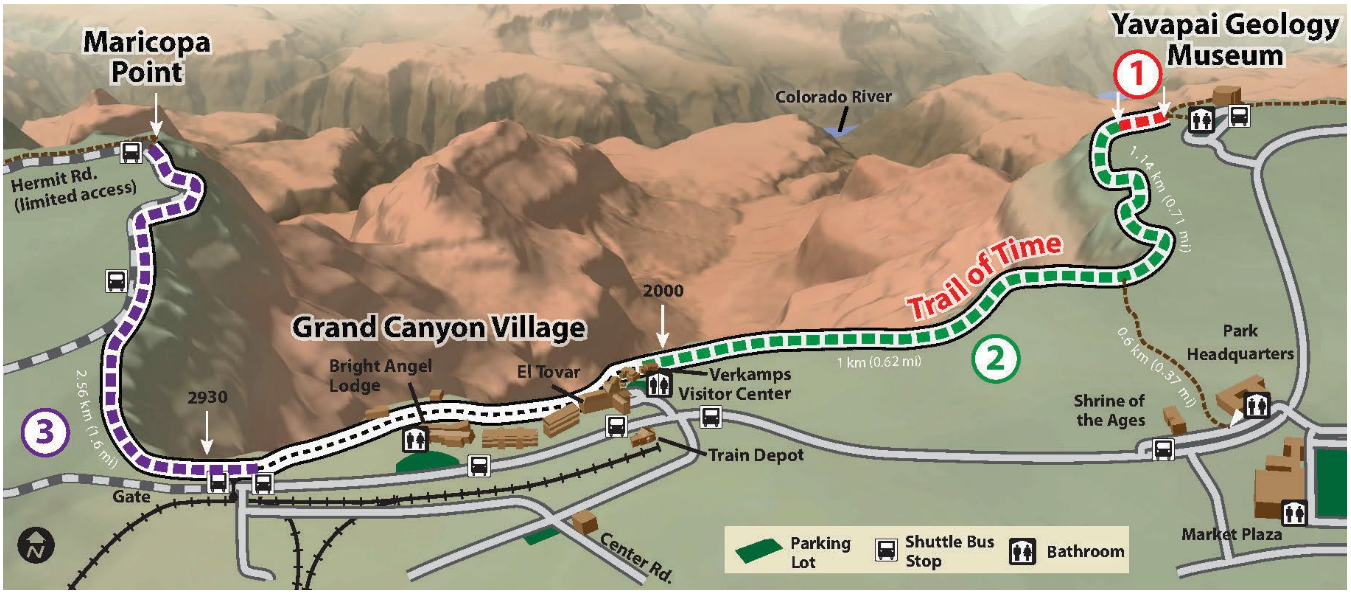

Figure 5. Perspective view of the Grand Canyon Village area on the South Rim of Grand Canyon. The Trail of Time exhibit extends from Yavapai Geology Museum to the Village, and then to Maricopa Point. The numbers and colors refer to segments of the Trail of Time: 1 = Million Year Trail; 2 = Main Trail of Time; 3 = Early Earth Trail.

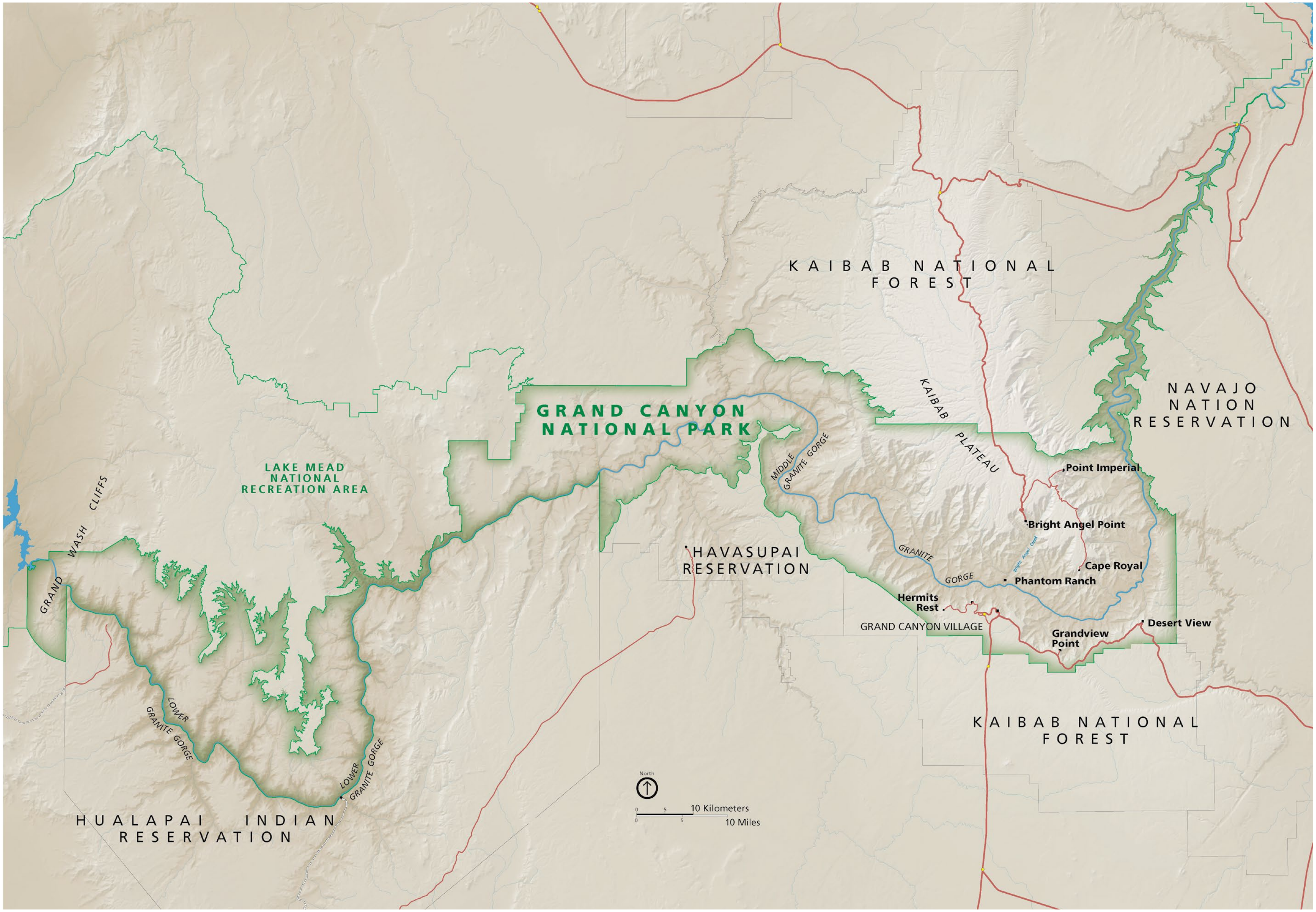

Figure 6. Grand Canyon National Park and associated federal lands in northern Arizona now include nearly the entire Grand Canyon from Lake Powell to Lake Mead.

required that individual units be placed at specific age markers along the trail. This was complicated. For example, sedimentary rocks required a simplification because sediments are laid down and turned to rock over intervals that span millions of years, rather than at a single age as shown in a time marker. Also, many rocks still do not have measured numeric ages so that the Trail of Time will change as new scientific age discoveries are made.

Trail of Time Companion 2019

Karlstrom and Crossey (2019) published *The Grand Canyon Trail of Time Companion*, a book and walking guide to provide additional layers of information for visitors. This recognizes the concept of multiple knowledge hierarchies (Perry 2012) that focuses on the learning journey of each visitor. Hence, the goal is to help each visitor move up the hierarchy from whatever their level of entry may be. The *Companion* also summarizes the making of the Trail of Time exhibit. And, in one section, the rock samples that are displayed along the trail provide a narration of Grand Canyon's geologic history, told (as if) by the rocks themselves. The *Companion* incorporated new research on the age of Grand Canyon rocks, including revisions to the stratigraphy of the Grand Canyon Supergroup and the Paleozoic Tonto Group, as well as refinements to the ages and nomenclature of many rock units.

2 Background and Methods

Geologic Timescale and Geologic Dating Techniques

Historians identify major periods in human history and broad global eras with descriptive terms such as the Stone Age or the Renaissance that do not rely on specific dates but relate various periods of history that are more or less defined in the public's mind. But historians have an advantage over geologists because people are more familiar with these terms and can infer the period of time from them.

Geologists have similar temporal subdivisions in the Geologic Timescale (Figure 7). The Paleoproterozoic, Mississippian, and Pliocene all define spans of time, but most laypeople are less familiar with these terms nor could they put them in chronological order.

Scientists use two major categories of geologic dating techniques, relative dating and numeric (or absolute) dating, to determine how old rocks are and identify major intervals in Earth's history.

Relative age dating determines the order in which a sequence of geologic events occurred (e.g., bottom-to-top sequential deposition of sedimentary strata, then carving of a geologically young canyon through those strata), but cannot determine how long ago events happened.

The Geologic Timescale (Figure 7) was first constructed by geologists in the 1800s before the discovery of radioactive decay that provides the clock used in many numeric dating techniques. Hence, it was originally based entirely on relative dating and stratigraphic principles, such as the principles of superposition, lateral continuity, and the change in fossil assemblages through time (faunal succession). Geologists depend on index fossils and fossil biozones to help constrain the relative ages of sedimentary rocks containing fossils. Index fossils are fossils or assemblages of fossils that are diagnostic of a particular time in Earth history. Fossil biozones are stratigraphic units defined by the fossils that they contain. Most of the Paleozoic sedimentary rocks exposed in Grand Canyon contain a rich fossil record that provides important information about their age.

The Geologic Timescale is regularly updated and refined. This study utilizes the most recent version of the International Stratigraphic Chart (v 2020/01) (Cohen et al. 2013, updated).

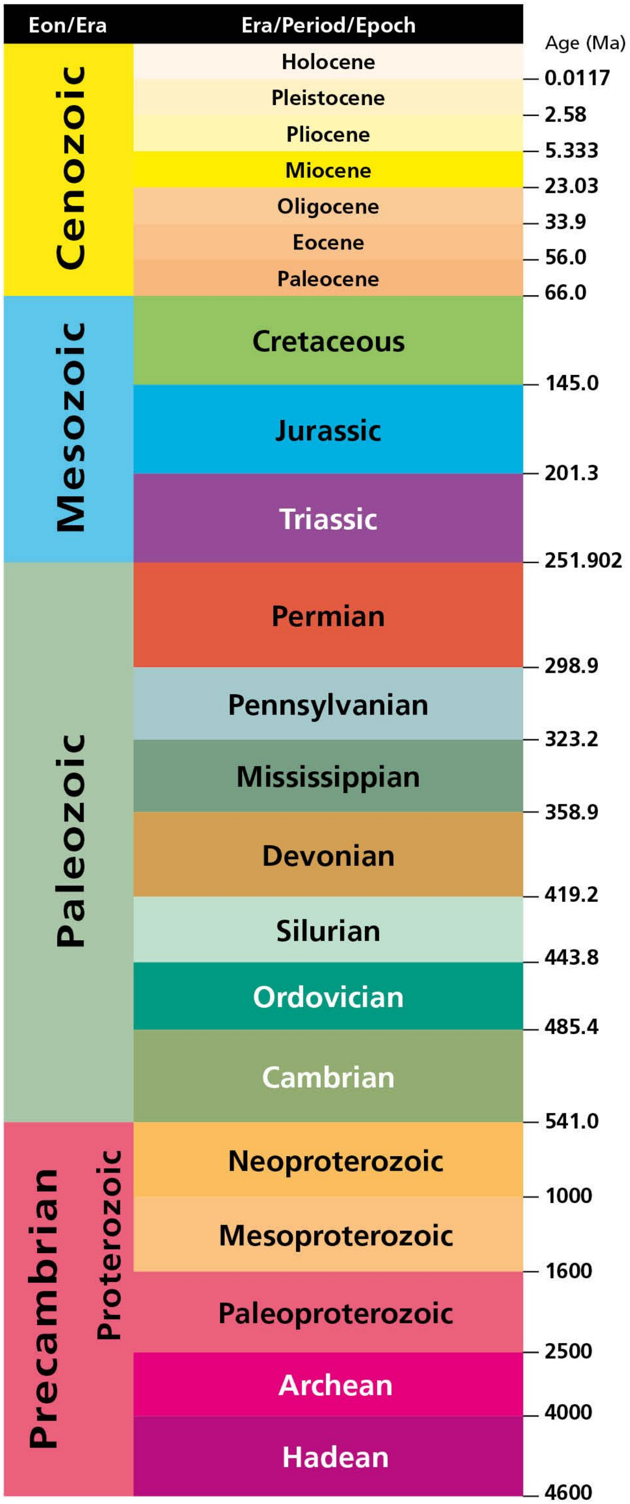

Figure 7. The Geologic Timescale is made up of Eons, Eras, Periods, and Epochs. Geologists generally made these subdivisions based on evolving life forms. Time period boundaries are from the International Stratigraphic Chart v 2020/01 (Cohen et al. 2013, updated).

The primary subdivisions of geologic time (Figure 7) follow the major events in the evolution of life and history of the planet. These are: Hadean Eon (referring to the underworld), Archean Eon (beginning life), Proterozoic Eon (earlier life), Paleozoic Era (old life), Mesozoic Era (middle life), and Cenozoic Era (recent life). Grand Canyon contains important rock records from the Proterozoic and the Paleozoic.

Numeric Ages

Absolute age determinations identify when in years specific events occurred. Rather than the term *absolute*, we prefer numeric because the ages are refined and updated as radiometric dating techniques improve. A variety of radioactive elements, each with its characteristic decay rate (and half life), have been used for numeric dating. Different elements can be used for different time spans, and/or to cross-check numeric dates obtained via other methods. Geologists identify these techniques by their radioactive parent and stable daughter elements and have used many of them, including uranium-lead (U-Pb), potassium-argon (K-Ar), rubidium-strontium (Rb-Sr), and rhenium-osmium (Re-Os), to determine numeric ages of Grand Canyon rocks.

For igneous rocks, radiometric age determinations directly measure when the minerals crystallized from a magma, essentially at the same time that the rock formed. For metamorphic rocks, most age determinations reflect the time when minerals formed during metamorphism or the time of cooling following metamorphism.

Sedimentary rocks are harder to date because most grains within them were not formed when the sediment was deposited. But several circumstances are particularly helpful in determining the age of a sedimentary rock. Some sedimentary rocks include discrete layers of volcanic ash containing datable igneous minerals that were deposited with the sediment as ash fall deposits from a distant eruption (Figure 8A). Ash may also be reworked by rivers or oceans after its initial deposit. In these cases, the age of the ash bed indicates the maximum age for the enclosing sedimentary rock since the original ash fallout deposit must have occurred before it was reworked into the sedimentary rock. Another circumstance is when an igneous intrusion cuts across a sedimentary unit (Figure 8B). In this case, the age of the dike provided a minimum age for the sedimentary rock.

Dating detrital zircons (zircon crystals that eroded from igneous rocks and deposited in sedimentary rocks) (Figure 8C) is another technique that can help constrain the numeric age for sedimentary rocks by providing the maximum depositional age.

Every analytical method used in scientific investigations, including radiometric age determinations, has a certain analytical error or precision that is expressed as a plus or minus from the measured age. Precision is different than accuracy, which is how close the measured date is to the *real* or *actual* age. Different dating techniques have different precisions due to limitations of the analytical equipment, while accuracy depends on a variety of geologic factors as well as the soundness of the relevant geological observations and interpretations. Geologists who use radiometric age determinations strive to both accurately and precisely measure geologic events by improving laboratory methods, controlling for geologic complexities, and applying multiple dating techniques when possible. Ages reported in the more recent geologic literature are commonly more precise and more accurate than ages

Figure 8A. Sedimentary rocks can be dated directly if they contain an igneous layer that was deposited within the sedimentary layers, like a volcanic ash. This 1-cm-thick ash bed in the uppermost Chuar Group provides a direct date of 729 ± 0.9 million years (LAURIE CROSSEY).

Figure 8B. The age of sedimentary rocks can be bracketed by cross-cutting igneous rocks; in this case, the black dike cuts across, and hence, is younger than the reddish Hakatai Shale. This dike is dated as 1,104 ± 2 million years old (LAURIE CROSSEY).

published in the older literature due to advances in dating techniques.

Each new numeric age within a stratigraphic sequence brackets the age of the units above and below it. Thus each new date provides cross-checks, and leads to increasingly well-known ages and durations.

Best Numeric Ages

This compilation of best numeric ages serves an important scientific purpose given the history of previously-reported numeric ages for Grand Canyon rocks, ongoing research into the age of Grand Canyon rocks, the difficulty in determining the ages of many rock units, and Grand Canyon's geologic significance. This paper can be used as a single source of up-to-date ages (as of 2020), including new dates obtained after installation of the Trail of Time exhibit. The primary audiences for this work are park managers, resource specialists, interpreters and naturalists

Figure 8C. The age of sedimentary rocks can also be bracketed by the age the youngest dated sedimentary grains (detrital zircon) within the sediment.

(including NPS rangers, commercial guides, authors, and publishers), but this compilation will also be useful to other geologists and geology students. Our goal was to develop a single list of updated numeric ages that users could apply consistently, thereby facilitating better comprehension of the geologic history and features of Grand Canyon. Research moves forward and the scientific excitement of obtaining new knowledge about old rocks is an important part of Grand Canyon's geologic story.

These best ages still have limitations and are approximations in some ways given the complexities of how rocks form through time, and are subject to revision as our understanding of Grand Canyon geologic history improves. For example, let us analyze the 1,840 Ma (mega annum; million years old) age of the Elves Chasm pluton (Figure 9), the oldest dated rock in Grand Canyon (Hawkins et al. 1996). The precision of the analytical measurement is within one million years; in other words, we are 95% sure that if we dated these same grains repeatedly using the same method (uranium-lead on zircon crystals), we'd get an age within a million years either side of 1,840 Ma. The accuracy of this date depends on not just the dating method, but also anything that may have happened to the grains to partially reset their geologic clock after crystallization. Fortunately, zircon crystals contain two different uranium isotope parents that decay at different rates to two different lead isotope daughters so that a single grain gives two independent dates that cross-check each other to produce highly accurate and precise ages. But outcrops of the Elves Chasm pluton are geologically complex. Figure 9 shows that dark inclusions were surrounded by

Figure 9. Specimen of the Elves Chasm pluton on the Trail of Time (left) and sketch (right); gd indicates the lithology of the main pluton (granodiorite) shown in gray, older inclusions are in purple and the younger granitic dike is in red (PHOTO: NPS/MICHAEL QUINN; SKETCH: KARL KARLSTROM).

and hence are older than the main Elves Chasm magma, then both were cross-cut by younger dikes. Thus, for full disclosure, only the main magma body crystallized 1,840 ± 1 million years ago, not the older inclusions or the younger dikes.

As mentioned above, sedimentary units present a still different complexity in determining their best age. Sedimentary rocks are usually deposited over long time periods so a single number is technically not correct even though it is of use for characterizing ages of rock units. The Bass Formation was deposited as a lime mud in shallow seas and contains stromatolites, the oldest visible/macroscopic fossils in Grand Canyon (Figure 10). Its best age is 1,255 ± 2 million years ago based on a U-Pb radiometric age determination on a volcanic ash bed within this unit. But the Bass Formation is more than 328 ft (100 m) thick and undoubtedly took many million years to deposit.

Fossiliferous sedimentary rocks often have well-known stratigraphic ages although numeric ages are commonly not available. For example, the Redwall Limestone (Figure 11) contains a distinctive assemblage of fossils. These fossils and the use of fossil biozones and the International Stratigraphic Chart v 2020/01 (Cohen et al. 2013, updated) indicate that the Redwall Limestone is late Early to Middle Mississippian in age (which is about 340 million years old). Again, the deposition of this unit likely occurred over a period of a few million years.

Grand Canyon Three Sets of Rocks

Beginning with John Wesley Powell (Powell 1875), geologists have recognized three main packages of rocks exposed in Grand Canyon (Figure 12; Table 1). The Vishnu Basement Rocks are the igneous and metamorphic rocks of the three Granite Gorges. The Grand Canyon Supergroup consists of tilted, mostly sedimentary rocks. The Layered Paleozoic Rocks

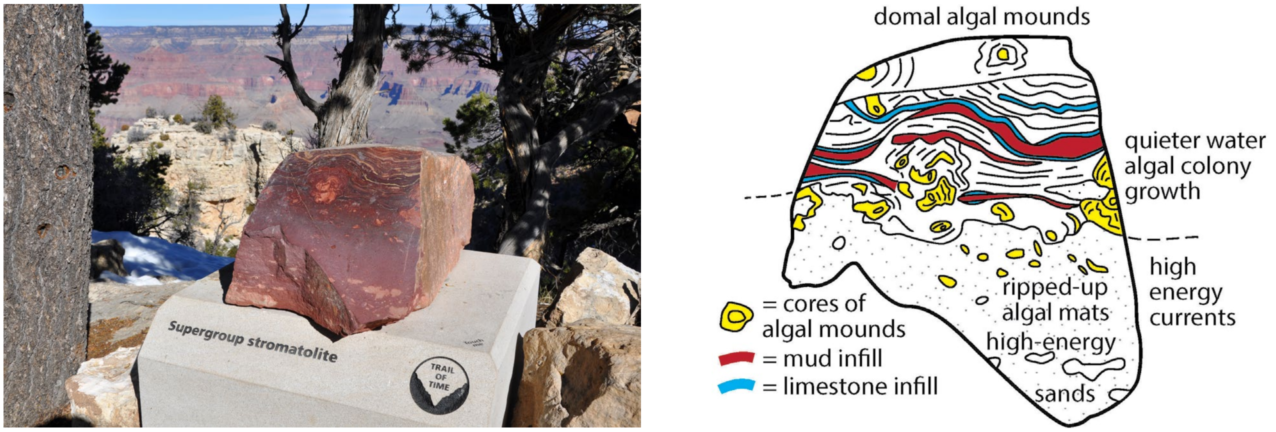

Figure 10. Specimen of the Bass Formation on the Trail of Time. This rock was deposited as a lime mud and contains the oldest fossils (stromatolites) in Grand Canyon. An ash bed within this formation was dated at 1,255 ± 2 Ma (PHOTO: NPS/ MICHAEL QUINN; SKETCH: KARL KARLSTROM).

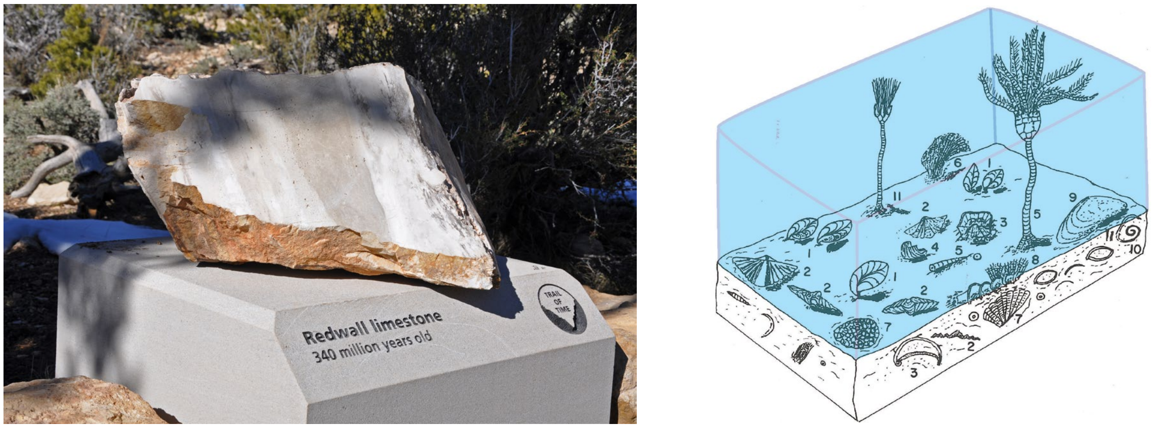

Figure 11. Redwall Limestone specimen on the Trail of Time (left). Diverse marine fossils are found in it including crinoids (1,2), bryozoa colonies (6,8), bivalves (9), and snails (10) that help constrain its age (PHOTO: NPS/MICHAEL QUINN; SKETCH: MODIFIED FROM STAN BEUS).

form the flat-lying strata in the upper two-thirds of the canyon.

Mathis and Bowman (2005b) first used the informal term "set" to refer to Powell's three main packages of rocks (Figure 12). This term is not part of the formal stratigraphic naming system of supergroups, groups, formations, and members, but is closest to the supergroup level and is convenient and very visual for Grand Canyon. Within these three main groupings of rocks are six packages at the group stratigraphic level, 35 individual formations, and numerous members,

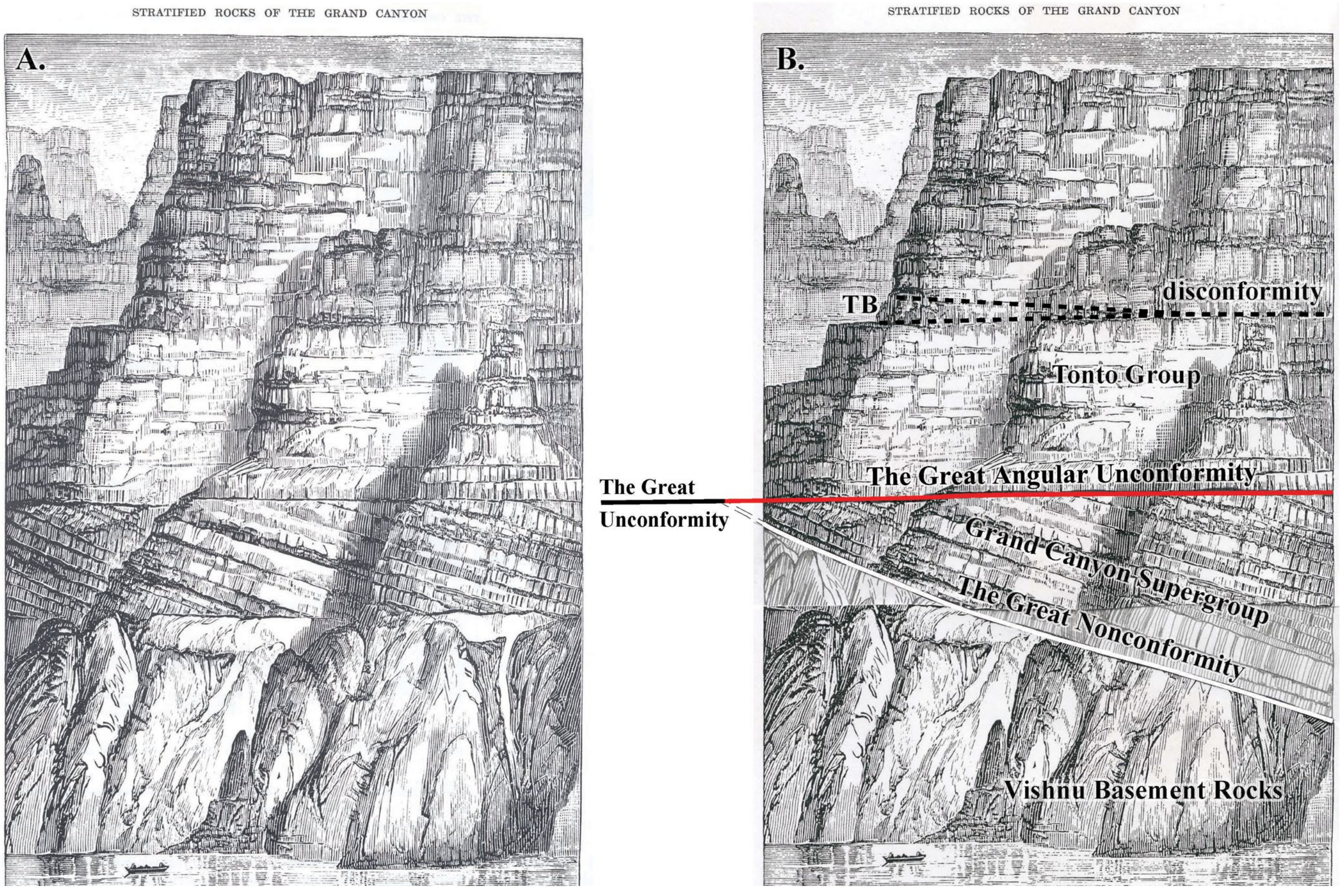

Figure 12. John Wesley Powell (1875) recognized the three main packages of rocks exposed in Grand Canyon (left). The image on the right shows newer names and an important correction; note how the contact between the Vishnu Basement Rocks and the Grand Canyon Supergroup was tilted the same amount as the overlying Grand Canyon Supergroup prior to the deposition of the Layered Paleozoic Rocks.

Table 1. Grand Canyon's three sets of rocks

Set	Rock Types	Environment	Age (Ma)
Layered Paleozoic Rocks	Horizontal sedimentary rock layers	Low coastal plain and shallow seas of the continental shelf along the proto-Pacific coast	Paleozoic Era 270–530
Grand Canyon Supergroup	Tilted sedimentary and igneous rock layers	Rivers and shallow seas far from the active plate margin as the supercontinent Rodinia assembled (Unkar Group) and rifted apart (Chuar Group)	Meso- and Neoproterozoic Eras (Precambrian) 729–1255
Vishnu Basement Rocks	Metamorphic and igneous rocks with vertical folds and foliation	Originally in volcanic island chains that collided with ancestral North America to form the southwest United States; rocks were metamorphosed and invaded by magmas in the deep crust.	Paleo- and Mesoproterozoic Eras (Precambrian) 1375–1840

Ma = mega annum = million years ago

with a total of more than 100 formal stratigraphic units named at Grand Canyon.

The Vishnu Basement Rocks consist of the ancient metamorphic rocks that formed and were intruded by igneous rocks in the deep crust nearly 2,000 million (2 billion) years ago. They have undetermined thickness because the original sedimentary succession has been intensely folded so the originally horizontal layering is now subvertical (Figure 13).

Grand Canyon Supergroup strata, only exposed in the eastern Grand Canyon, are late Precambrian sedimentary and volcanic rocks predominantly deposited in rift basins from about 729 to 1,255 million years ago. These strata are about 12,000 feet (3,600 m) thick (Figure 14).

The Layered Paleozoic Rocks include the flat-lying sedimentary rocks in the "stair-step" upper canyon walls throughout Grand Canyon (Figure 15). These strata are 3,000–5,000 feet (900–1,500 m) thick (Figure 16). The layers record many changing environments from shallow oceans to large sand dunefields, and the history of life on Earth about 530 to 270 million years ago.

Significance of Grand Canyon's Rock Record

Grand Canyon NP's rock record has global significance and provides important information about the geologic history of the southwestern portion of the North American continent (Timmons and Karlstrom 2012).

The Vishnu Basement Rocks provide one of the best views into the early history of North America in the Colorado Plateau region where outcrops of basement rocks are few. The history of the Vishnu Basement Rocks can be compared to rocks of similar age exposed in Colorado NM, Black Canyon of the Gunnison NP, Rocky Mountain NP, and elsewhere in and around the Colorado Plateau. Together, these exposures provide a synthesis of the early history of North America (Whitmeyer and Karlstrom 2007) that can then be compared to similar rocks on other continents (e.g., Karlstrom et al. 1999) to reconstruct global plate configurations.

The Grand Canyon Supergroup provides one of the best records in North America of the Proterozoic Eon from 1.25 to 0.7 Ga. Similar rocks of this age exist only in a few places like at Death Valley NP, central Arizona, and the Uinta Mountains in northern

Figure 13. Vishnu Basement Rocks were tightly folded during plate collisions 1.7 billion years ago in the Yavapai orogeny. These folds are such that estimating original sedimentary thickness is difficult. The layers in this picture are Vishnu (light colored) and Brahma (dark colored) schists (LAURIE CROSSEY).

Figure 14. Chuar Group shales in the Chuar Valley. The Grand Canyon Supergroup cannot all be seen in one view (LAURIE CROSSEY).

Utah. Hence, the Grand Canyon record anchors the scientific understanding of the geologic history of this time period (Timmons et al. 2005).

Units in the Layered Paleozoic Rocks are also proving to be of global importance, especially for understanding the Cambrian Period (Karlstrom et al. 2018). Together with the mostly younger rocks exposed in the rest of the Colorado Plateau, Grand Canyon provides one of the world's best sedimentary rock records for studying the evolution of life.

Missing Time

The rock sets are separated by sharp and interesting rock contacts known as unconformities that represent gaps in the rock record (Figure 12). There has been considerable work trying to assign numeric ages to the time missing along the unconformities to complement knowledge of the time recorded by rocks. As noted by Grand Canyon's preeminent stratigrapher and former park naturalist Eddie McKee (1969): "These unconformities were discussed by Powell (1875, p. 212), who pointed out that each represents a sequence of events of tremendous importance in Earth history, including the formation of mountains by tectonic forces, the erosion of these mountains to a condition of base level, and finally, the burial of the erosion surface by sediments of advancing seas."

For clarity, Karlstrom and Timmons (2012) introduced different names for Grand Canyon's major unconformities, in addition to designating them by their overlying rock unit. They used Powell's original term, the Great Unconformity, for the contact below the Tonto Group where the Layered Paleozoic Rocks overlie the Vishnu Basement Rocks (Figures 17 and 18). There is approximately 1.2 billion years (or about 30 percent) of Earth history missing (e.g., not recorded) at this contact. The name Great Nonconformity was used to refer to the contact below the Grand Canyon Supergroup where it overlies the Vishnu Basement Rocks (Figure 18). This sub-Supergroup contact can represent up to 500 million years of missing record when the Vishnu Basement Rocks were exhumed by erosion from 12 mile (20 km) depths. The term Great Angular Unconformity is used for the contact between the Layered Paleozoic Rocks and the Grand Canyon Supergroup; this contact can span up to 750 million years of missing rock record.

Lipan Point is an outstanding viewpoint where all of these three unconformities can be seen in one place (Figure 19). The view reveals how the Great Unconformity is a composite erosion surface representing the merger of the Great Nonconformity and the Great Angular Unconformity. All three

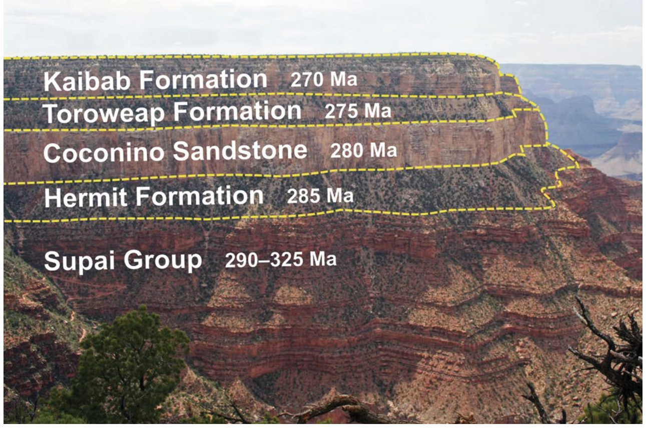

Figure 15. The topmost (youngest) of the Layered Paleozoic Rocks seen from the South Rim's Trail of Time (LAURIE CROSSEY)

Figure 16. The Layered Paleozoic Rocks as viewed from the Hermit Road on the South Rim (NPS/MICHAEL QUINN)

unconformities are also visible from Yavapai Geology Museum and numerous places near Grand Canyon Village (Figure 20). Another kind of unconformity is a disconformity, a gap in time across a contact between sedimentary strata above and below it (Figure 21). Disconformities are present between some formations in the Layered Paleozoic Rocks (Figure 22).

An evaluation of the unconformities present between Grand Canyon's sets of rocks and within them reveals three important concepts (Figure 23). First, the vertical mile of rock revealed in Grand Canyon looks like a spectacularly complete rock record, but more time is missing in it than is preserved. While it is tempting to equate missing time with unknown events, this is not entirely true. By looking at the rock layers on either side of an unconformity, a geologist may deduce significant events that occurred in the gap. For example, during the Great Nonconformity, erosion reduced a rugged mountain landscape to a nearly smooth plain with a prodigious amount of erosion over a prodigious amount of time. Second, we can assign numeric ages to the time missing along the unconformities based on the best numeric age of rocks directly above versus directly below these erosion surfaces. Third, it is often possible to understand part of what went on across a given unconformity by looking elsewhere, sometimes nearby as in the case where the Grand Canyon Supergroup is present between the basement and the Layered Paleozoic Rocks, or more globally.

Figure 17. The Great Unconformity is the erosional contact that separates the vertical layering of the Vishnu Schist (below) from horizontal bedding of the Paleozoic Rocks (above) (LAURIE CROSSEY).

Figure 18. The Great Unconformity above the Granite Gorge has Vishnu Basement Rocks below the white line and the Layered Paleozoic Rocks above it. At this location, there are 1.2 billion years (about 25 percent of Earth history) missing (not recorded) across this contact (LAURIE CROSSEY).

Figure 19. The Grand Canyon Supergroup is not exposed everywhere, but this view, looking north from Horseshoe Mesa in eastern Grand Canyon, shows the Great Nonconformity (white line) with the 1.25 Ga basal Grand Canyon Supergroup resting on the 1.75 Ga Vishnu Basement Rocks. Up to 500 million years of Earth history is missing (not recorded) at this contact. Also shown is the Great Angular Unconformity (red line) where the 510 Ma Layered Paleozoic Rocks rest on the tilted 1,100 to 1,250 Ma Unkar Group of the Grand Canyon Supergroup, with 590 to 740 million years of history missing (not recorded) along this contact. These two profound erosion surfaces come together to form the Great Unconformity (black line) where the Layered Paleozoic Rocks overlie Vishnu Basement Rocks (black line) (CARL BOWMAN).

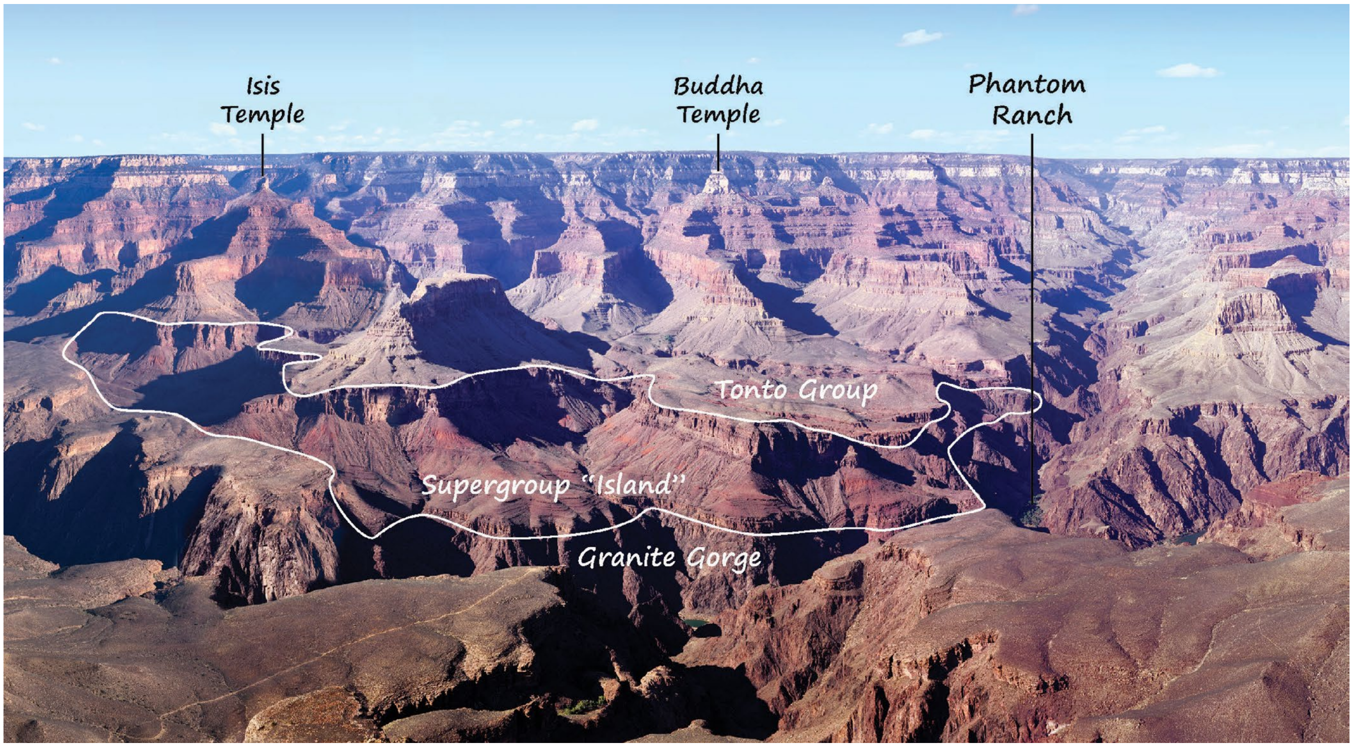

Figure 20. View from the center window of Yavapai Geology Museum. Vishnu Basement Rocks are at the bottom of Grand Canyon in the Granite Gorge. Look within the layers to see the ancient island (monadnock) of tilted Grand Canyon Supergroup rocks that was fringed by 505 million year old beach sands and eventually got covered up by muds of the Tonto Group as the lowest layers of the Layered Paleozoic Rocks accumulated (LAURIE CROSSEY).

Figure 21. Some disconformities, like this minor one in the Supai Group between the Esplanade Sandstone and Watahomigi Formation, are subtly revealed by a pebble conglomerate layer left at the end of a period of erosion in the Supai Group (CARL BOWMAN).

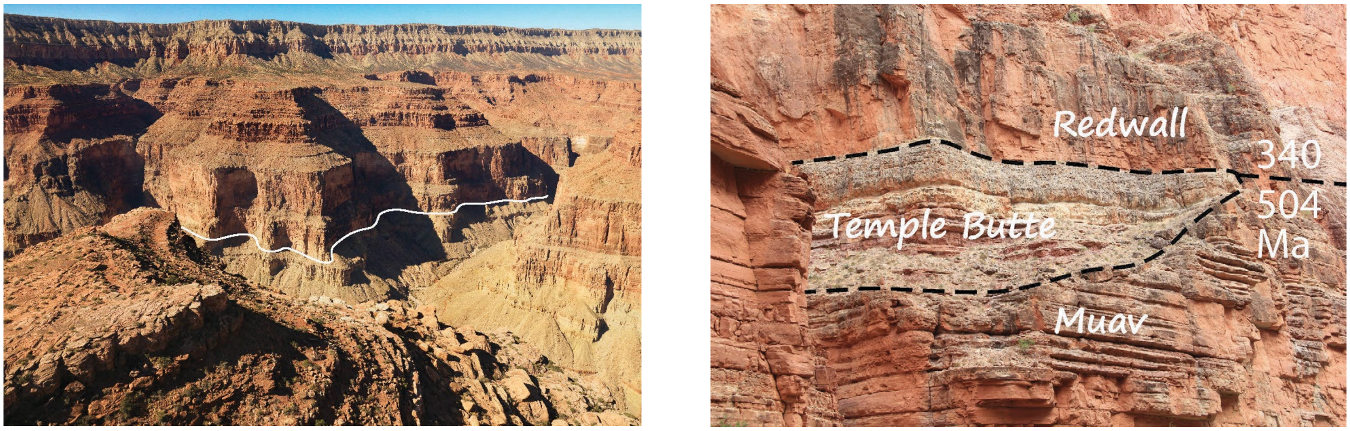

Figure 22. A major disconformity occurs at the base of the Redwall Limestone (along line) (left). Without the fossil evidence, it would be hard to recognize that about 150 million years of rock record is missing along this flat lying contact. In detail, in eastern Grand Canyon, one can see channels that reveal some of the missing layers (right) (LEFT: CHAPPELL AERIAL PHOTO/COURTESY NPS; RIGHT: LAURIE CROSSEY).

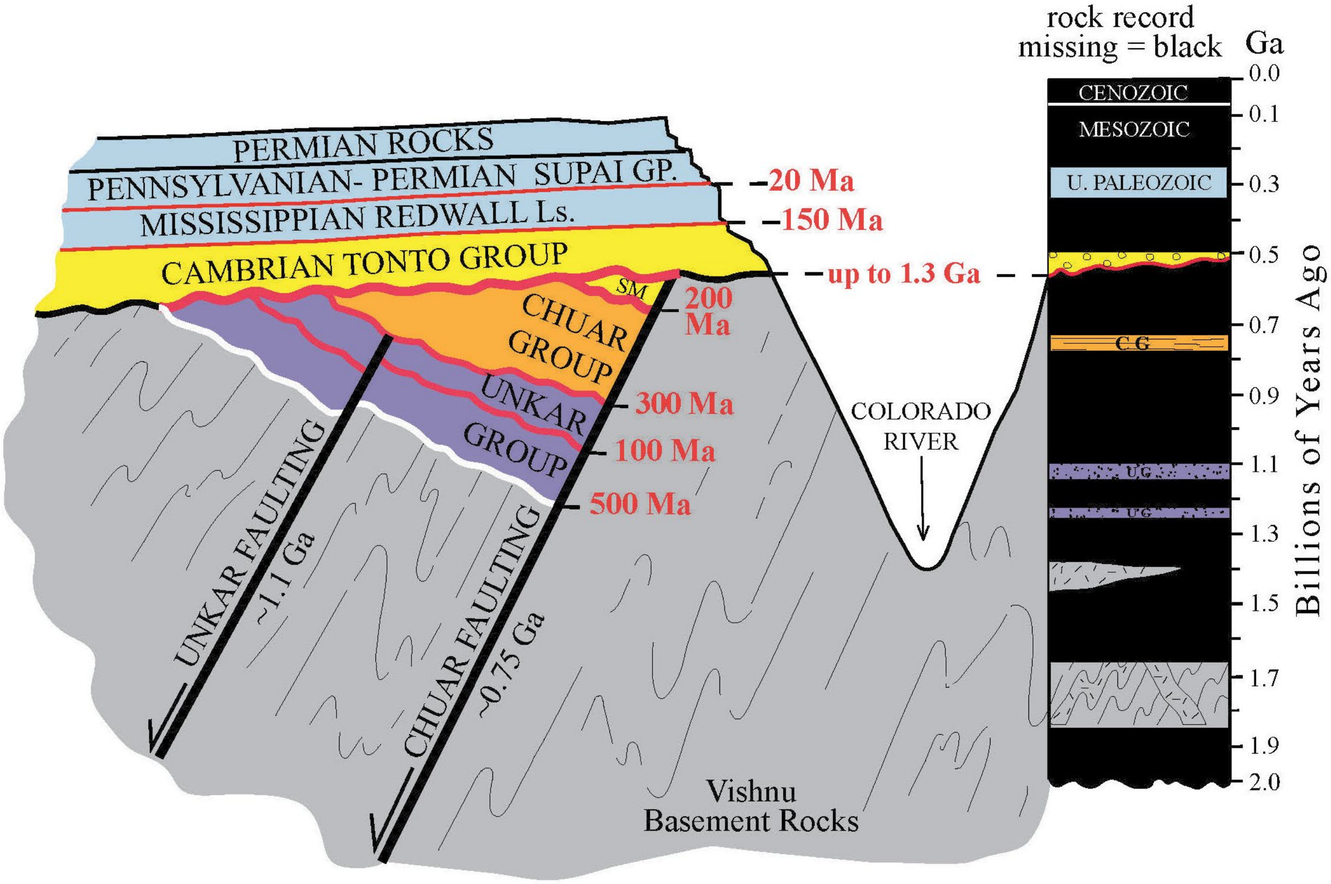

Figure 23. Rock and Time. Grand Canyon has one of the world's most complete geologic records, yet more time is missing (black = time not recorded in the column on the right) than preserved. We assign approximate numeric ages to the time missing along the unconformities based on the age range of rocks directly above versus below these erosion surfaces. Note that the modern erosion surface on top of the Kaibab Formation has 270 million years missing. Diagram does not show all formations and unconformities in the Layered Paleozoic Rocks because of space considerations.

3 The Numeric Ages of Grand Canyon Rocks

Grand Canyon's three sets of rocks are categorized based on stratigraphic position, age, physical characteristics, and overall geologic history (Figure 24).

Vishnu Basement Rocks

We use the informal name Vishnu Basement Rocks for the ancient crystalline rocks at the bottom of the Grand Canyon as first established by Mathis and Bowman (2005a; 2005b) because formal nomenclature does not encompass all of Grand Canyon's metamorphic units and all individual igneous plutons. The terminology uses "Vishnu" because the public is familiar with the Vishnu Schist and "basement" to indicate the type of rock assemblage and its position. These rocks span from 1,840 to 1,375 Ma (Table 2), a duration of 465 million years. A nominal age of about one and three quarter billion years ago (1.75 Ga) focuses attention on the tectonic collisions that added this tract onto the North American continent and is a general number for the age of the Vishnu Basement Rocks.

Our updates to the age of the Vishnu Basement Rocks consisted of identifying informal groupings and providing the age of individual plutons and metamorphic units (Tables 2, 3, and 4). The *Nature Notes* compilation (Mathis and Bowman 2005a; 2005b) only provided numeric ages for the igneous and metamorphic rocks as a whole, and did not present ages for individual igneous plutons or the three metamorphic units as shown in the Trail of Time or in this report. The *Nature Notes* compilation also excluded the Quartermaster granite, which is significantly younger than the rest of the basement rocks. We also updated the name of the Elves Chasm Gneiss to the Elves Chasm pluton as the numeric age reflects its igneous origin, not its later metamorphism (Table 4).

The many reliable radiometric age determinations of the Vishnu Basement Rocks were obtained using the U-Pb method on the mineral zircon (Hawkins et al. 1996; Ilg et al. 1996; Karlstrom et al. 2003). It was a challenge to present the geologic significance of these dates in a meaningful context for non-geologists. We settled on breaking up the basement rocks into five informal groupings reflecting distinct time periods and tectonic histories (Tables 2 and 3). Of these groupings, only the Granite Gorge Metamorphic Suite (Ilg et al. 1996) and the Zoroaster Plutonic Complex have been formally defined in the geologic literature.

The Elves Chasm pluton (1,840 Ma) (Figure 9) is the oldest basement identified in Grand Canyon. It is only exposed in the vicinity of Elves Chasm near River Mile 115. The age of this rock reflects its crystallization age from magma. Since it is an intrusive rock, it must have intruded older rocks, but these rocks have not yet been identified.

An unconformity of 90 million years separates the Elves Chasm pluton from the overlying Granite Gorge Metamorphic Suite, which consists of the 1,751 Ma Rama Schist and the 1,750 Ma Vishnu and Brahma schists. The Brahma and Rama schists originated as volcanic rocks, and the Vishnu Schist as sedimentary rocks. These rocks were deposited in volcanic island arcs that were later welded to the growing continent in the Yavapai orogeny approximately 1,700 Ma. They were metamorphosed during the mountain building event when the folds and vertical foliation that characterize these units was developed (Figures 25 and 26).

These rocks were intruded at great depths by two main types of magma: an early group of granodiorite plutons, and a later group of granite plutons and pegmatite dikes. Most of the granodiorite intrusions are part of the Zoroaster Plutonic Complex (Babcock et al. 1990). These plutons formed during the Yavapai orogeny and were likely related to the magma chambers that fed the volcanic arcs above subduction zones and range in age from 1,740 to 1,713 Ma.

Later granites and dike swarms (Figure 27 and 28) formed more than 12 mile (20 km) below the surface due to crustal melting during the plate collisions that thickened and metamorphosed the crust during the Yavapai orogeny. These plutons and dikes can be differentiated from plutons in the Zoroaster Plutonic Complex by cross-cutting relationships and differences in composition. They are also slightly younger in age, ranging from 1,698–1,662 Ma.

The Quartermaster pluton in the western Grand Canyon is substantially younger than the rest of the Vishnu Basement Rocks at 1,375 Ma. It is part of a belt of similar-age plutons that extends from southern California to Labrador that formed during a period of crustal melting due to later plate collisions.

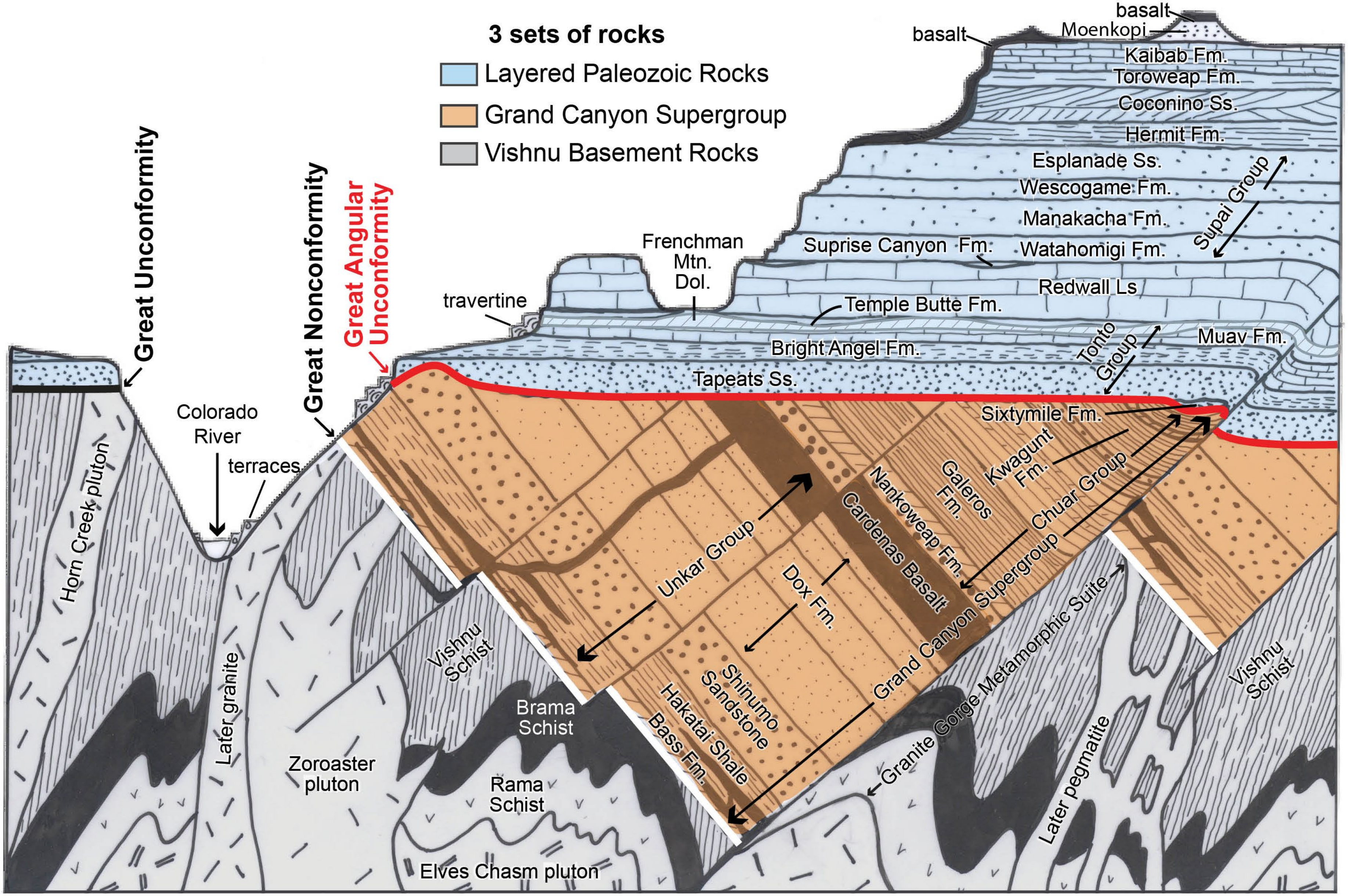

Figure 24. Stratigraphic column of rocks of the Grand Canyon region showing the three sets of rocks and major unconformities: Great Nonconformity (white line), Great Angular Unconformity (red line) and Great Unconformity (black line). Fm = Formation; Ss = Sandstone; Ls = Limestone

Table 2. Best numeric ages of the Vishnu Basement Rocks

Group	Formation	Stratigraphic Age	Numeric Age (Ma)	Precision (Ma)
Youngest granite	Quartermaster granite	Mesoproterozoic	1,375	± 2
Later granites / dike swarms	Phantom granite	Paleoproterozoic	1,662	± 1
	Cremation pegmatite	Paleoproterozoic	1,698	± 1
Zoroaster Plutonic Complex	Horn Creek granite	Paleoproterozoic	1,713	± 2
	Ruby gabbro	Paleoproterozoic	1,716	± 0.5
	Trinity granite	Paleoproterozoic	1,730	± 93
	Diamond Creek granite	Paleoproterozoic	1,736	± 1
	Zoroaster granite	Paleoproterozoic	1,740	± 2
Granite Gorge Metamorphic Suite	Vishnu Schist	Paleoproterozoic	1,750	± 2
	Brahma Schist	Paleoproterozoic	1,750	± 2
	Rama Schist	Paleoproterozoic	1,751	± 2
Oldest basement	Elves Chasm pluton	Paleoproterozoic	1,840	± 1

Ma = mega annum = million years ago

Precision is the analytical error in the radiometric age determinations for each unit.

An unconformity is present below the Granite Gorge Metamorphic Suite.

Only the Zoroaster Plutonic Complex and the Granite Gorge Metamorphic Complex have formal stratigraphic names at the group level. The youngest granite, later granites / dike swarms, and oldest basement are informal designations based on their shared geologic history.

Table 3. Tectonic environments of the Vishnu Basement Rocks

Group	Tectonic Environment	Age Range (Ma)
Youngest granite	Younger granites derived from crustal melting were widespread in the Southwest US, probably formed as other continental fragments collided with the growing North American continent far to the south of what is now the Grand Canyon region.	1,375
Later granites / dike swarms	The last crustal melts from the waning Yavapai orogeny	1,662–1,698
Zoroaster Plutonic Complex	Granodiorite magma chambers similar to modern ones under the Cascade volcanoes of the Pacific Northwest. The Zoroaster magmas formed during plate tectonic collisions during the Yavapai orogeny.	1,713–1,740
Granite Gorge Metamorphic Suite	Volcanic and sedimentary rocks were deposited on the Elves Chasm pluton; they were metamorphosed as they were buried up to 12-mile (20-km) depths during the Yavapai orogeny. This event was similar to the collision of Italy with Europe to form the Alps. The Yavapai orogeny added new continental crust onto the then-southern margin of North America.	1,750–1,751
Oldest basement	An older crustal pluton (magma chamber) in one of the microcontinents that gradually united to form North America	1,840

Ma = mega annum = million years ago

The radiometric age determinations on the Vishnu Basement Rocks are all highly precise, with analytical errors that are within ± 2 Ma, except for the 1,730 Ma Trinity Granite, which has an error of ± 93 Ma (Table 2). This imprecise age is due to mixed zircon populations in this granite that, with newer methods, could now be improved.

The dates we report for the Vishnu Basement Rocks are from Hawkins et al. (1996) and Karlstrom et al. (2003) and have not been revised much in the past two decades. Additional research efforts are needed to further unravel their complex history. For example, the Vishnu Schist contains zircon grains whose ages were not reset during metamorphism, and can be used to determine the age of the sediment source. The oldest zircon grains are as old as 3.8 Ga, with many grains dated at about 2.4 and 1.8 Ga (Shufeldt et al. 2010; Holland et al. 2018). A next step is to

Table 4. Numeric ages from the *Nature Notes* compilation (Mathis and Bowman 2005a; 2005b) (Table 4a) and in this study (Table 4b) for the Vishnu Basement Rocks

Table 4a. Numeric ages from the *Nature Notes* compilation

Group	Numeric Age (Ma)
Vishnu, Brahma, & Rama schists; most plutonic rocks	1,680–1,750 (~1,700)
Elves Chasm Gneiss	1,840

Ma = mega annum = million years ago

The *Nature Notes* compilation is Mathis and Bowman (2005a; 2005b).

Table 4b. Best numeric ages of the Vishnu Basement Rocks (this study)

Group	Formation	Numeric Age (Ma)	Explanation & Notes
Youngest granite	Quartermaster granite	1,375	The youngest granite was left out of the Natures Notes compilation.
Later granites / dike swarms	Phantom granite	1,662	The *Nature Notes* compilation grouped all igneous & metamorphic rocks together.
	Cremation pegmatite	1,698	The *Nature Notes* compilation grouped all igneous & metamorphic rocks together.
Zoroaster Plutonic Complex	Horn Creek granite	1,713	The *Nature Notes* compilation grouped all igneous & metamorphic rocks together.
	Ruby gabbro	1,716	The *Nature Notes* compilation grouped all igneous & metamorphic rocks together.
	Trinity granite	1,730	The *Nature Notes* compilation grouped all igneous & metamorphic rocks together.
	Diamond Creek granite	1,736	The *Nature Notes* compilation grouped all igneous & metamorphic rocks together.
	Zoroaster granite	1,740	The *Nature Notes* compilation grouped all igneous & metamorphic rocks together.
Granite Gorge Metamorphic Suite	Vishnu Schist	1,750	The *Nature Notes* compilation grouped all igneous & metamorphic rocks together. The specific date is the same as the interlayered Brahma Schist (ToTC).
	Brahma Schist	1,750	The *Nature Notes* compilation grouped all igneous & metamorphic rocks together. The specific date is derived from a U-Pb zircon age of an ash bed within this unit (ToTC).
	Rama Schist	1,751	The *Nature Notes* compilation grouped all igneous & metamorphic rocks together. The Rama Schist is underneath and interbedded with the Brahma Schist (ToTC).
Oldest basement	Elves Chasm pluton	1,840	No change

Ma = mega annum = million years ago

The *Nature Notes* compilation is Mathis and Bowman (2005a; 2005b)

ToTC = *Trail of Time Companion* (Karlstrom and Crossey 2019)

Figure 25. Dramatic evidence that the metamorphic rocks in the Vishnu Basement Rocks flowed like taffy and got intruded by granites and pegmatites at high temperatures and pressures in the deep crust (LAURIE CROSSEY).

pinpoint the potential source regions outside Grand Canyon from which these grains were derived.

The igneous and metamorphic rocks of Vishnu Basement formed beneath the now-eroded Vishnu mountains. The erosional demise of those mountains to sea level was complete by the time the Grand Canyon Supergroup was deposited atop the Great Nonconformity erosion surface.

Grand Canyon Supergroup

The rocks of the Grand Canyon Supergroup are primarily sedimentary strata, are divided into the lower Unkar Group and the upper Chuar Group, and range in age from 1,255 Ma to 729 Ma (Figures 23 and 24; Tables 5, 6, and 7). These rocks formed in fault-bounded continental rift basins.

Major revisions to the stratigraphy of the Grand Canyon Supergroup have occurred since the publication of the original compilation of numeric ages (Mathis and Bowman 2005a; 2005b) and the 2010 installation of the Trail of Time. The Nankoweap Formation was assigned to the Chuar Group (Dehler et al. 2017), and the Sixtymile Formation was moved from the Supergroup to the base of the Tonto Group in the Layered Paleozoic Rocks

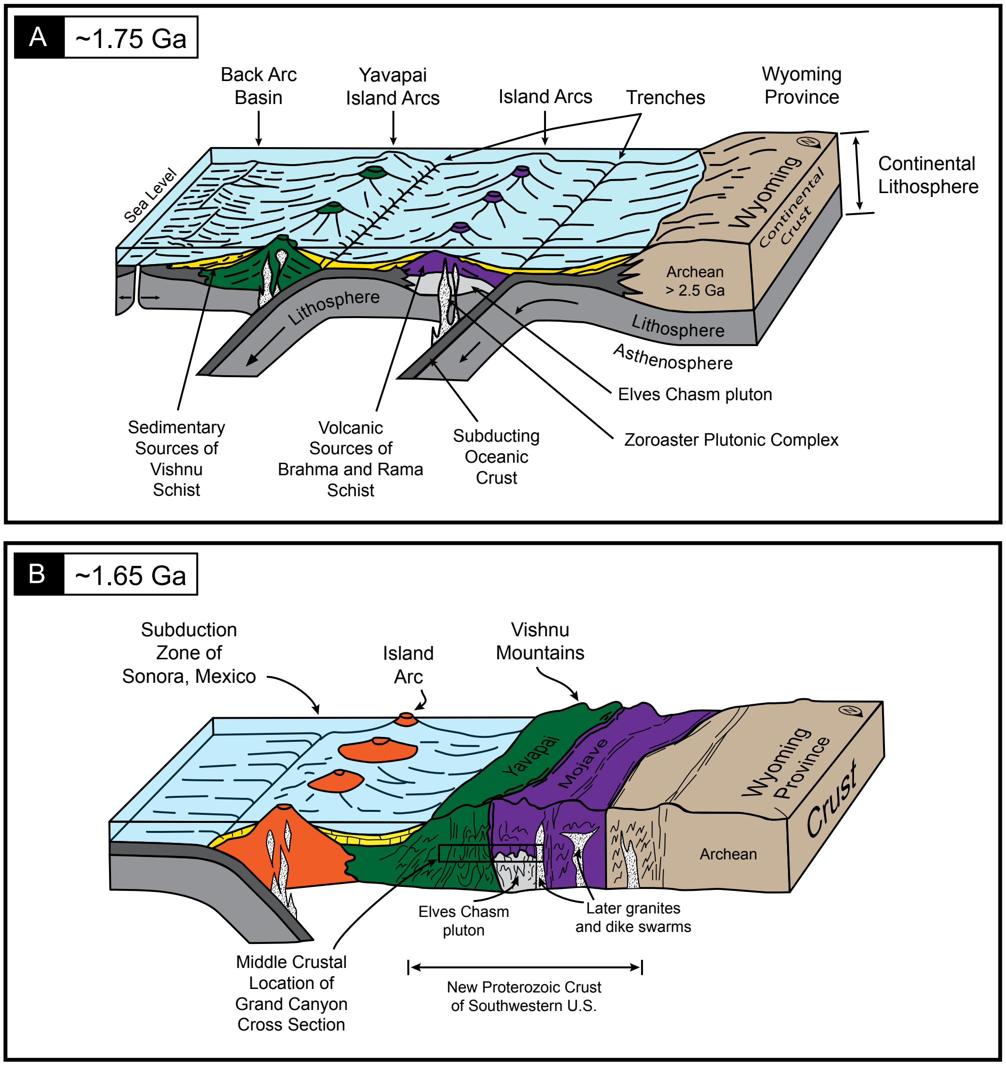

Figure 26. Tectonic evolution of the continent during the formation of the Vishnu Basement Rocks. A) The volcanic and sedimentary precursors of the Granite Gorge Metamorphic Suite were deposited on the flanks of volcanic island chains, and the granodiorite plutons formed as magma chambers underneath the islands. B) Later granite and pegmatite intrusions formed as the volcanic islands were added to the Wyoming Province, part of the growing North American continent.

Figure 27. Vishnu Basement Rocks include both metamorphic rocks of the Rama, Brahma, and Vishnu schists (dark in this photo) and granitic intrusions of several types and ages (lighter colors). This picture shows the Cremation pegmatite swarm near Phantom Ranch; one of these intrusions has been dated as 1,698 ± 1 million years old (LAURIE CROSSEY).

Figure 28. Granite intrusions of different sizes and compositions intruded the metavolcanic and metasedimentary rocks at great depths in the Vishnu mountains. The top image shows the edge of a large early intrusion; the bottom image shows granite from the later magmas filling a fracture network in the schist (LAURIE CROSSEY).

(Karlstrom et al. 2017) (Table 7). The formal names of several formations were also changed to better reflect their composition (Karlstrom et al. 2020). The Bass Limestone is now the Bass Formation, the Shinumo Quartzite was renamed the Shinumo Sandstone to clarify that the unit is not metamorphic, and the Dox Sandstone became the Dox Formation (Timmons et al. 2005).

New age determinations have also refined the age of several formations within the Grand Canyon Supergroup (Table 7). This compilation also provides detail on the age of each individual unit in the Supergroup by reporting numeric ages at the formation level. Numeric ages for members in the Kwagunt and Galeros formations in the Chuar Group are given because geologists have studied each member extensively and treat them with the attention generally given to formations.

The Unkar Group (Figures 29 and 30) consists of sediments that were shed off mountains in the region now part of west Texas that formed during the assembly of the Rodinia supercontinent. The Unkar Group was deposited between 1,255 Ma and 1,104 Ma. The age of the Bass Formation at the base of the Unkar Group is constrained by a volcanic ash bed that was dated to 1,255 ± 2 Ma. The ages of the overlying Hakatai Shale, Shinumo Sandstone, and Dox Formation are constrained by detrital zircon data (Mulder et al. 2017) (Tables 5 and 7). A 100-million-year unconformity separates the Hakatai Shale from the overlying Shinumo Sandstone.

Stacked basalt lava flows of the Cardenas Basalt that were erupted at 1,104 Ma are the youngest preserved units in the Unkar Group. The lava flows were fed by dikes and sills of diabase magma of similar age like the one shown in Figure 8C. These basalts formed at a time of incipient, but failed, rifting of ancient North America that caused the tilting of the Unkar Group.

A slight angular unconformity separates the Unkar Group from the overlying Chuar Group. New zircon data has indicated that the Nankoweap Formation is younger than previously thought, with a maximum age of 775 Ma (Dehler et al. 2017) instead of the 900 Ma date used in Mathis and Bowman (2005b). As a result of the new date, as well as it having a similar depositional history to the units above it, the Nankoweap was incorporated into the Chuar Group.

Direct ages have also been obtained by application of the rhenium-osmium radiogenic dating method on

Table 5. Best numeric ages of the Grand Canyon Supergroup

Group	Formation	Stratigraphic Age	Numeric Age (Ma)	Precision (Ma)	Duration (Ma)
Chuar Group	Kwagunt Formation *Walcott Member*	Neoproterozoic	729	± 1	729–745
	Kwagunt Formation *Awatubi Member*	Neoproterozoic	750	± 8	745–751
	Kwagunt Formation *Carbon Butte Member*	Neoproterozoic	753	–	751–755
	Galeros Formation *Duppa Member*	Neoproterozoic	755	–	755–757
	Galeros Formation *Carbon Canyon Member*	Neoproterozoic	757	± 7	757–760
	Galeros Formation *Jupiter Member*	Neoproterozoic	765	–	760–765
	Galeros Formation *Tanner Member*	Neoproterozoic	770	–	765–770
	Nankoweap Formation	Neoproterozoic	775	–	770–775
Unkar Group	Cardenas Basalt	Mesoproterozoic	1,104	± 2	1,100–1,104
	Dox Formation	Mesoproterozoic	1,120	–	1,105–1,140
	Shinumo Sandstone	Mesoproterozoic	1,130	–	1,140–1,150
	Hakatai Shale	Mesoproterozoic	1,230	–	1,230–1,245
	Bass Formation	Mesoproterozoic	1,255	± 2	1,245–1,250
	Bass Formation *Hotauta Conglomerate Member*	Mesoproterozoic	1,255	–	1,250–1,255

Ma = mega annum = million years ago

Precision is indicated when radiometric age determinatons are available. The Bass Formation and Walcott Member of the Kwagunt Formation of the Chuar Group have U-Pb zircon dates on interbedded ash deposits; Cardenas has an Ar-Ar date on the basalt; Awatubi and Carbon Canyon dates are Re-Os dates. Ar-Ar dating uses the K-Ar decay scheme, and is more accurate and precise than K-Ar dating since it provides ways to internally cross-check the results.

Members of the Kwagunt and Galeros Formations are presented because modern geologic investigations have focused on these mappable members. The members are also displayed individually along the Trail of Time.

Unconformities are present between the Chuar and Unkar Groups, and between the Shinumo Sandstone and Hakatai Shale

Table 6. Tectonic and depositional environments of the Grand Canyon Supergroup

Group	Formation	Tectonic and Depositional Environment	Age Range (Ma)
Chuar Group	Kwagunt Formation	As the supercontinent Rodinia broke up, rift basins were filled with sediments. The Chuar sediments were deposited in shallow inland seaways that extended to Death Valley, northern Utah, and beyond.	729–755
	Galeros Formation	As the Chuar basin subsided, muds and limes were deposited in a seaway that intermittently dried out and reflooded.	755–770
	Nankoweap Formation	These sandstones formed near the shore of an intracontinental seaway.	770–775
Unkar Group	Upper Unkar Group (Cardenas Basalt, Dox Formation, Shinumo Sandstone)	NW-SE compression from continental collisions to the south (present coordinates) caused the continent to rift along NW-trending basins that filled with sediments from rivers and floodplains. Finally, these basins were intruded by molten rock forming dikes and sills that fed eruptions of the Cardenas Basalt lava flows.	1,100–1,150
	Lower Unkar Group (Hakatai Shale, Bass Formation)	Continental collisions taking place far to the south (in modern coordinates) formed the supercontinent Rodinia and squeezed southwestern North America. This compression caused NE-trending folds that formed basins flooded by shallow seas.	1,230–1,255

Ma = mega annum = million years ago

carbonates in the 757 Ma Carbon Canyon Member, and the 751 Ma Awatubi Member where nodules of iron-sulfide (marcasite) were dated (Table 5; Rooney et al. 2018). Because the relative sequence of layers is so clear (Fig. 14), the durations of most Chuar members is estimated to be just 3–5 million years each (Table 5).

The Chuar Group is made up of mudstone with interbeds of sandstone and carbonate (Figure 14). It contains a rich diversity of single-celled organisms (Figure 31). Its fossils include the first heterotrophic predators (organisms that ate each other). Tectonically, the Chuar Group records the breakup and rifting of the Rodinia supercontinent and the

Table 7. Numeric ages from the *Nature Notes* compilation (Mathis and Bowman 2005a; 2005b) (Table 7a) and in this study (Table 7b) for the Grand Canyon Supergroup

Table 7a. Numeric ages from the *Nature Notes* compilation

Group	Numeric Age (Ma)
Sixtymile Formation	≤740
Chuar Group	740–770
Nankoweap Formation	900
Unkar Group	1,100–1,200

Ma = mega annum = million years ago

The *Nature Notes* compilation is Mathis and Bowman (2005a; 2005b).

Table 7b. Best numeric ages with explanation from this study

Group	Formation	Numeric Age (Ma)	Explanation & Notes
–	–	–	≤740 Ma age in *Nature Notes* compilation was constrained only as being younger than Chuar Group; no datable material had been found (Mathis and Bowman 2005b).The Sixtymile Formation was placed at 650 Ma on the Trail of Time based on the incorrect interpretation that it was related to sea level drawdown during glaciations of the Snowball Earth. The Sixtymile Formation was moved to Cambrian Tonto Group based on the age of the youngest detrital zircons (Karlstrom et al. 2017) that are as young as 530 Ma at the base of the section and 508 Ma at the top.
Chuar Group	Kwagunt Formation *Walcott Member*	729	Zircons give a U-Pb age of 729 ± 1 Ma (Rooney et al. 2018), a refinement of a previous 742 ± 6 Ma U-Pb zircon age reported in Karlstrom et al. (2000); ToTC
	Kwagunt Formation *Awatubi Member*	750	Marcasite nodules at the base of this member give a Re-Os date of 751 ± 8 Ma (Rooney et al. 2018), ToTC
	Kwagunt Formation *Carbon Butte Member*	753	Stratigraphic fit between Duppa Member and Awatubi Member
	Galeros Formation *Duppa Member*	755	Stratigraphic fit between 751–757, ToTC
	Galeros Formation *Carbon Canyon Member*	757	Organic-rich carbonates give a date of 757 ± 7 Ma based on Re-Os radiometric date (Rooney et al. 2018), ToTC
	Galeros Formation *Jupiter Member*	765	Stratigraphic fit between Carbon Canyon Member and Nankoweap Formation, ToTC
	Galeros Formation *Tanner Member*	770	Stratigraphic fit between Carbon Canyon Member and Nankoweap Formation, ToTC
	Nankoweap Formation	775	Nankoweap Formation is moved into the Chuar Group because of similar age and depositional setting; youngest detrital zircons give a U-Pb date of <775 Ma (Dehler et al. 2017), ToTC
Unkar Group	Cardenas Basalt	1,104	Radiometric Ar-Ar dating of dikes that fed the basalts gives 1,104 ± 2 Ma (Timmons et al. 2005), ToTC
	Dox Formation	1,120	Youngest zircons indicate <1,130 but is greater than 1,104 Ma Cardenas (Mulder et al. 2017), ToTC
	Shinumo Sandstone	1,130	Youngest zircons indicate <1,150, but is greater than 1,104 Ma Cardenas, (Mulder et al. 2017), ToTC
	Hakatai Shale	1,230	Youngest zircons are 1,255–1,230 Ma (Mulder et al. 2017), ToTC
	Bass Formation	1,255	Radiometric U-Pb zircon date is 1,255 ± 2 Ma from volcanic ash bed (Timmons et al. 2005), ToTC
	Bass Formation *Hotauta Conglomerate Member*	1,255	Interlayered with the carbonate and sandstone of the rest of the Bass Formation so it is the same age

Ma = mega annum = million years ago

The *Nature Notes* compilation is Mathis and Bowman (2005a; 2005b)

ToTC = *Trail of Time Companion* (Karlstrom and Crossey 2019)

Ar-Ar dating uses the K-Ar decay scheme, and is more accurate and precise than K-Ar dating since it provides ways to internally cross-check the results..

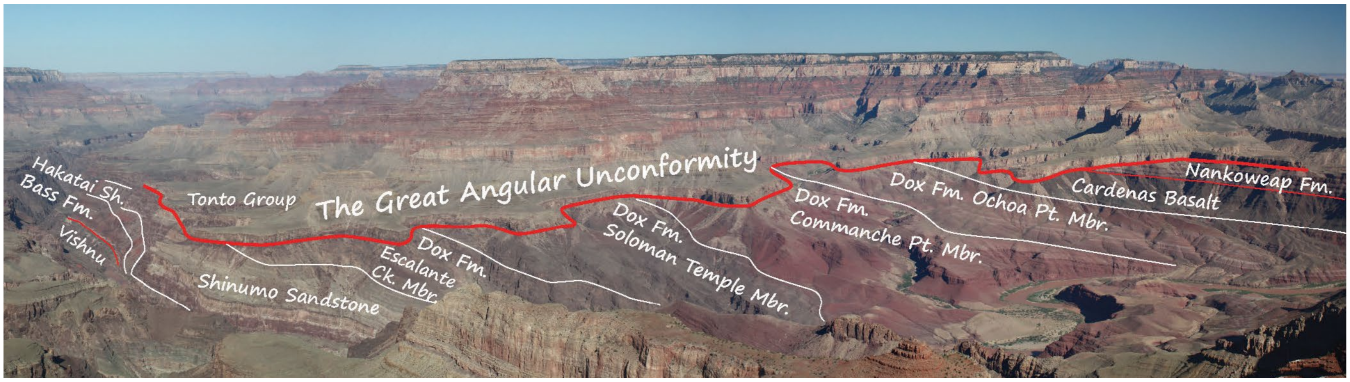

Figure 29. Units of the Unkar Group as seen from the South Rim at Lipan Point. The members of the Dox Formation are also labeled (LAURIE CROSSEY).

formation of the proto-Pacific ocean. Chemically, the Chuar Group shows wild oscillations in ocean chemistry as the expanding biosphere was interacting with the atmosphere and hydrosphere during the interval leading to the Snowball Earth (717 to 635 million years ago, a time not recorded by Grand Canyon rocks).

Layered Paleozoic Rocks

The Layered Paleozoic Rocks consist of the classic sedimentary strata that make up the upper portion of Grand Canyon's rock walls (Figure 15; Tables 8, 9, and 10); this is the stratigraphic sequence that most people think of when they consider the canyon's geology.

Figure 30. The Unkar Group exposed near Unkar Rapid (NPS).

The biggest changes in the Layered Paleozoic Rocks are the revisions to the stratigraphy of the Tonto Group, with the Sixtymile Formation being assigned to the base of the group (Karlstrom et al. 2018), and the formal designation of the "undifferentiated dolomites" as the Frenchman Mountain Dolostone (Table 10; Figure 32) (Karlstrom et al. 2020). These changes to the Tonto Group are the first major change to the stratigraphic nomenclature of the Paleozoic units at Grand Canyon since McKee defined the Supai Group (McKee 1975) and Billingsley and Beus identified the Surprise Canyon Formation (Billingsley and Beus 1985).

The Cambrian versus the Proterozoic age and the style of deposition of the Sixtymile Formation resulted in its formal addition to the base of the Tonto Group. Furthermore, because the youngest detrital zircon grains in the upper Sixtymile Formation are less than 508 million years old, the rest of the overlying Tonto Group must be less than 508 million years old, younger than previously thought (Karlstrom et al. 2018) (Tables 8, 9, and 10). The Bright Angel Shale and

Figure 31. Stromatolites were formed by single-celled cyanobacteria that formed colonies in shallow oceans (far left). Vase-shaped microfossils of the Chuar Group (near left) were single-celled shell-forming amoebae about 1/10 of a mm long. They show evidence of the first predators who attacked the amoebae's shells and left tiny holes (FAR LEFT: LAURIE CROSSEY; NEAR LEFT: SUSANNAH PORTER).

Table 8. Best numeric ages of the Layered Paleozoic Rocks

Group	Formation	Stratigraphic Age	Numeric Age (Ma)
–	Kaibab Formation	Early Middle Permian	270
–	Toroweap Formation	Late Early Permian	275
–	Coconino Sandstone	Early Permian	280
–	Hermit Formation	Early Permian	285
Supai Group	Esplanade Sandstone	Early Permian	290
	Wescogame Formation	Late Pennsylvanian	300
	Manakacha Formation	Early Pennsylvanian	315
	Watahomigi Formation	Early Pennsylvanian	320
–	Surprise Canyon Formation	Late Mississippian	325
–	Redwall Limestone	Late Early – Middle Mississippian	340
–	Temple Butte Formation	Middle – Late Devonian	385
Tonto Group	Frenchman Mountain Dolostone	Late Middle Cambrian	500
	Muav Formation	Late Middle Cambrian	504
	Bright Angel Formation	Middle Cambrian	506
	Tapeats Sandstone	Middle Cambrian	508
	Sixtymile Formation	Early Middle Cambrian	510

Ma = mega annum = million years ago

Unconformities are present between many formations. The main ones are at the base of the Tonto Group, and on both the upper and lower contacts for the Temple Butte Formation, Redwall Limestone, and Surprise Canyon Formation.

Table 9. Depositional environments of the Layered Paleozoic Rocks

Group	Formation	Depositional environment	Age Range (Ma)
–	Kaibab Formation	Shallow sea, similar to modern Persian Gulf	269–273
–	Toroweap Formation	Near the coast of a shallow sea, similar to modern Persian Gulf	273–278
–	Coconino Sandstone	Desert sand dunefields along coast, similar to modern Arabian Desert	276–282
–	Hermit Formation	Rivers and swamps in arid environment, similar to modern Nile Delta	284–290
Supai Group	Esplanade Sandstone	Arid coast and dunefields, similar to modern Namibia	290–294
	Wescogame Formation	Arid coast and dunefields, similar to modern Namibia	299–303
	Manakacha Formation	Arid coast and dunefields, similar to modern Namibia	314–317
	Watahomigi Formation	Coastal lowlands and shallow sea, similar to modern US Gulf Coast	318–323
–	Surprise Canyon Formation	Limestone plateau, similar to modern Yucatan Peninsula	324–326
–	Redwall Limestone	Tropical sea, similar to modern Java Sea	335–338
–	Temple Butte Formation	Shallow sea in the west and tidal channels in the east	375–385
Tonto Group	Frenchman Mountain Dolostone	Tropical sea, similar to modern Bahama Banks	497–503
	Muav Formation	Tropical sea, similar to modern Bahama Banks	503–505
	Bright Angel Formation	Muddy sea floor, similar to modern Gulf of Mexico	505–507
	Tapeats Sandstone	Sandy beaches and river bottoms, similar to modern Atlantic sandy coastlines	507–509
	Sixtymile Formation	Sediments ranging from rockslide deposits to fine-grained sandstones deposited below uplifted cliffs	509–530

Ma = mega annum = million years ago

Muav Limestone have been formally redesignated the Bright Angel Formation and Muav Formation because they contain a variety of sedimentary rock types. Fossils from the Frenchman Mountain Dolostone are more than 497 million years old. The deposition and paleoenvironment of the Frenchman Mountain Dolostone were continuations of the marine environments of the underlying Muav Formation, so it was also added to the Tonto Group (Karlstrom et al. 2020). In just 10 million years (remarkably fast), the marine transgression that deposited most of the Tonto Group advanced from Nevada across Arizona, into

Table 10. Numeric ages from the *Nature Notes* compilation (Mathis and Bowman 2005a; 2005b) and in this study for the Layered Paleozoic Rocks

Group	Formation	Numeric Age (Ma) (*Nature Notes*)	Numeric Age (Ma) (this publication)	Explanation & Notes
–	Kaibab Formation	270	270	No change
–	Toroweap Formation	273	275	Refined by Geologic Timescale recalibrations of fossil data (ToTC)
–	Coconino Sandstone	275	280	Age adjusted to predate Toroweap Formation
–	Hermit Formation	280	285	Age adjusted to predate Coconino Ss and match fossil data
Supai Group	Esplanade Sandstone	285	290	Individual formation ages in the Supai Group ages were not defined in the *Nature Notes* compilation. Dates reflect fossil data and relative positions of the formations.
	Wescogame Formation	295	300	Individual formation ages in the Supai Group ages were not defined in the *Nature Notes* compilation. Dates reflect fossil data and relative positions of the formations.
	Manakacha Formation	305	315	Individual formation ages in the Supai Group ages were not defined in the *Nature Notes* compilation. Dates reflect fossil data and relative positions of the formations.
	Watahomigi Formation	315	320	Individual formation ages in the Supai Group ages were not defined in the *Nature Notes* compilation. Dates reflect fossil data and relative positions of the formations.
–	Surprise Canyon Formation	320	325	Age adjusted to predate Watahomigi Formation and match fossil data
–	Redwall Limestone	340	340	No change
–	Temple Butte Formation	385	385	No change
Tonto Group	Frenchman Mountain Dolostone	–	500	This is a new stratigraphic name for the "undifferentiated dolomites" of McKee and Resser (1945) which they included in the Tonto Group. Karlstrom et al. (2020) named this unit and assigned it to the Tonto Group based on similar age and depositional setting to Muav Formation.
	Muav Formation	505	504	Date adjusted to match fossil trilobite data. Name changed from Muav Limestone because of multiple lithologies (Schuchert 1918; Rose 2011; Karlstrom et al. 2020)
	Bright Angel Formation	515	506	Date adjusted to match fossil trilobite data. Name changed from Bright Angel Shale because of multiple lithologies (Rose 2011; Karlstrom et al. 2020)
	Tapeats Sandstone	525	508	Date adjusted based on detrital zircon ages. (Karlstrom et al. 2020)
	Sixtymile Formation	650	510	Sixtymile Formation moved from Neoproterozoic Grand Canyon Supergroup to the Cambrian Tonto Group based on the age of detrital zircons and depositional environment (Karlstrom et al. 2017)

Ma = mega annum = million years ago

The Sixtymile Formation was part of the Grand Canyon Supergroup in the *Nature Notes* compilation (Mathis & Bowman 2005a; 2005b)

ToTC = *Trail of Time Companion* (Karlstrom and Crossey 2019)

eastern Colorado, and beyond into the mid-continent (Figure 33).

Assigning numeric ages for the other units of the Layered Paleozoic Rocks has been difficult because there are no directly datable volcanic beds, and existing detrital zircon data do not have enough young grains to refine depositional ages (Gehrels et al. 2011). Nevertheless, their rock type, age, and overall geologic setting have been extensively studied and their ages are well constrained by index fossils. Units with richer fossil records have more precise age constraints, and global calibration of fossil biozones is becoming more precise in the v 2020/01 International Stratigraphic Chart (Cohen et al. 2013, updated).

Our updates to the numeric ages of the Layered Paleozoic Rocks are based on Karlstrom and Crossey (2019), who used the International Stratigraphic Chart to better constrain the numeric ages for Paleozoic rocks in Grand Canyon NP. This resulted in changes of only a few million years for many

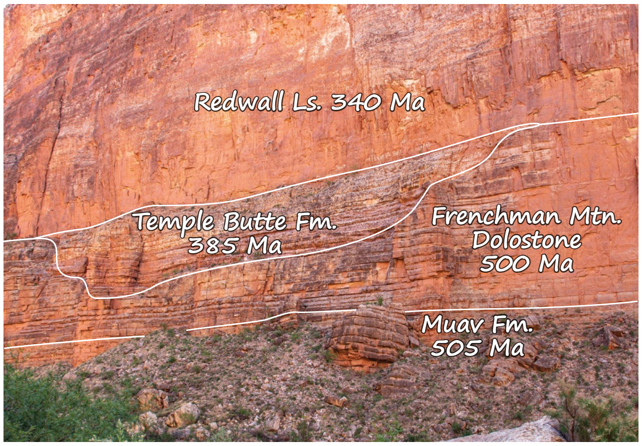

Figure 32. The uppermost unit of the Tonto Group is now called the Frenchman Mountain Dolostone (changed from the "undifferentiated dolomites;" McKee and Resser 1945).

units (Table 10). A related challenge for the Layered Paleozoic Rocks was identifying the best central age for the age of each unit.

Sedimentary deposition was nearly continuous between the Hermit Formation, Coconino Sandstone, Toroweap Formation, and Kaibab Formation during the Permian with the different formations being designated based on lithology resulting from distinct depositional environments. The only fossils known from the Coconino Sandstone are trace fossils (tracks of both invertebrates and vertebrates) (Figure 34), with some tetrapod traces indicating that they are from the Early Permian biochron (approximately 280 Ma) (Santucci and Tweet 2020). The Kaibab Formation forms the rim of Grand Canyon, and is the youngest Paleozoic rock in Grand Canyon. It is early Middle Permian based on microfossils and invertebrate fossils (Santucci and Tweet 2020).

Future revisions to the age of units in the Layered Paleozoic Rocks may come as additional detrital zircon dates are derived across key faunal transitions within them.

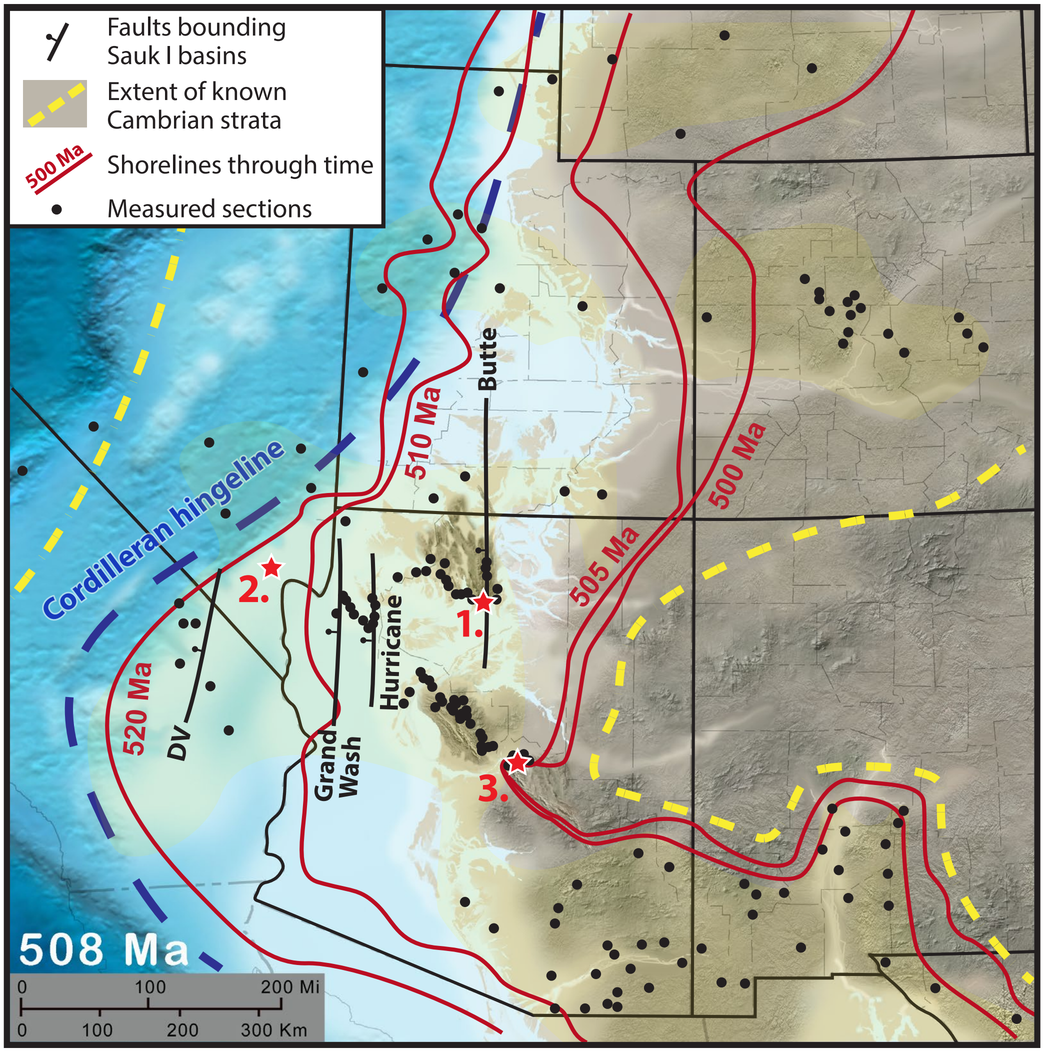

Figure 33. Paleogeographic map of the Tonto Group transgression shows progression of 510 to 500 Ma shorelines (red) as shallow seas covered a very low relief continent leaving about 328 ft (100 m) thick sheet sandstones (yellow) of the Tapeats Sandstone followed by mudstones and carbonates of the rest of the Tonto Group. Stars and numbers show locations of newly dated samples of <508 Ma. Sixtymile Formation (at location #1) developed near the Butte fault in eastern Grand Canyon which was reactivated at that time.

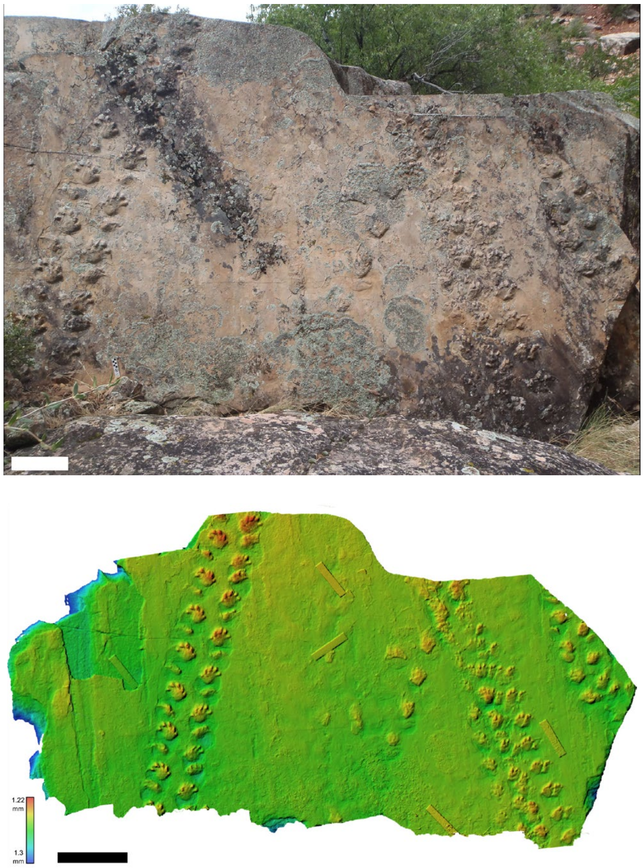

Figure 34. A fallen boulder of Coconino Sandstone located adjacent to the Dripping Springs Trail shows trackways of a tetrapod, or mammal-like reptile, that walked on the sand dune and predated the dinosaurs. The tracks are enhanced by a false-color depth map (depth in mm). (TOP: FRANCISCHINI ET AL. (2019); BOTTOM: SPENCER LUCAS).

The Fourth and Fifth Sets of Rocks

A full account of Grand Canyon's geologic story (McKee 1931) includes fourth and fifth sets of rocks. Providing detailed descriptions and a summary of the numeric ages of these sets is outside the scope of this report, but these rocks are important parts of Grand Canyon's larger geologic story and of the larger Colorado Plateau.

The fourth set of rocks would incorporate the Mesozoic and early Cenozoic sedimentary rocks that were deposited on top of the Kaibab Formation. Although a few remnants of these rocks are preserved in Grand Canyon NP such as at Cedar Mesa, these rocks are widely exposed in the Grand Staircase and across southern Utah (Figure 35) (Hintze and Kowallis 2009).

The fifth set of rocks contains the younger rocks that drape the erosional landscape and that can be used to decipher the history of uplift and erosion of the region, as well as the age of the carving of Grand Canyon. These rocks consist of volcanic cinder cones and lava flows (Figure 3), spring-fed travertines, and weakly to unconsolidated sand and gravel deposits. These rocks are fundamentally different than those in the three main sets. The surficial rocks and deposits are more local in scale whereas the three main sets are regionally widespread units that make up the fundamental architecture of the crust of the Colorado Plateau.

Figure 35. The Jurassic Navajo Sandstone in Zion National Park, part of the White Cliffs of the Grand Staircase (LAURIE CROSSEY).

4 Discussion

This paper summarizes what is known about the age of rocks exposed in Grand Canyon NP as of 2020, as well as provides what we consider to be their best numeric ages. Our hope is that this updated and comprehensive chronology of the age of Grand Canyon rocks, as well as the Trail of Time exhibit on the South Rim, can catalyze better understanding of Grand Canyon's geologic story for people at all levels of geologic understanding.

The numerous revisions to the ages of Grand Canyon rocks, as well as the stratigraphic revisions, especially in the Grand Canyon Supergroup and Tonto Group, demonstrates that even though Grand Canyon has been one of the most-studied and most-heralded geologic locales in the United States since Powell's pioneering river expedition, there is still much left to be learned about Grand Canyon geology. In turn, new scientific discoveries in this iconic field laboratory can have global reverberations for the progress of the geosciences and for science literacy for national and international visitors. These new and refined understandings of geology and deep time are essential for the future sustainability of our planet with limited resources and growing populations.

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