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The Great Big Data Challenge – From Overwhelming to Understanding

A River Runs Through It – Geological History in Grand Canyon National Park

Illuminating Luminescence – A New Teaching and Research Resource

2019 VOLUME 46

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Cover Image: View, looking towards the north rim of the Colorado River and Phantom Ranch area along Bright Angel Creek, taken from the Kaibab Trail. Photo credit: Laurie Crossey.

PRESIDENTIAL ADDRESS

The Challenges of Big Data in Expanding Geoscience: Embracing New Initiatives to Untangle our World

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PREAMBLE

It was my pleasure to serve as the president of this organization through 2018 and part of 2019, and such an experience cannot help but remind me of the effort that comes from GAC staff and our many volunteers, but it also brought home the challenges that all of us face in organizing our time and activities in this so-called Information Age. We live in a world where both space and time are increasingly compressed, and all of us at times struggle to manage the demands of our work and our lives beyond the office walls. So I will start this address by asking you all to imagine that you had one extra day a week given to you - some time that you could spend on fun science and investigating exciting questions, or just catching up on work and life. Would we not all welcome such a gift? But then look back over the last few weeks, months or even years and think about how much time you spent searching for information, skimming papers to finding sample locations, compiling and cleaning up data, georeferencing maps….just some of the many basic things that need to get done before you can get to the fun part of your job as a geoscientist. There are estimates that geologists now spend 80% of their time searching for, formatting and organizing information and data, and I do not find these hard to believe.

A recent article highlighted the approach taken by Cameco, one of Canada's leading mining companies, to change how they manage data in order to save 20% of their geologists' time – one day a week – so that they would not have to spend countless hours looking for data and could do geology instead (Heffernan 2015). There are many efforts to amalgamate and process data in ways that make this process easier and more amenable to automation. A young student geologist at Princeton University, Julia Wilcots, undertook a summer project with a senior researcher at University of Wisconsin to examine the distribution of stromatolites through geological time by searching descriptive literature. Anyone who has worked in the Precambrian, or indeed in sedimentary rocks of any Eon or Era, can well imagine the immensity of that search. However, through the use of computer search techniques and the 'Geodeepdive' database, she was quickly able to identify over 10,000 papers that mentioned stromatolites (in the text, but not necessarily in the title) and extract the associated rock unit names from 10% of them. Then, by linking these results to the 'Macrostat' database, she was then able to come up with an estimate of the percentage of shallow marine rocks that contain stromatolites within different geological time periods. A more senior researcher at the University involved with the project estimated that doing this same search would have taken him sixteen months of tedium. The overall conclusions of the study – that the distribution of stromatolites is most closely linked to the abundance of dolomitic carbonate rocks (Peters et al. 2017) – are important, but the methodology demonstrates the ability of new techniques to unravel seemingly infinite tangles of data. What other questions could we address and what other problems could we solve as Earth Scientists if we were routinely able to query efficiently organized data with such rapidity?

As a science, geology continues to evolve towards a bigger view - from rocks alone, to facies, to entire sedimentary systems, to geodynamic environments, and to the Earth System as a whole. We increasingly recognize the interconnected nature of all geoscience data, and the need for a 'Big Context' to make sense of 'Big Data'. This address seeks to emphasize the great potential of the data explosion that confronts us but sometimes confounds us, and also to specifically highlight some of the new and exciting tools and techniques that can help us exploit it. I seek to provide but a glimpse of an ever-expanding branch of our science, which will feature more and more in our professional lives in the 21st century.

SNAPSHOTS OF SOME NEW INITIATIVES IN GEOSCIENCE DATA MANAGEMENT

In the 21st century, we hear so much about Big Data, Artificial Intelligence, Machine Learning, Data Analytics and their 'vast potential', but we are increasingly challenged to actually make use of that potential. Most of us are inundated with data and struggle to even keep up with the scientific literature. We think of the state of our own incomplete and fragmented datasets, and we find ourselves falling from the "Peak of Inflated Expectations" on the "Gartner Hype Cycle" into the aptly-named "Trough of Disillusionment" (Fig. 1;

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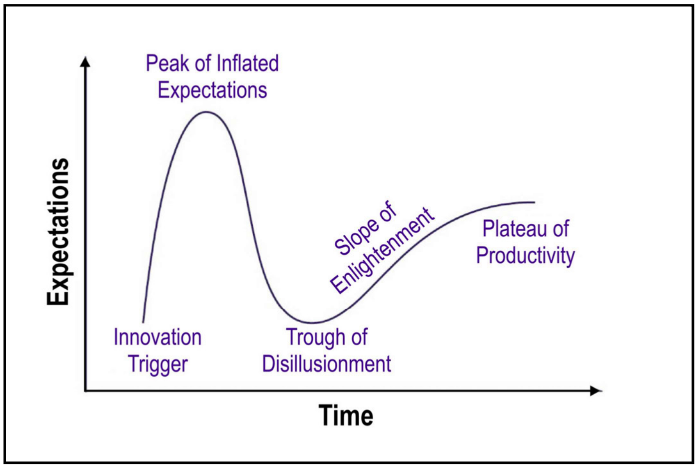

Figure 1. The "Gartner Hype Cycle", a concept that applies in many human endeavours. It was originally outlined by the Gartner Group, a global research and advisory firm in the United States, and has been widely applied to the development and marketing of new technologies, although it has also received some criticism from experts in the field. Figure source: https://www.gartner.com/en/research/methodologies/gartner-hype-cycle.

https://www.gartner.com). My hope is that we can eventually climb the "Slope of Enlightenment" and reach the "Plateau of Productivity", and that some of the new initiatives discussed below might measurably ease that ascent.

Several new 'nodes' have now sprung up to try to bring order to this overwhelming data chaos, and not just in academia. Mining companies are addressing the challenge, because they constantly need to revisit their historic archives, or those of predecessors, to try to find the next mine. The Prospectors and Developers Association of Canada (PDAC) recently initiated the Exploration Assessment Digital Data Formats (EADDF) project, which developed standard guidelines for all digital data submitted as part of mineral exploration company assessment reports. Such an effort is immensely valuable for the continuity of exploration as properties pass from company to company, and also to Government and academic researchers who tap into these valuable corporate data reservoirs.

Many analytical laboratories and related service providers now market data-management services along with the analyses or results that they provide to customers. Relatively high-priced subscription services such as SNL/IntierraRMG and Geofacets (available through Elsevier) recognize the additional value in providing their information in formats that are readily usable by the customer, including maps or other graphical products. The extra costs involved for the customer in acquiring such processed data are more than compensated by the elimination of the time and frustration involved in integrating and correlating raw results.

Australia is now a world leader in compiling and integrating mineral exploration industry data, and in bringing it together with information from Government geological surveys and other research sources. For example, it is now possible to view and download all the geological survey field sites for the country and all of the borehole locations drilled by industry projects via a single portal (https://portal.ga.gov.au). In Canada, most Provincial Geological Surveys provide geoscience data compilations via their websites, including advanced web application formats such as the excellent SIGÉOM system in Québec, and the Resource Atlas GIS maintained by the Geological Survey of Newfoundland and Labrador. These are just two examples of data delivery from Provincial geoscience, and most organizations now provide some system of this type. However, we have yet to achieve the nation-wide accessibility of federal, state and corporate data now provided to Australian geoscientists, or to reach a desirable level of consistency among the various delivery platforms.

However, many other data compilation initiatives have sprung up over the years across Canada. Bruce Eglington maintains the DateView and StratDB geochronological and lithostratigraphy databases, respectively, at the Saskatchewan Isotope Laboratory as part of some IGCP projects (most recently IGCP 648). These are key inputs to his global paleoenvironmental reconstruction modelling and other projects.

Elsewhere in the world, there are some excellent examples of similar initiatives that are linked to specific disciplines. For geochemistry, we have data repositories such as EarthChem (https://www.earthchem.org/), which is funded by the United States National Science Foundation (NSF), and GEOROC, a geochemical rock database in Germany. Other international and NSF-funded projects include the Paleobiology Database, Macrostrat for stratigraphy, and Neotoma for paleoecology. In Geophysics, there are several paleomagnetic databases such as the PALEOMAGIA Precambrian Database hosted at the University of Helsinki, and another version developed offline by Sergei Pisarevsky at Curtin University, Australia, based on an original compilation by Dr. M.W. McElhinney.

Many of these databases, and numerous others that cannot be referenced in this short article, are relatively isolated, standalone initiatives that are promoted and maintained by core groups of indefatigable academics, who most often maintain them as a side project alongside their main research and teaching roles. This is time-consuming work but of immense value to a much wider community in geoscience. Voluntary data submissions represent a very incomplete sample of the published data, as illustrated by the many obvious gaps in geochronological data compared to geochemistry data, which is clearly shown by maps produced from EarthChem (Figure 2).

In the final analysis, the true value of any database depends on the ease of searching for and retrieving data. Collections of data alone do not solve the problems that we face. Some really exciting work aimed at 'data harvesting' is happening at the University of Wisconsin-Madison where Shanan Peters leads the GeoDeepDive team (https://geodeepdive.org/). This initiative uses natural language processing (NLP) to identify contextual relationships and applies text and data mining (TDM) to harvest information from close to 300,000 newly published documents per month. This is where Julia Wilcot's summer project on stromatolites and geologic time was initiated. Shanan's team now has agreements with most major scientific publishers to access their publications via automated search methods. GeoDeepDive is one of several projects within the larger EarthCube initiative funded by the United States NSF.

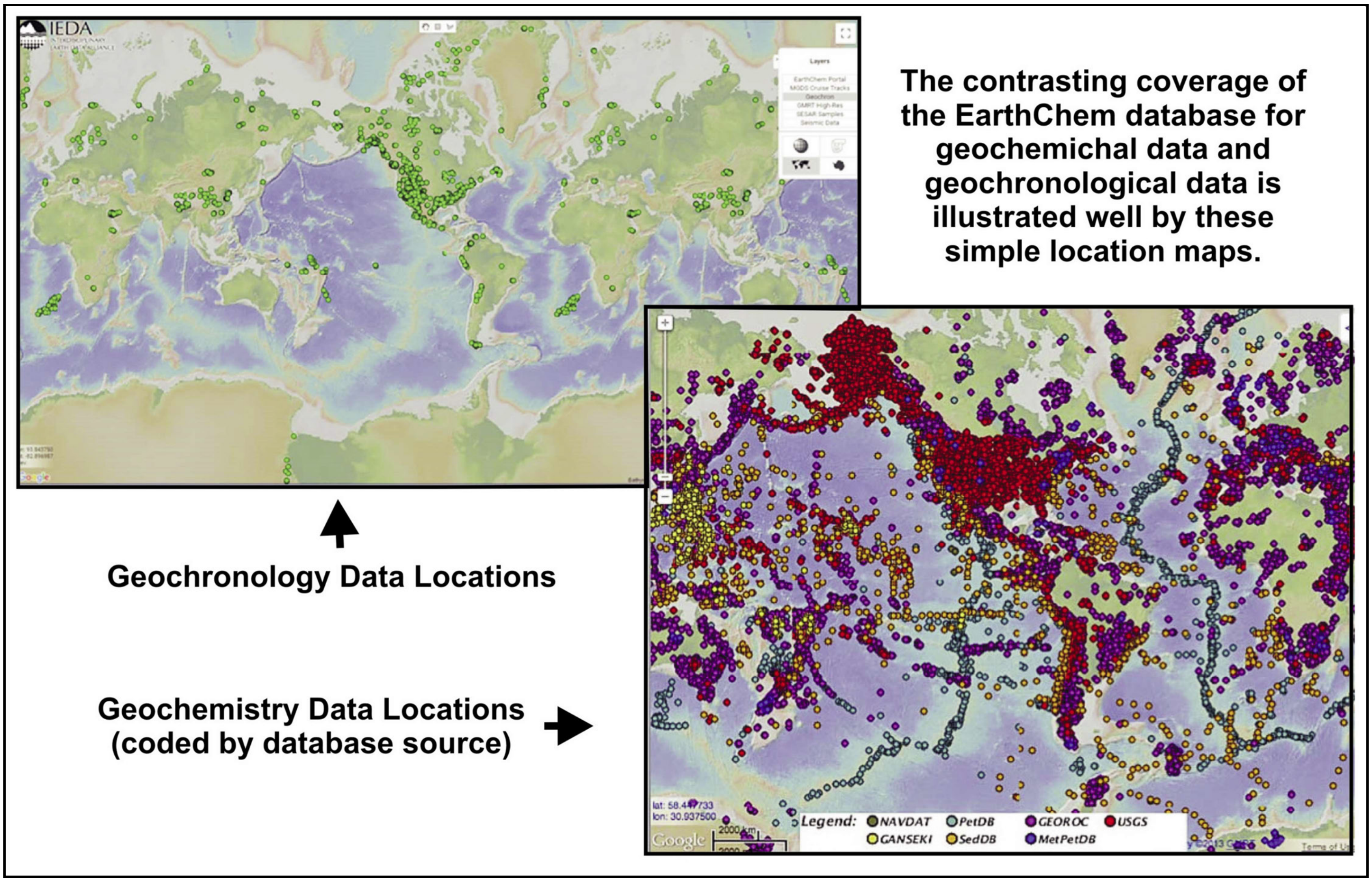

Figure 2. Maps produced from the EarthChem database showing the geographical restrictions of geochronological data compared to lithogeochemical data. IEDA = Interdisciplinary Earth Data Alliance. Figure sources: http://earthchem.org/portal (geochemistry sample image); http://app.iedadata.org/databrowser/ (geochronology image).

GeoDeepDive currently provides access to some 10 million documents and represents a very valuable tool for researchers in all sectors of geoscience.

To make it easier to get data from published research, the main scientific publishers are phasing in new standards for supplementary data over the next two years. One of these is a requirement for the use of the System for Earth Sample Registration (SESAR; http://www.geosamples.org/) in which researchers must register samples with a unique sample identifier termed an alphanumeric International Geo Sample Number (IGSN). This works like the more familiar doi or ISBN reference used for publications (see http://www.geosamples.org for more discussion). It will ensure that basic data such as sample location are accurately captured, and allow unambiguous linking of information in cases where different analyses such as lithogeochemistry, U–Pb dating or isotopic analyses are completed on material from the same sample, even if they are from different laboratories and published in different papers over the years. This is in its own right a valuable initiative that can bring order to data and avoid unnecessary duplication of effort.

FUNDING AND SUPPORT

Of course, initiatives in data management and compilation require funding, just like any other scientific endeavour. There are several funding models for making geoscience data more accessible and useable. The EarthCube project is a joint effort funded by the United States NSF Directorate for Geosciences and the Division of Advanced Cyberinfrastructure. Its wider objective is to develop the cyber-infrastructure of technology and systems that will allow sharing and accessing all types of geoscience data and related resources. It is probably the most robust data system presently used by the North American geoscience community. Other funding models include industry-academia consortia, of which the Mineral Deposits Research Unit at the University of British Columbia is probably one of the best-known examples in Canada. Direct government support for data integration initiatives is present through many geological survey data portals around the world, and through International consortia such as OneGeology (http://www.onegeology.org/). This includes geological surveys from around the world, representing 118 countries, and also UNESCO, the International Union of Geological Sciences (IUGS) and the Commission for the Geological Map of the World. Other services are available as subscription services aimed more at corporate clients, including SNL/IntierreRMG and Geofacets.

China recently announced $75 million in funding over ten years for a Deep Time Digital Earth (DDE) database initiative developed as an International Union of Geosciences (IUGS) project, although there is currently no funding outside of China for this. Non-experts will do much of the data harvesting, which will be verified by experts. The DDE grew out of the Geobiodiversity Database, which was started by paleontologist Fan Junxuan of Nanjing University in 2006 and became the official database of the International Commission on Stratigraphy in 2012. DDE was officially supported by the IUGS in February 2019 as one of its projects.

Extensive collaboration between EarthCube and DDE is unlikely at this stage due to political issues, although technical discussions between scientists continue. The co-chairs of some of the working groups within the IUGS-DDE initiative include North American researchers such as Bruce Eglington in Saskatchewan, Kirsten Lehnert at the Lamont-Doherty Earth Observatory in New York (on geochronology, geochemistry and petrology) and Isabella Montanez at University of California, Davis (on sedimentology).

CLOSING REMARKS AND SUGGESTIONS

In an age of highly collaborative research and systems thinking, efficient access to good data provides a competitive edge to companies, and promotes scientific insight and discovery. As members of the geoscience community, we all need to be more aware of how we can use these resources in our work and also make efforts to enhance them to improve the activities of our community. I urge GAC members to get actively involved in these North American and International Geoscience Data initiatives, by harnessing the power of 'Big Data' to investigate your own scientific problems and, above all, to further the growth of this potential by contributing data and information. Ask what queries to a system like GeoDeepDive could do for your own research questions, and also think about how the research of others might be aided through access to information that you could contribute. I also strongly encourage the promotion of skills development in these areas amongst employees, students and professional colleagues. The challenge of unravelling 'Big Data' may at times seem overwhelming, but it provides methods to visualize forests as well as identify individual trees. Canadian geoscientists have much to contribute to these valuable initiatives!

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SERIES

Classic Rock Tours 3.
Grand Canyon Geology, One Hundred and Fifty Years after John Wesley Powell: A Geology Guide for Visiting the South Rim of Grand Canyon National Park

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SUMMARY

The year 2019 is the 150th anniversary of John Wesley Powell's epic exploration of the Colorado River through Grand Canyon and the 100th anniversary of the establishment of Grand Canyon National Park. This is an excellent moment to look back 150 years to think about where we have come from as a science and society, and look forward 100 years towards the accelerated change we expect in the future. For historians, archaeologists, geologists and astronomers, of course, this century-long time scale is short compared to other perspectives. They might choose also to celebrate the 479th anniversary of the first sighting of Grand Canyon by Europeans in 1540, the 1000th anniversary of Ancestral Puebloan farmers in Grand Canyon, the 12,000th anniversary of the arrival of humans migrating south from the Bering Land Bridge, the 5 millionth anniversary of the integration of the Colorado River through Grand Canyon to the Gulf of California, the 4.6 billionth anniversary of the formation of Earth, or the 13.75 billionth anniversary of the Big Bang and the formation of our Universe. Geology is all about time, and knowing some geology helps with the difficult endeavour of placing human time-frames into perspectives of deep time.

This guide is for geology students of all levels and types visiting the South Rim of Grand Canyon. It is designed as a 3-day field trip and introduction to the rocks and landscapes. The term 'students' in our view also includes visitors who want to know about the basics of Grand Canyon geology while taking scenic hikes to see the geology first-hand. It is organized as if you enter the Park at its East entrance, near Cameron, and exit the Park at the South entrance, towards Flagstaff, but the three activities can be done in any order. As an introduction, we present a brief summary of the history of geologic maps and stratigraphic columns, and the geologists who made them. The maps and depictions of Grand Canyon geology over the past 160 years record a visual progression of how geoscience knowledge in general has developed and matured. The first sixty years, before the Park was founded, may have been the greatest in terms of the rapid growth that merged geology, art and public outreach. The second fifty years (to about 1969) saw important advances in stratigraphy and paleontology and solid efforts by the Park to apply and interpret Grand Canyon geology for the public. The most recent 50 years have seen major advances in regional geological mapping, dating of rocks, plate tectonics, and improved geoscience interpretation. The next 100 years will hopefully see additional innovative efforts to use the iconic field laboratory of Grand Canyon rocks and landscapes to resolve global geoscience debates, inform resource sustainability imperatives and contribute to science literacy for an international public.

The three activities described are as follows: **Activity 1** (an hour or two) is an overview from Lipan Point. This is a vehicle pull-out on the East Rim drive and serves as an introduction for those entering the Park, or a recap for those who are leaving. **Activity 2** (most of a day) is a day hike on the South Rim with visits to Yavapai Geology Museum and the Trail of Time Exhibit. The Trail of Time is a geology timeline trail laid out at a scale of one metre = 1 million years along the Rim Trail. It is a great family hike, fully accessible, with magnificent views of Grand Canyon. The rocks were collected along the river and have been placed at their 'birthdays' along the Trail for you to see and touch and sketch. If you walk the entire 4.56 km

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(2.8 mile) Trail of Time, a long way, you get a visceral feeling for the age of the Earth and you also go through historic Grand Canyon Village for lunch and shops. **Activity 3** (all day) is a hike to Plateau Point along the Bright Angel Trail. One has not really seen and appreciated Grand Canyon geology until you delve its depths. You can go any distance down, but if you do the entire 19 km (12 mile) hike, you descend through a 1 km (3300 foot) thick set of Paleozoic rock layers to a spectacular vista where you feel like you can touch the Colorado River as well as the Grand Canyon Supergroup and Vishnu basement rocks of the inner Granite Gorge. The Plateau Point Trail takes off at Indian Gardens, or alternatively, this guide describes some good geology stops a short way down Garden Creek. The Bright Angel Trail continues to the Colorado River and to Phantom Ranch at the bottom of the canyon, but this is generally done as an overnight endeavour. You can get campground reservations (https://www.nps.gov/grca/planyourvisit/campsite-information.htm) or reservations at Phantom Ranch well in advance through a lottery (https://www.grandcanyonlodges.com/lodging/lottery/).

RÉSUMÉ

L'année 2019 marque le 150e anniversaire de l'exploration épique du fleuve Colorado par John Wesley Powell à travers le Grand Canyon ainsi que le 100e anniversaire de la création du parc national du Grand Canyon. C'est un excellent moment pour regarder 150 ans en arrière et se rappeler le chemin parcouru par la science et la société, et envisager le changement accéléré auquel nous nous attendons pour les 100 prochaines années. Pour les historiens, les archéologues, les géologues et les astronomes, bien sûr, cette échelle d'un siècle est courte par rapport à d'autres perspectives. Ils pourraient également choisir de célébrer le 479e anniversaire de la première observation du Grand Canyon par les Européens en 1540, le 1000e anniversaire des agriculteurs Pueblo ancestraux dans le Grand Canyon, le 12 000e anniversaire de l'arrivée d'humains migrant depuis l'isthme de Béring vers le sud, le 5 millionième anniversaire de l'intégration du fleuve Colorado à travers le Grand Canyon jusqu'au golfe de Californie, le 4,6 milliardième anniversaire de la formation de la Terre ou le 13,75 milliardième anniversaire du Big Bang et de la formation de notre univers. La géologie est une question de temps, et connaître un peu de géologie facilite la tâche difficile qui consiste à placer l'échelle de temps humaine dans le contexte du « temps profond ».

Ce guide est destiné aux étudiants en géologie de tous niveaux et de tous types qui visitent le South Rim du Grand Canyon. Il est conçu comme une excursion de trois jours et une initiation aux roches et aux paysages. Selon nous, le terme « étudiants » inclut également les visiteurs qui souhaitent en savoir plus sur la géologie de base du Grand Canyon tout en faisant des randonnées panoramiques pour observer la géologie. Il est organisé comme si vous entrez dans le parc par son entrée est, près de Cameron, et quittez le parc par l'entrée sud, en direction de Flagstaff, mais les trois activités peuvent être effectuées dans n'importe quel ordre. En guise d'introduction, nous présentons un bref résumé de l'histoire des cartes géologiques et des colonnes stratigraphiques, ainsi que les géologues qui les ont réalisées. Les cartes et les représentations de la géologie du Grand Canyon au cours des 160 dernières années montrent une progression visuelle de l'évolution et de la maturation des connaissances géoscientifiques en général. Les soixante premières années, avant la création du parc, ont peut-être été les meilleures en termes de croissance rapide résultant de la fusion de la géologie, de l'art et de la vulgarisation. Les cinquante années suivantes (jusqu'en 1969 environ) ont été marquées par d'importants progrès en stratigraphie et paléontologie et par les efforts soutenus du parc pour permettre au public d'accéder à l'application et l'interprétation de la géologie du Grand Canyon. Au cours des 50 dernières années, la cartographie géologique régionale, la datation des roches, la tectonique des plaques et l'amélioration de l'interprétation géoscientifique ont considérablement progressé. Espérons que les 100 prochaines années verront des efforts novateurs supplémentaires visant à utiliser l'emblématique laboratoire des roches et du paysages du Grand Canyon pour résoudre les débats géoscientifiques mondiaux, informer sur les impératifs de durabilité des ressources et contribuer à la culture scientifique d'un public international.

Les trois activités décrites sont les suivantes. L'activité 1 (une heure ou deux) est une vue d'ensemble de Lipan Point. Il s'agit d'une sortie en véhicule sur East Rim Drive et sert d'introduction pour ceux qui entrent dans le parc ou de récapitulation pour ceux qui en partent. L'activité 2 (presque une journée) est une randonnée d'une journée sur le South Rim avec la visite du musée de géologie de Yavapai et de l'exposition « Trail of Time ». Le « Trail of Time » est un sentier chronologique géologique tracé à une échelle d'un mètre pour un million d'années le long de Rim Trail. C'est une excellente randonnée en famille, entièrement accessible, avec des vues magnifiques sur le Grand Canyon. Les roches ont été collectées le long de la rivière et ont été placées à leurs « anniversaires » le long du sentier pour que le public puisse les voir, les toucher et les dessiner. Le parcours entier du « Trail of Time » sur 4,56 km (2,8 miles) offre une représentation intuitive de l'âge de la Terre et permet de passer également par le village historique du Grand Canyon pour déjeuner et faire les boutiques. L'activité 3 (toute la journée) consiste en une randonnée vers Plateau Point, le long de Bright Angel Trail. On n'a pas vraiment vu et apprécié la géologie du Grand Canyon tant qu'on n'en a pas exploré les profondeurs. N'importe quelle distance peut être parcourue, mais en arpentant les 19 km (12 milles) de la randonnée entière, on descend à travers un ensemble de couches de roches paléozoïques épaisses de 1 km (3 300 pieds) jusqu'à une vue spectaculaire où on a l'impression de pouvoir toucher le fleuve Colorado ainsi que le super-groupe du Grand Canyon et les roches du socle de Vishnu de la gorge granitique intérieure. Le Plateau Point Trail commence à Indian Gardens mais ce guide propose d'autres points de départ avec une géologie intéressante non loin de Garden Creek. Le Bright Angel Trail continue vers le fleuve Colorado et le Phantom Ranch au fond du canyon, mais cela se fait généralement de manière nocturne. Des emplacements aux terrains de camping peuvent être réservés (https://www.nps.gov/grca/planyourvisit/campsite-information.htm) ou des réservations au Phantom Ranch peu-

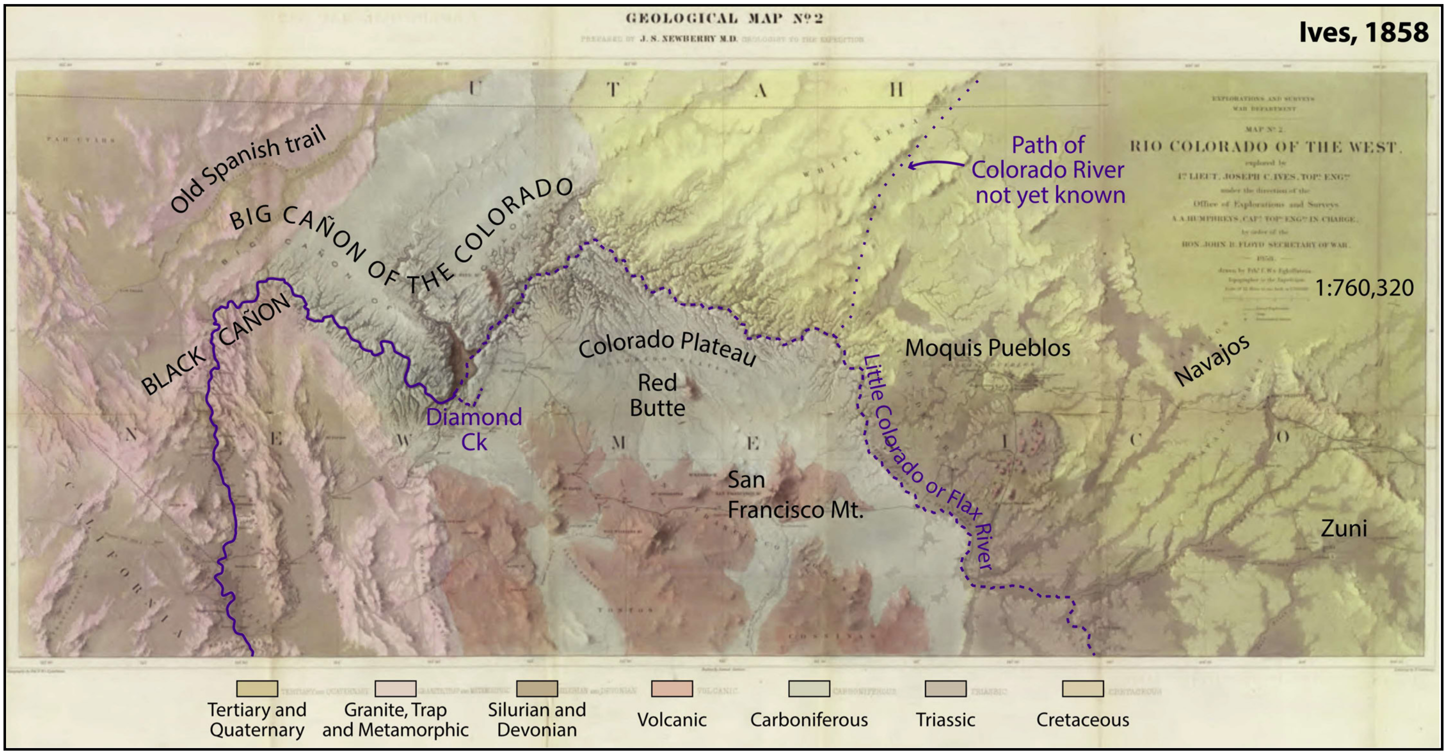


Figure 1. Geologic map from the Ives (1861) report. Annotations added: Grand Canyon was called "Big Cañon of the Colorado", Colorado Plateau was labeled for what we now call Coconino Plateau (Beus and Morales 2003), and locations of Native American tribes and the Old Spanish trail from Santa Fe to Los Angeles were marked. Grand Canyon was within the Territory of New Mexico (not Arizona) at that time, original scale was 1:760,320.

vent être obtenues bien à l'avance par le biais d'une loterie (https://www.grandcanyonlodges.com/lodging/lottery/).

Traduit par la Traductrice

HISTORICAL BACKGROUND

Impetus for creating Grand Canyon National Park in 1919 included a natural history legacy that involved pre-eminent American explorers, geologists, and artists. Stephen Pyne (1968) observed that between about 1875 and 1915: "*In roughly forty years the Canyon had become Grand*", nineteenth century geology was done in the context of the Civil War, its aftermath, and as part of the transcontinental railroad surveys that opened up the American West. Findings were written and illustrated for the combined audiences of scientists, the public, and policy makers. Early American geologists were among the greatest in the sense that they assimilated so much in uncharted regions. They understood and met the challenge of depicting the vast scales, spectacular landscapes, the rock record, and the depth of geologic time.

The first geologic map of western Grand Canyon was created as a result of the Ives 1857–1858 survey (Ives 1861). Joseph Christmas Ives was a New York-born, West Point-trained, engineer who was the commander of the expedition to explore the navigability of the lower Colorado River from its delta northwards. The expedition included Connecticut-born John Strong Newberry, with college training from Western Reserve College in both natural science and medicine and German-born Frederick W. von Egloffstein, who acted as topographer and artist. The Ives Expedition report contained a geologic map (Fig. 1) that was prepared by Newberry and engraved and produced by von Egloffstein using a shaded relief technique of his own design for depicting topography (Ives 1861). The maps are accurate as far north as Black Canyon where the steamboat "*Explorer*" ran aground as it attempted to navigate up the lower Colorado River. Newberry's party then continued overland to Diamond Creek and later to Havasu Canyon and Fort Defiance. The path of the Colorado River from the northeast was not yet known and the map incorrectly showed the Little Colorado River as the headwaters of the Colorado River. However, the depiction of geological units, based in part on fossil identifications by Newberry, was remarkably good for its time, ten years before J.W. Powell's 1869 river expedition.

The first rock column depiction was also from Newberry. Figure 2 shows that Newberry accurately depicted flat-lying Paleozoic strata, correctly correlated the basal sandstone (now Tapeats Sandstone) with the Potsdam Sandstone of New York and identified lower Carboniferous (Mississippian) fossils (Redwall Limestone). He also depicted the nonconformity above granite. Artist F.W. von Egloffstein of the same expedition engraved a lithograph (Fig. 2B) that portrays dramatic and precipitous canyons and perhaps some terror about the canyons of the western Colorado River and of Diamond Creek tributary.

John Wesley Powell completed the first scientific exploration of unmapped segments of the Green and Colorado rivers in 1869 and repeated most of the trip again in 1871–1872. Starting in 1875 and continuing while he was Director of

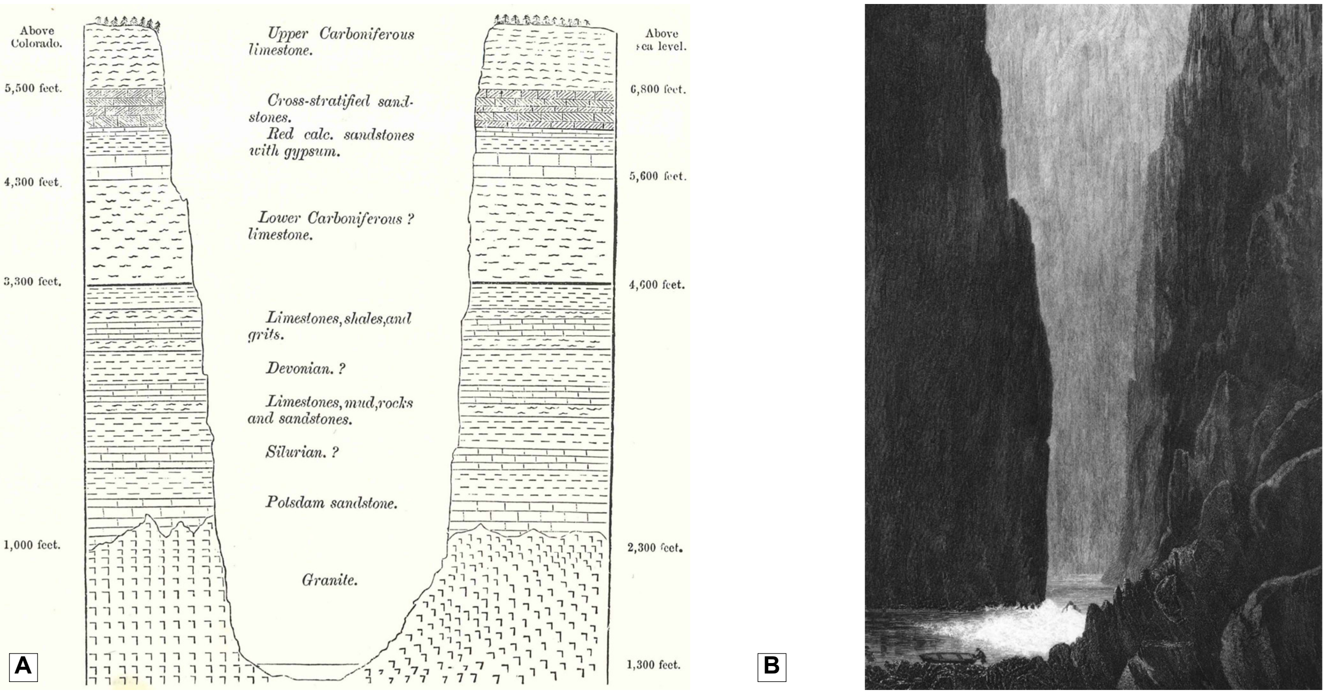


Figure 2. A. John Strong Newberry's (1861, p. 42) rock column was developed from examination of strata in Diamond Creek and the Aubrey cliffs (Ives 1861). As Edwin Mckee wrote: "*their conclusions were remarkable considering the difficult conditions under which they worked and the state of general knowledge at the time.*" B. Friedrich W. von Egloffstein's engraving *Black Canyon* was made from a sketch of Lt. Ives and is Plate V of the Ives (1861) report.

the newly formed U.S. Geological Survey, Powell was in charge of the Geographical and Geological Survey of the Rocky Mountain Region. He forged a team that included geologists Grove Karl Gilbert, Clarence Dutton, and Charles Doolittle Walcott, as well as artists including Jack Hillers, Thomas Moran, and William Henry Holmes. They dramatically advanced the field of geology of the Colorado Plateau and generated public appreciation for Grand Canyon and other western landscapes, and scientific exploration. Powell (1875a) worked with artists to merge landscapes with geological depictions of the rocks. He recognized two great unconformities separating three sets of rocks (Fig. 3). In today's terminology, from bottom to top these are: Vishnu basement schist and granite (A), overlain nonconformably by tilted Grand Canyon Supergroup (B), overlain with angular unconformity by flat-lying Paleozoic rocks (C). Edwin D. McKee (1978), Grand Canyon's greatest stratigrapher, gave due credit:

> "*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*".

Clarence Dutton was Yale-trained but also became self-educated in geology following his Civil War involvement. His 1882 reports (Dutton 1882a, b) brought together the geological understanding of the Colorado Plateau region from the Powell's USGS team with descriptive scientific writing and inspirational images. The geologic map (Fig. 4) was drawn on an artistically stylized topographic base published in the large-format folio. It was a geologic masterpiece. The map showed: 1) the Colorado River's path through Grand Canyon; 2) the igneous and metamorphic basement rocks, then called Archean, now known to be Paleoproterozoic in age; 3) the tilted rocks, then called Silurian, now the Neo- and Mesoproterozoic Grand Canyon Supergroup; 4) Paleozoic flat-lying rocks, then called Permian and Carboniferous, now known to extend downward to include Cambrian strata; 5) the Grand Staircase of Mesozoic and Tertiary strata that were stripped back from the Grand Canyon during what Dutton called "The Great Denudation"; and 6) Cenozoic volcanic fields of varying composition deposited on the stratified rocks. This monograph remained the best geologic map and overall understanding of the Grand Canyon region for many decades. Clarence Dutton's and William Henry Holmes's portrayals presented amazing detail of Grand Canyon rocks and landscapes. As noted by Dutton (1882a, p. XVI): "*Only the artist and the geologist combined could have graphically presented the subject in a manner so instructive and beautiful.*"

Charles Doolittle Walcott was hired by G.K. Gilbert in 1879 to work for the U.S. Geological Survey. He soon joined Dutton for work on the High Plateaus of Utah and then spent numerous field seasons in eastern Grand Canyon. He and Powell forged a horse-trail from the North Rim called the Nankoweap Trail to access remote areas of eastern Grand Canyon's Chuar Valley. Walcott spent many seasons unraveling the stratigraphy of Proterozoic and Paleozoic layers and published numerous papers between 1880 and 1920. His work was focused on paleontology, but also resulted in the first detailed geologic map of the Chuar Group of what he named the

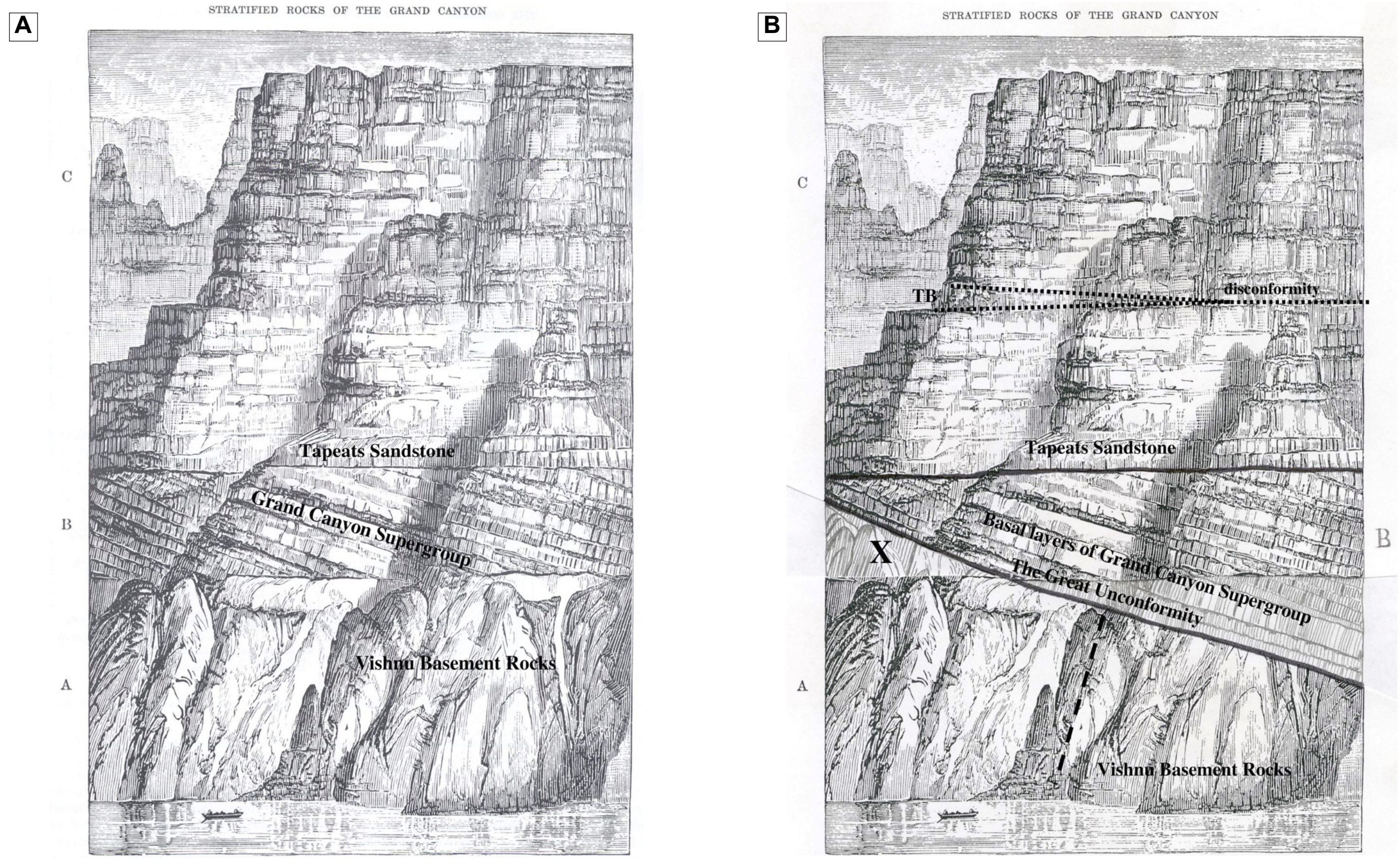


Figure 3. A. John Wesley Powell (1875a) recognized two major unconformities that bound the three main sets of rock but the strata above the lower unconformity were depicted incorrectly. B. shows the lower nonconformity drawn correctly (by University of New Mexico graduate student Micah Jessup). Powell corrected this error (but not the drawing) in his next rock column in 1876.

Grand Canyon Series, later to become Grand Canyon Supergroup (Fig. 5). He recognized these strata to be from the Proterozoic Era. He also described Cambrian fossils in the Tonto Group and discovered in the Chuar Group a sub-millimetre fossil of a single-celled organism that he named *Chuaria*. Walcott's (1894) geologic map (Fig. 5) appeared on one of the first topographic contour maps (200 foot elevation contours) that was surveyed during the same expeditions. As usual, new mapping led to numerous scientific advances: Walcott described the Proterozoic lava flows now known as the Cardenas Basalt, made important paleontology collections, and refined Grand Canyon's stratigraphy. His later work included discoveries in the Burgess Shale of soft-bodied early animals and global correlations of trilobites.

Levi Fatzinger Noble was born in New York in 1882, the same year Clarence Dutton's *Tertiary History* monograph was published. In 1908, at age 26 while working on his PhD at Yale, he first visited Grand Canyon. He hiked down the South Bass Trail to the river and crossed the river on John Bass's cable car. He had hiked through the full section of Paleozoic strata and saw the tilted rocks of Grand Canyon Supergoup. Many of these layers had not been examined in detail and many were unnamed. A few years later, he described this experience as "*casting a spell from which the observer is never entirely free*" (Wright and Troxel 2002). Noble's (1914) *Geologic Map of the Shinumo Quadrangle* resulted in the formal definition (generally still used) of most of the Paleozoic and Unkar Group stratigraphic units. Noble's stratigraphic column evolved into the archetypal portrayal of Grand Canyon rocks and weathering profiles also shown, for example, by Breed and Roat (1976; Fig. 6).

In the 1930s, remarkably nuanced and sophisticated geoscience interpretation was going on at the South Rim. Figure 7 shows geology columns constructed from Grand Canyon's real rocks and built by Mary Colter at Bright Angel Lodge (Fig. 7A) and Edwin McKee at Yavapai Geology Museum (Fig. 7B). These were 'to scale' for Paleozoic rock thickness. They showed canyon erosional profiles, and creatively depicted rock islands (monadnocks) of Shinumo Sandstone (then called Shinumo Quartzite) onlapped by the Tonto Group. Inner Canyon geological interpretative signs and displays on Kaibab and Bright Angel trails in the 1960s used a similar rock column (Fig. 7C). These signs nicely integrated stratigraphic columns, environments of deposition, paleobiology, and physical processes of lithification. From about 1933 to 1978, Edwin McKee's stratigraphic work (McKee 1978) continued to redefine Grand Canyon units for global audiences.

In 1969, the Park Superintendent wanted a completed geologic map of the entire park on one sheet. Peter Huntoon and George Billingsley, who were completing their graduate work

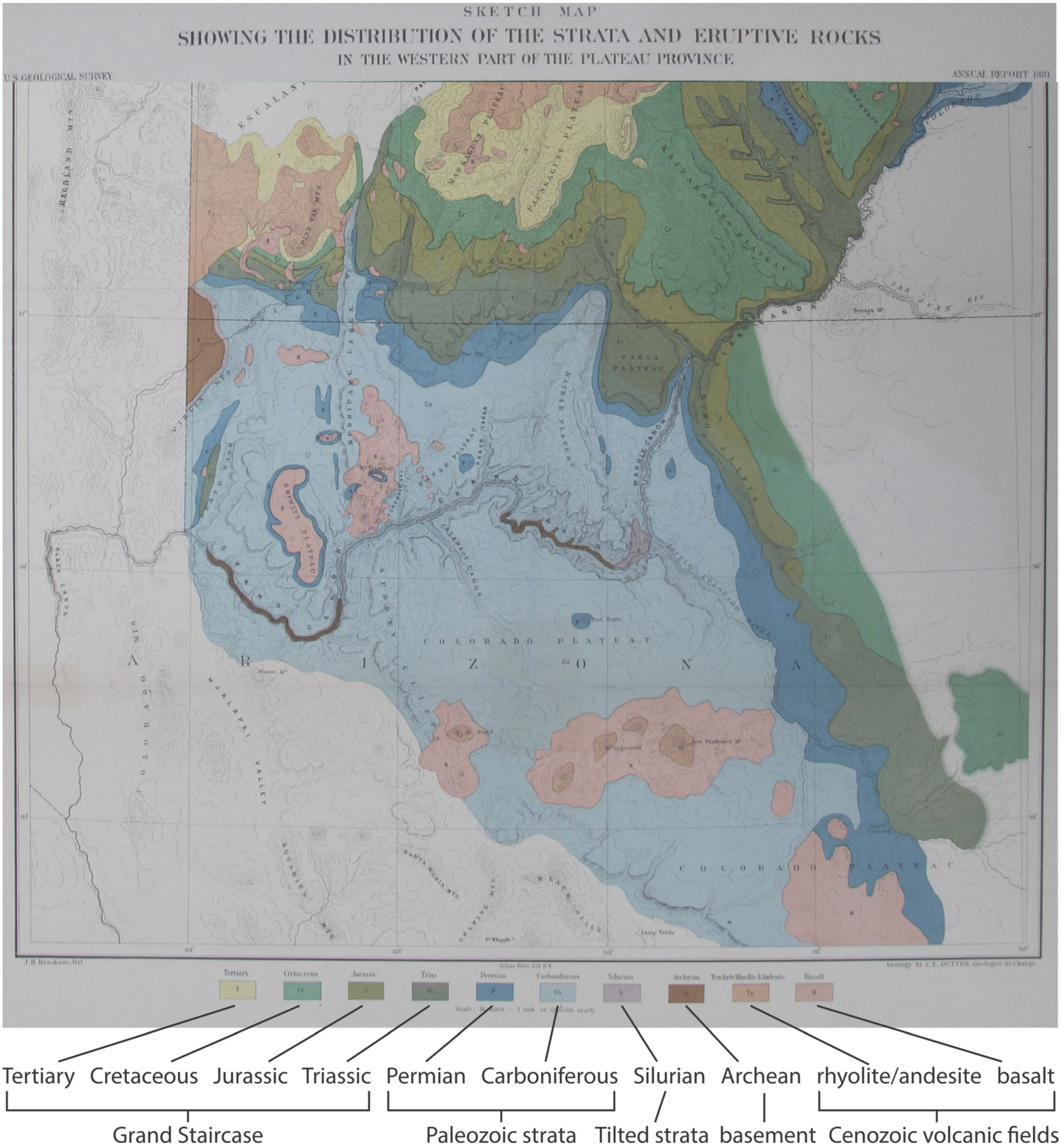


Figure 4. South half of Dutton's (1882a) *Sketch map showing the distribution of the strata and eruptive rocks in the western part of the Plateau Province*; later printed as Dutton's (1882b, sheet II) *Geologic map of the western part of the Plateau Province*; original scale was ~ 1:1,000,000.

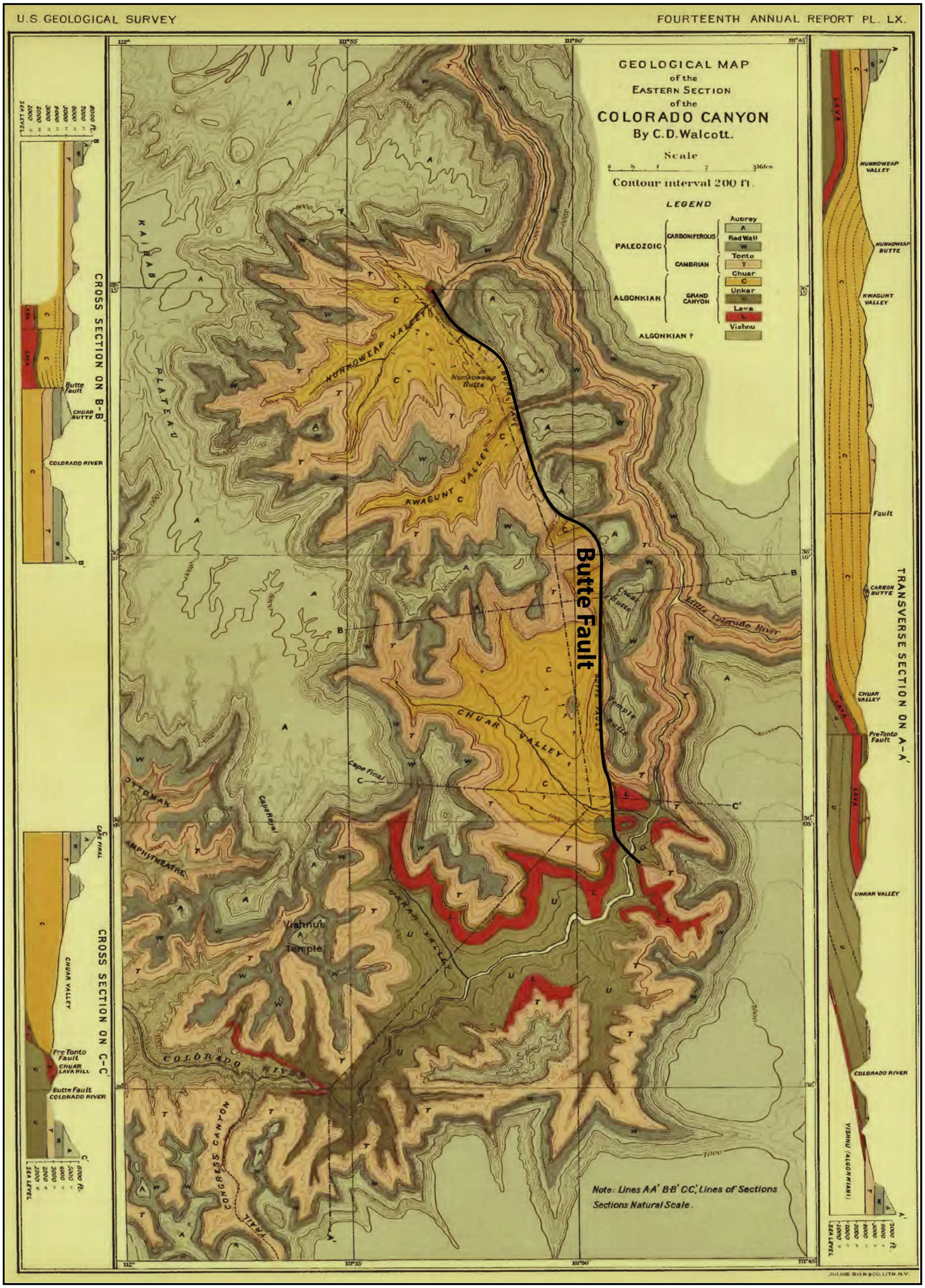


Figure 5. Walcott's (1894) *Geologic map of the Eastern Section of the Colorado Canyon* identified the "Algonkian" (Proterozoic) Unkar and Chuar "terranes" (now groups) within the Grand Canyon "Series" (now Supergroup) and the Cambrian Tonto Group.

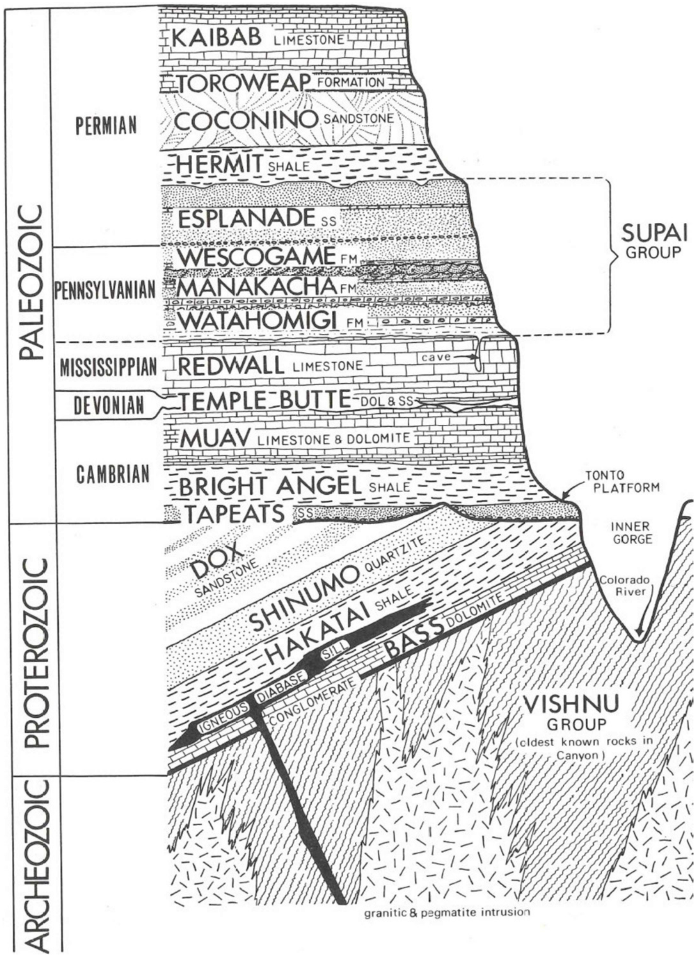


Figure 6. The iconic rock column depiction of Grand Canyon's three sets of rocks was modified from John Wesley Powell (1876) and Levi Noble (1914). It has been refined by many authors, including R.P. Sharp (1940), John Maxson (1961), and this one by Breed and Roat (1976).

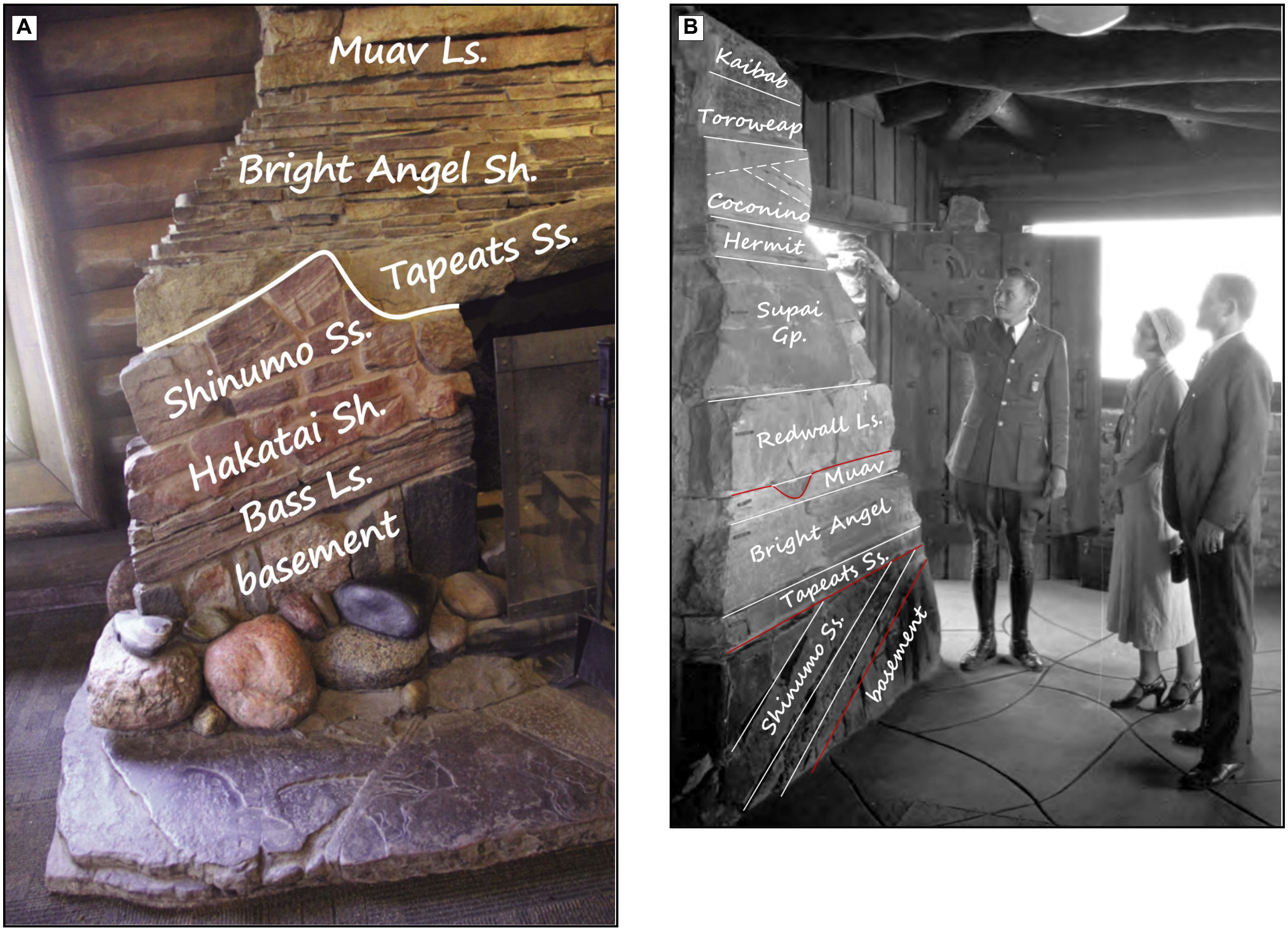
at University of Arizona and Northern Arizona University respectively, undertook this effort. Publication of the four editions (1976, 1980, 1986 and 1996) of the Huntoon et al. (1996) "*Geologic Map of the Grand Canyon National Park, Arizona*" became known as the "Blue Dragon" because of the dominance of blue colors for the Paleozoic strata and the Chinese dragon-like shape made by the Grand Canyon and its tributaries (Fig. 8). The map was dynamic in that Huntoon's and Billingsley's coauthors changed, and succeeding editions incorporated corrections and revisions. Together these editions became the best-selling and most widely distributed geologic map of all time owing to sales by the Grand Canyon Natural History Association to an international public.

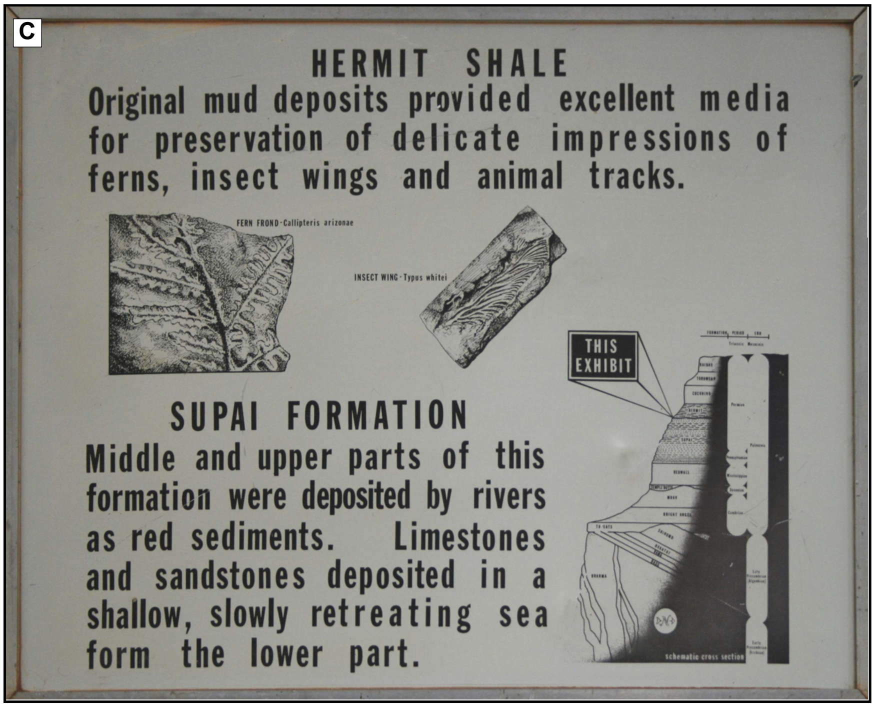
In the 1980s, while at Northern Arizona University (NAU), Karl Karlstrom and his students and collaborators began mapping the Lower Granite Gorge of Grand Canyon at 1:24,000. Brad Ilg, a graduate student at NAU and later University of New Mexico (UNM), mapped the Upper and Middle Granite Gorges at 1:12,000. Results included discovery of the oldest rocks in the southwest (the 1.84 billion year old Elves Chasm Gneiss), subdivision of three schist units that comprise the Granite Gorge Metamorphic Suite, and precise U–Pb dating and characterization of basement rocks (Hawkins et al. 1996; Ilg et al. 1996; Karlstrom et al. 2003). Collectively, these Vishnu basement rocks formed in the plate tectonic setting of colliding volcanic arc microplates. These plate collisions built the Vishnu Mountains about 1.7 billion years ago, and then these mountains were eroded flat by 1.25 billion years ago to form the Great Nonconformity.

In the 1990s, mapping by UNM graduate students, Karlstrom, Crossey, and colleagues refined mapping of the Grand Canyon Supergroup with Mike Timmons working on the Unkar Group (Timmons et al. 2005) and Carol Dehler working on the Chuar Group (Dehler et al. 2005, 2017). These rocks record basins within the interior of North America that formed during plate tectonic assembly and break-up of the supercontinent Rodinia. The Timmons and Karlstrom (2012) geologic map of Eastern Grand Canyon (Fig. 9) is the first of a series of 1:24,000 map sheets planned to cover the Colorado River corridor. Cross sections and refined stratigraphic and time columns depict new dating. Accompanying scientific papers in a GSA Special Paper (Timmons and Karlstrom 2012) help explain geological progress made while making this map. The map also includes mapping of surficial deposits that record the rates of carving of Grand Canyon by the Colorado River. It shows the distribution of travertine deposits, the youngest rocks in Grand Canyon. These deposits record groundwater flow in the past million years including degassing of mantle–derived CO_2 and ^3He (Crossey and Karlstrom 2012).

George Billingsley of the U.S. Geological Survey undertook a 1:100,000 compilation of the nine 30 by 60 minute quadrangle sheets centered on the Blue Dragon map. The first, the Grand Canyon sheet, was released as an Open File Report in 2000; the last, Glen Canyon Dam sheet, was released in 2013. These maps integrate his extensive new mapping with digital compilation of all previous mapping. They include reports that summarize the geology of each sheet and collectively form a comprehensive geologic map of the 'new' Grand Canyon National Park that extends from Lake Powell to Lake Mead. An interactive version of parts of this map is available from the Arizona Geological Survey (http://rclark.github.io/grand-canyon-geology/).

Figure 10 is a new rock column that shows the entire 6 km thickness of stratified rocks of the Grand Canyon region at correct thickness (Karlstrom and Crossey 2019). It also shows the major unconformities (in red) with the length of the time breaks as informed by current geochronology and fossil evidence. It depicts the additional 2 km of Mesozoic rocks that have been eroded back from the rims of Grand Canyon but are present at Lees Ferry, Zion/Bryce National parks, and the Grand Staircase. The rock column also depicts the importance of faults, the reactivated nature of the Butte fault, monoclines, and water pathways through sandstone aquifers, karst, and fault networks, as well as many features of prior rock columns such as the weathering profile of weak and strong layers.





HERMIT SHALE

Original mud deposits provided excellent media for preservation of delicate impressions of ferns, insect wings and animal tracks.

SUPAI FORMATION

Middle and upper parts of this formation were deposited by rivers as red sediments. Limestones and sandstones deposited in a shallow, slowly retreating sea form the lower part.

Figure 7. A. Grand Canyon's three sets of rocks were shown in the early 1930s in the Mary Colter fireplace, which is still present at Bright Angel Lodge. B. 1932 NPS photo of ranger Ralph Reburn and tourists looking at a rock column in the Yavapai Geology Museum that was built by Eddie McKee, but dismantled perhaps in the 1960s. C. In the 1960s, inner Canyon geology interpretation on Kaibab and Bright Angel trails used a version of the Noble (1914) rock column and showed "This Exhibit" at every rock contact where hikers learned the layer names and some basic geology.

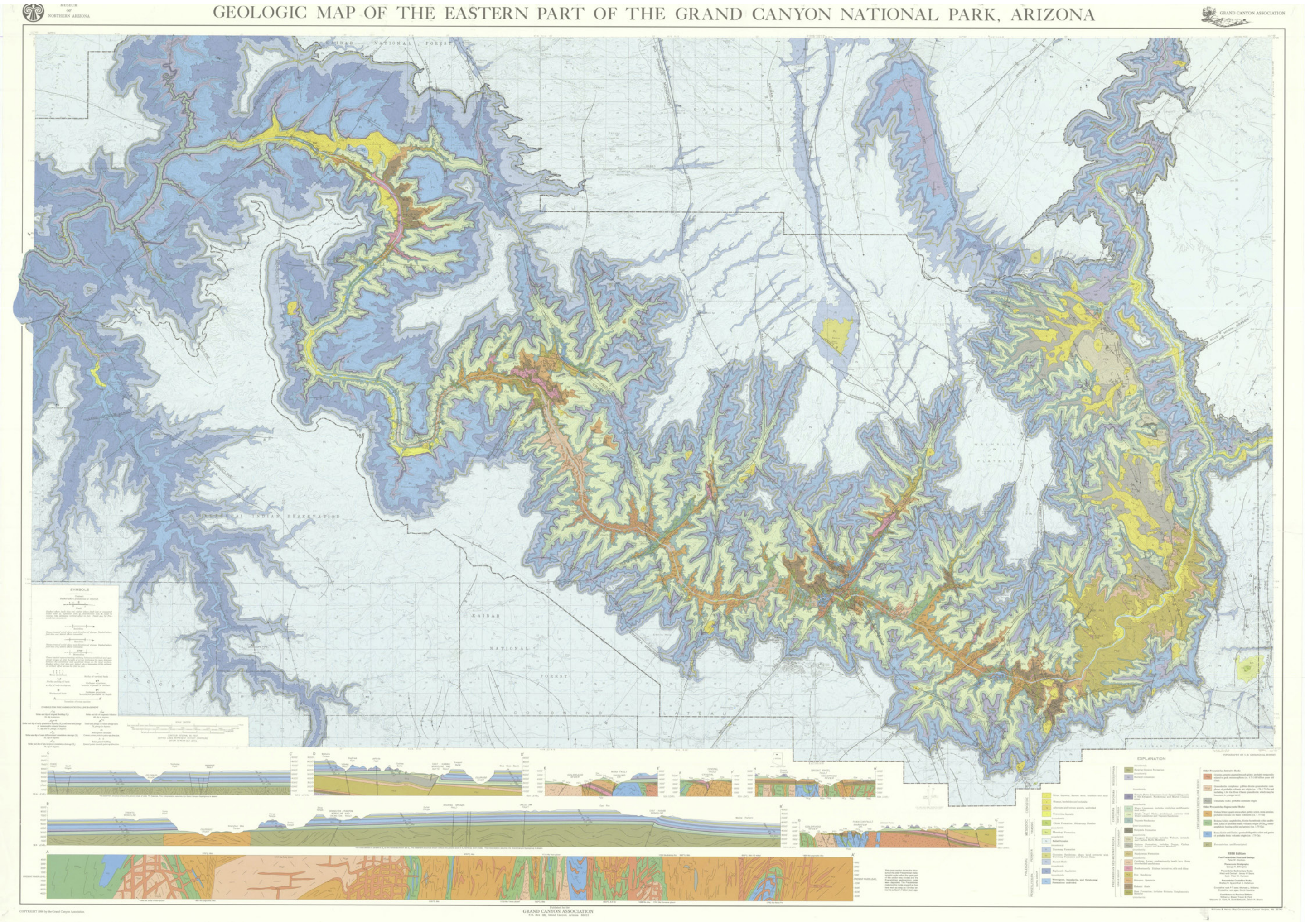


Figure 8. The Huntoon et al. (1996) *Geologic map of the eastern part of the Grand Canyon National Park, Arizona,* 1:62,500, published by the Grand Canyon Natural History Association, became known as the "Blue Dragon". This map is out of print.

ACTIVITY 1: LIPAN POINT ON THE EAST RIM DRIVE – GET TO KNOW THE LANDSCAPE AND THE GRAND CANYON SUPERGROUP

There are many pull-outs where one can view Grand Canyon, but Lipan Point is one of our favourites. If you are just entering the Park from the east (or just leaving), this stop provides a good introduction (or a good review). This area has high elevation viewpoints (2280 m; 7500 feet) because it is near the crest of the Kaibab uplift. Locate yourself on Figure 11 and see if you can identify the labeled features. To the north, across the river, is the Kaibab Plateau with strata bending gently down towards the east called the East Kaibab monocline. At the far right, off to the east, you can see the colourful Mesozoic rocks of the Triassic Chinle Formation of the Painted Desert. The confluence with the Little Colorado River historically marked the start of Grand Canyon. Powell camped there in 1869 and noted in his journal (1875b):

> *August 13th. We are now ready to start on our way down the Great Unknown.*
>
> *Our boats, tied to a common stake, chafe each other as they are tossed by the fretful river. They ride high and buoyant, for their loads are lighter than we could desire. We have but a month's rations remaining. The flour has been resifted through the mosquito-net sieve; the spoiled bacon had been dried, and the worst of it boiled; the few pounds of dried apples have been spread in the sun and reshrunken to their normal bulk. The sugar has all melted and gone on its way down the river. But we have a large sack of coffee. The lightening of the boats has this advantage, they will ride the waves better and we shall have but little to carry when we make a portage.*
>
> *We are three quarters of a mile in the depths of the earth, and the great river shrinks into insignificance as it dashes its angry waves against the walls and cliffs that rise to the world above; the waves are but puny ripples, and we but pygmies, running up and down the sands or lost among the boulders.*
>
> *We have an unknown distance yet to run, an unknown river to explore. What falls there are, we know not, what rocks beset the channel, we know not; what walls rise over the river, we know not. Ah, well! we may conjecture many things. The men talk as*

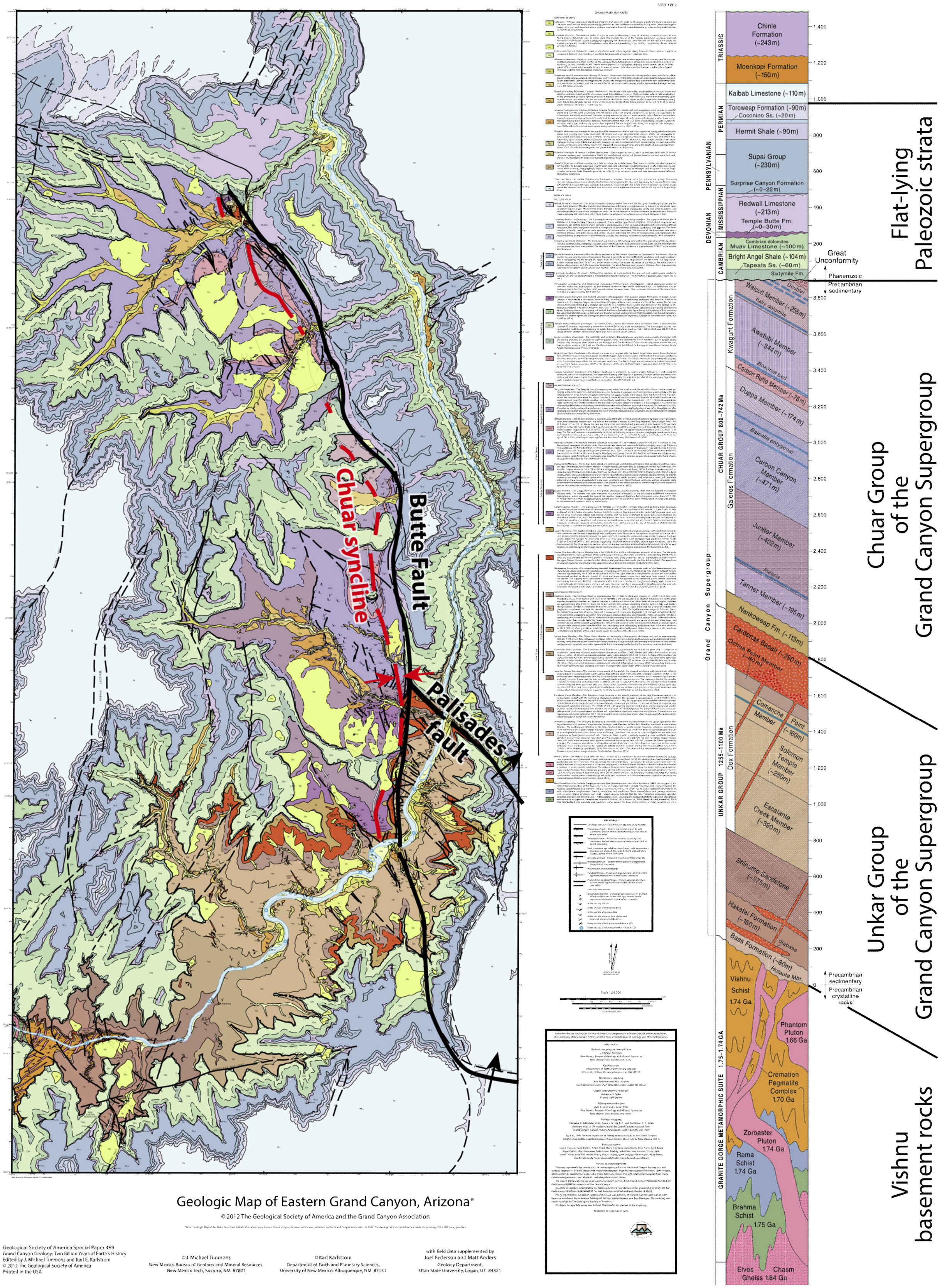


Figure 9. Timmons and Karlstrom (2012) *Geologic map of Eastern Grand Canyon, Arizona* showing updated rock column (from sheet 2, on backside). This map and the accompanying Geological Society of America Special Papers v. 489 are available as pdfs from the Geological Society of America (https://rock.geosociety.org/Store/detail.aspx?id=SPE489P).

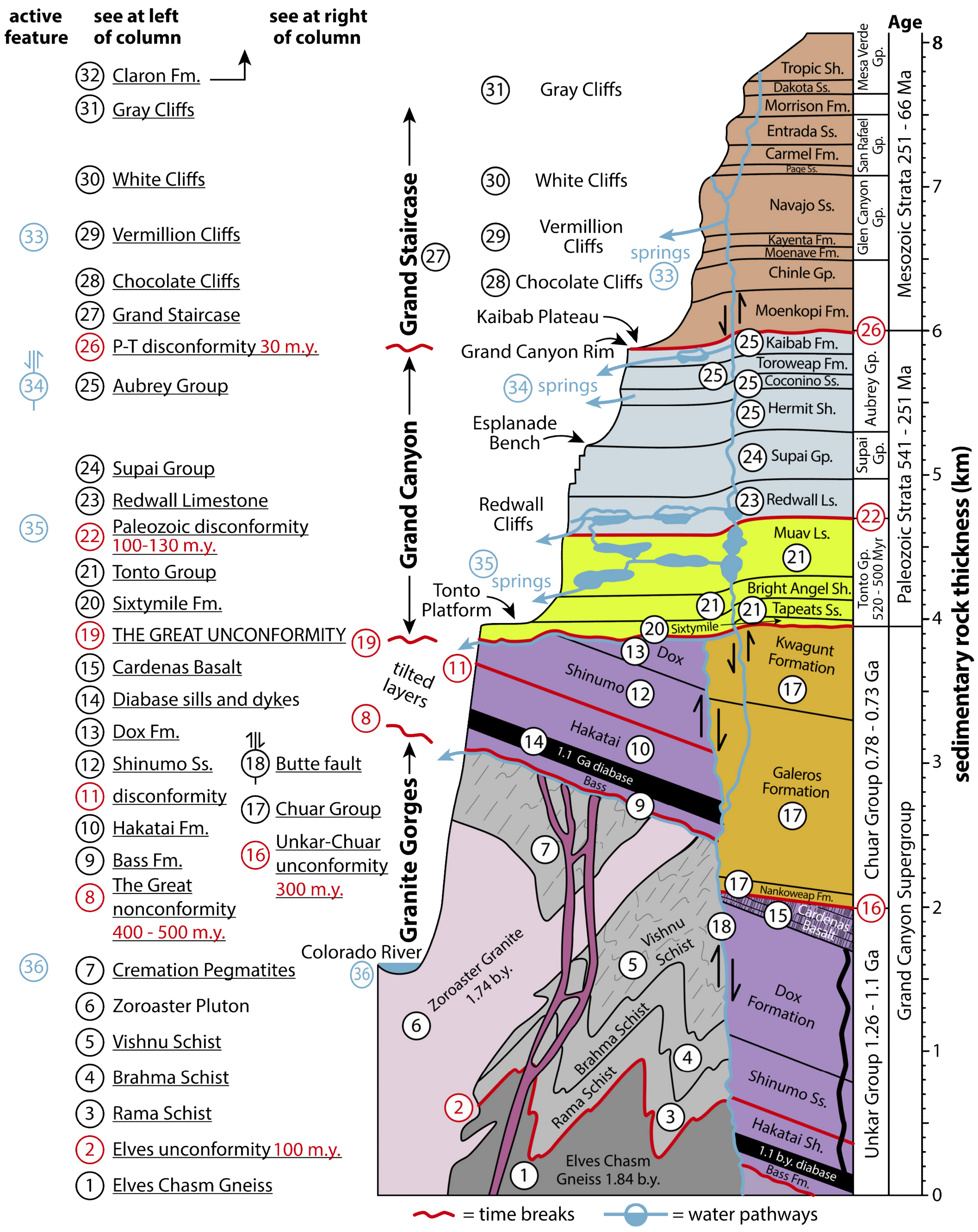


Figure 10. Stratigraphic column of rocks of the Grand Canyon region showing correct stratigraphic thicknesses for all stratified rocks, numeric ages of units based on 2019 geochronology, major unconformities (red) and time missing at each, faults, and water pathways; from Karlstrom and Crossey (2019).

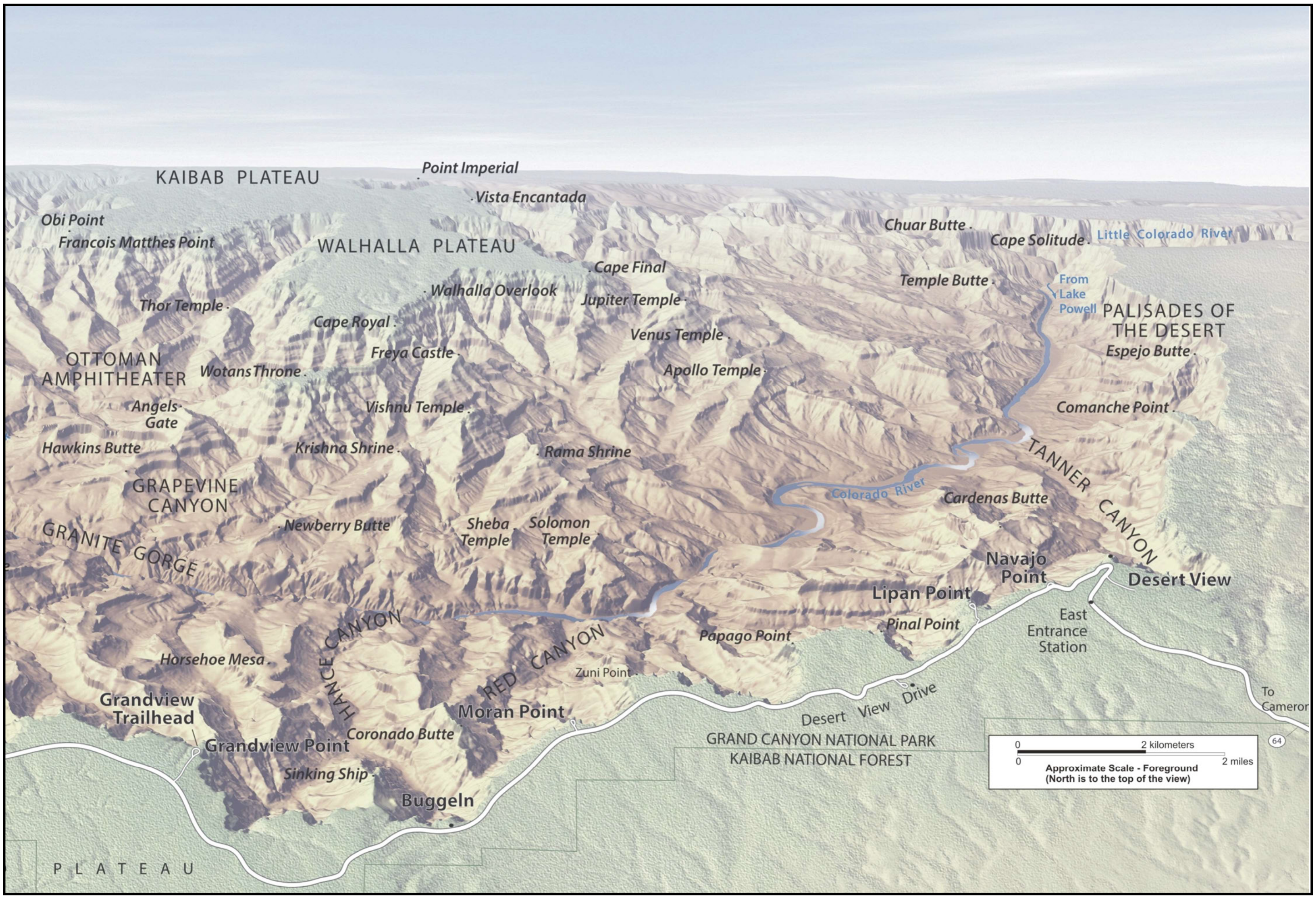


Figure 11. Eastern Grand Canyon perspective overview from the South Rim. From Lipan Point, see if you can spot the temples and towers and other features of the inner canyon; modified from a 2012 Park map made from a 10 m resolution digital elevation model (DEM).

> *cheerfully as ever; jests are bandied about freely this morning; but to me the cheer is somber and the jests are ghastly.*
>
> *With some eagerness and some anxiety and some misgiving we enter the canyon below and are carried along by swift water through walls which rise from its very edge. They have the same structure that we noticed yesterday – tiers of irregular shelves below, and, above these, steep slopes to the foot of marble cliffs. We run six miles in a little more than half an hour and emerge into a more open portion of the canyon, where high hills and ledges of rock intervene between the river and the distant walls....*"

To the far west, you can look into the Granite Gorge where basement rocks are first encountered on a river trip. Powell noted as they entered the Upper Granite Gorge: "*Heretofore hard rocks have given us a bad river; soft rocks, smooth water; and a series of rocks harder than any we have experienced sets in. The river enters the gneiss!*" And later: (August 27): "*About nine o'clock we come to the dreaded rock. It was with no little misgiving that we see the river enter these black, hard walls.*"

The big meander bend below is around Unkar delta which was once farmed by Ancestral Puebloans ~ 1000 years ago. To the south, away from the canyon, is the San Francisco volcanic field, one of numerous Quaternary volcanic fields in the region that were constructed over the past 10 million years by many eruptions; the volcanic field contains lava flows just 1000 years old at Sunset Crater National Monument.

Figure 12 shows and labels landscape features of the Grand Canyon region. Above Lees Ferry there is no Grand Canyon; this is Canyonlands country where thick Mesozoic strata are present, for example in the Vermillion Cliffs, Echo Cliffs, and Grand Staircase. At Lipan Point you are standing on the Permian Kaibab Limestone that was buried beneath about 2–3 km of Mesozoic strata until 25 million years ago. The south-flowing Colorado River through Marble Canyon makes a right turn to the west across the Kaibab uplift. The canyon here, between North and South Rim, is the widest and deepest part of Grand Canyon, 1.6 km (1 mile) deep and >16 km (>10 miles) wide. Thermochronology studies (Karlstrom et al. 2014) indicate that an earlier paleocanyon cut across the Kaibab uplift 25–15 million years ago; imagine a paleovalley in the air above and in front of you with its base below your feet and its rims made up of Mesozoic strata like those of the Vermillion Cliffs. Other Grand Canyon segments are very narrow (Marble Canyon and Muav Gorge) and some wider (Hurricane fault

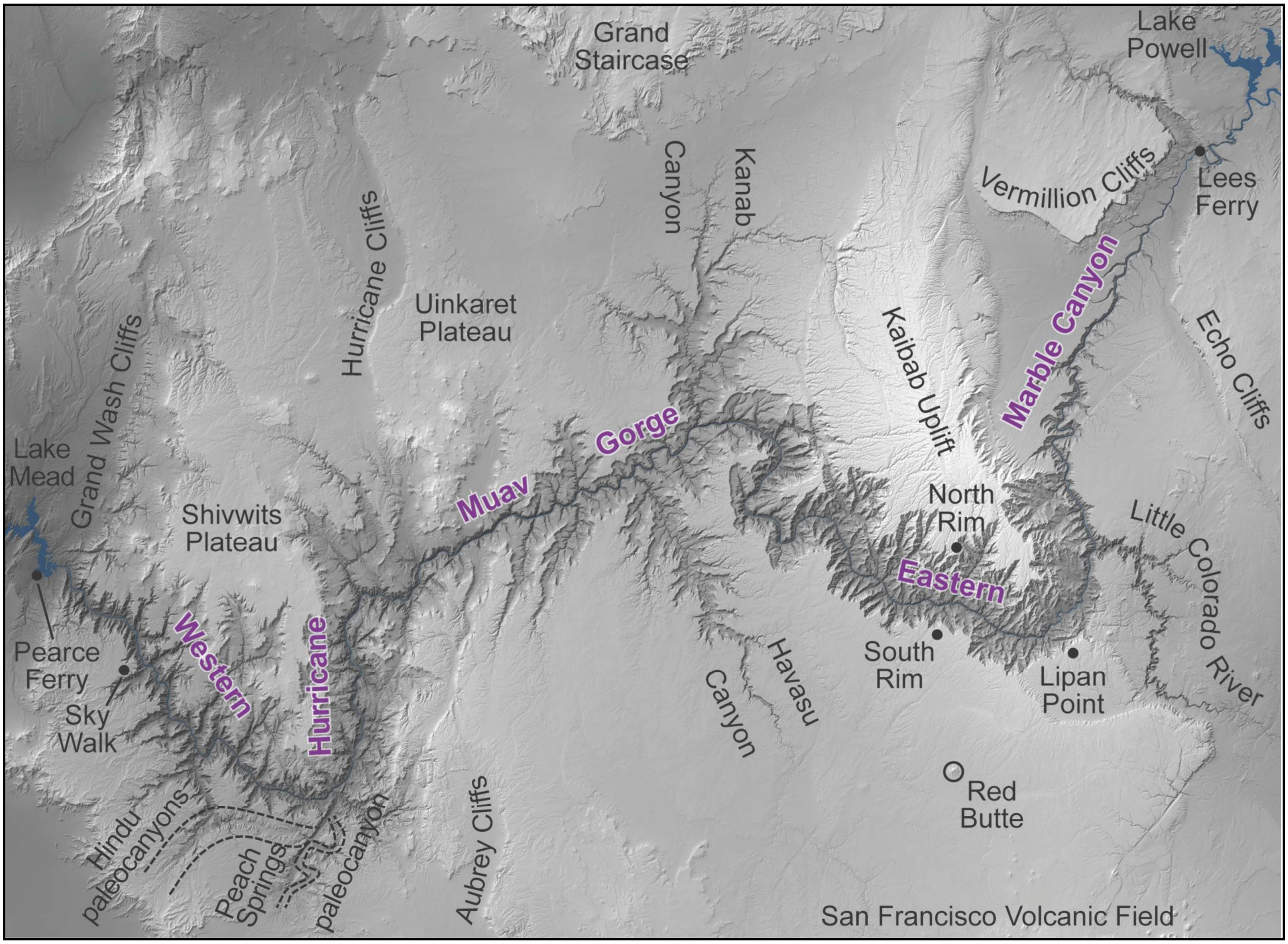


Figure 12. Labeled landscape elements of the Grand Canyon region that scientists and visitors alike need to know about to understand the century-long debate about the age and carving of Grand Canyon (discussed in text). The path of the Colorado River is a zigzag with distinct segments that have had different incision histories.

and Western segments). The Hurricane fault zone segment is where the Colorado River has re-occupied the path of an older north-flowing 65–55 Ma "Music Mountain" paleoriver. Hindu paleocanyon is still preserved in the landscape as a remnant of a paleocanyon filled with gravels of the 60–50 Ma Music Mountain Formation. Westernmost Grand Canyon is a young segment, cut into the Hualapai Plateau in the past 6 million years (Winn et al. 2017). The Grand Canyon ends amazingly abruptly where the Colorado River emerges through the Grand Wash cliffs and leaves the Colorado Plateau to enter the Basin and Range. Based upon sedimentary evidence (the Muddy Creek constraint) in the Lake Mead area, there was no Colorado River here until after 6 million years ago. The Red Butte (10 Ma) and Shivwitts (8–6 Ma) volcanic fields predated Grand Canyon, whereas the Uinkaret basalt flows cascaded into Grand Canyon over the past 800,000 years damming the Colorado River at least seventeen times (Crow et al. 2015).

Lipan Point is one of the best places to see much of the 4 km thick Grand Canyon Supergroup. The view is annotated in Figure 13. Powell noted the tilted red sandstones of the Dox Formation as he floated the section of the river below you. He called them "Old Red" because he thought they were like the Old Red Sandstone of Scotland (Kerr 2018). The colour was right, and so was the fact that the tilted Dox Formation overlies folded subvertical schist with an angular unconformity (the lower unconformity of Fig. 3B), just as the tilted Devonian Old Red Sandstone rests with angular unconformity above vertical Silurian greywacke across Hutton's famous angular unconformity (Hutton 1788). Powell's Great Unconformity (actually named with an upper case "G" and "U" by Dutton) encodes more missing time and different orogenic events than Hutton's unconformity, but the analogy made by Powell was astute and reflected his global knowledge. Figure 13 also directs your eye to the two major unconformities that Powell drew (Fig. 3). The lower one, far to the left in this view, is where tilted but unmetamorphosed sedimentary rocks of the Grand Canyon Supergroup (Bass Formation) overlie igneous and metamorphic Vishnu basement rocks, a nonconformity. More evident, across the river, is the Great Angular Unconformity where the flat-lying Cambrian Tonto Group overlies the

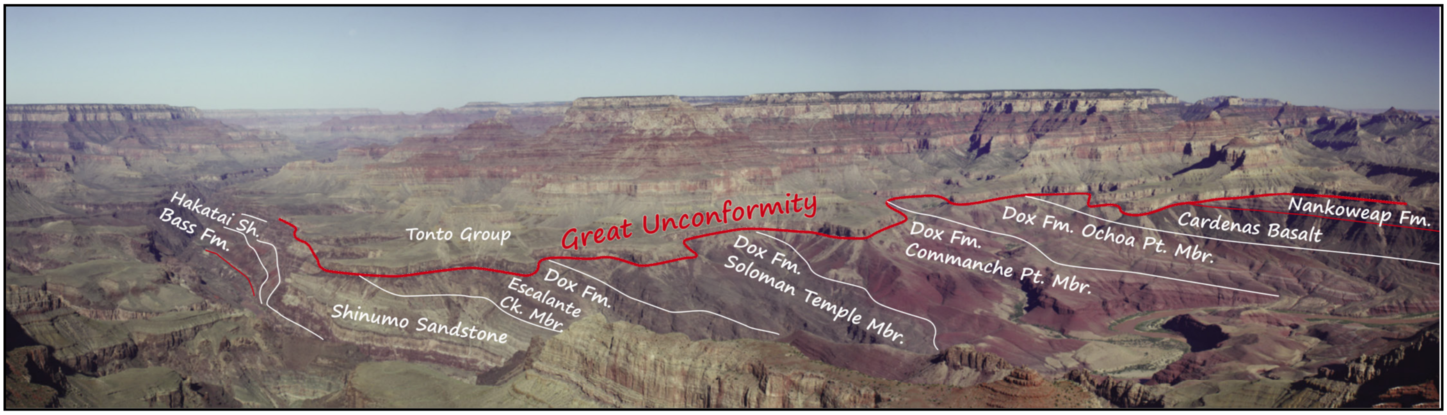


Figure 13. Looking north from Lipan Point in eastern Grand Canyon, flat-lying Tapeats Sandstone (508 Ma) rests on tilted Unkar Group (1250 to 1100 Ma). Up to 750 million years of history are missing between them. This is called an angular unconformity because the Unkar Group was tilted and eroded before the Tapeats Sandstone of the Tonto Group was deposited.

tilted Grand Canyon Supergroup. The amount of time across these unconformities varies and one needs to know the ages of rocks below and above the erosion surface. About 500 million years are missing (not recorded) across the sub-Bass Formation Great Nonconformity where rocks are 1750 Ma below and 1250 Ma above the nonconformity. Where the 1250 Ma Bass Formation is below the 508 Ma Tapeats Sandstone (far left) about 740 million years are missing. Where the 1100 Ma Cardenas Basalt is below the 508 Ma Tapeats Sandstone (at right) 592 million years are missing. Where the 785 Ma Nankoweap Formation of the Chuar Group is below the 508 Ma Tapeats Sandstone (at far right) 'only' 277 million years are missing. You can see Grand Canyon's unconformities again from the Yavapai Geology Museum and the Trail of Time, but they are harder to spot there and it helps if you can unravel this spectacular and classic view first.

ACTIVITY 2: YAVAPAI GEOLOGY MUSEUM AND THE TRAIL OF TIME EXHIBIT

From Lipan Point, drive about 35 km (22 miles) west to Yavapai Geology Museum and the start of the Trail of Time (Fig. 14). You can easily occupy half to a full day seeing Grand Canyon's geology from Yavapai Observation Station plus a hike on the Rim Trail along the Trail of Time Exhibit. In the late 1990s there was an effort to re-invigorate the link between research advances and Park geoscience interpretation. This led to renovation of the Yavapai Geology Museum in the early 2000s and the opening of the Trail of Time Exhibit in 2010. The Trail of Time Companion walking guide was published in 2019 to enrich the exhibit (Karlstrom and Crossey 2019). This walking guide is entitled "*The Grand Canyon Trail of Time Companion: Geology essentials for your Canyon adventure*". It is available at the bookstores of the Grand Canyon Conservancy at each end of the Trail, at the Park Visitor Center, and online (https://rock.geosociety.org/Store/SearchResults.aspx?searchterm=trail+of+time&searchoption=ALL).

Yavapai Geology Museum. This historic building (Fig. 15) was opened to the public in 1928. Its location was chosen by Edwin McKee and other geologists as the best place to view and interpret Grand Canyon's geology. It was called "The Room with a View" in the days when it was open air and had no windows. Some of the highlights include the three dimensional landscape model that provides a bird's-eye view of eastern Grand Canyon, rock columns that show the stratigraphy, and the views from the parapet. Figure 16 shows some key features and some complex geology seen from the central window. The Vishnu basement rocks are in the Granite Gorge about 1.6 kilometre (1 mile) below you. The Unkar Group of the Grand Canyon Supergroup can be seen beneath the Cambrian Tonto Group. The resistant Shinumo Sandstone stuck up as much as 250 m (800 feet) as islands (monadnocks) in the Cambrian sea that were fringed by 508 Ma beach sand of the Tapeats Sandstone. These islands eventually got covered by mud of the Bright Angel Formation as the Tonto Group strata accumulated during the advance of the sea across the continent 500 million years ago (see section on Sauk transgression; stop #9). Temples were named by early explorers and geologists. Both rims of Grand Canyon are formed by the resistant Permian (270 Ma) Kaibab Limestone that also forms wide erosional benches to the north and south of Grand Canyon (Kaibab and Coconino plateaus). In the foreground is Plateau Point, the hike described as Activity 3. The flat area it traverses in this picture is the Tonto Platform, which was eroded flat on top of the weak Bright Angel Formation as resistant cliffs of the Muav Formation retreated back from the river.

The Trail of Time Exhibit is a geological timeline exhibit along the Rim Trail between Yavapai Point and Maricopa Point. It has 3 segments that can be walked all as one hike, or separately as time allows (Fig. 17). The Trail of Time Exhibit was funded by the National Science Foundation in partnership with Grand Canyon National Park, and academics (Karlstrom et al. 2008). It starts a few hundred metres west of the west door of Yavapai Geology Museum. The Trail of Time has four entry portals: two near Yavapai Geology Museum (Fig. 18), Verkamps Visitors Center in Grand Canyon Village, and near Park Headquarters. The portals were built from the 'real rocks' that were collected on the river and brought out on rafts. We also collected the 45 rock exhibits by raft, and some using helicopters. The three-dimensional portals are useful as teachable visualizations

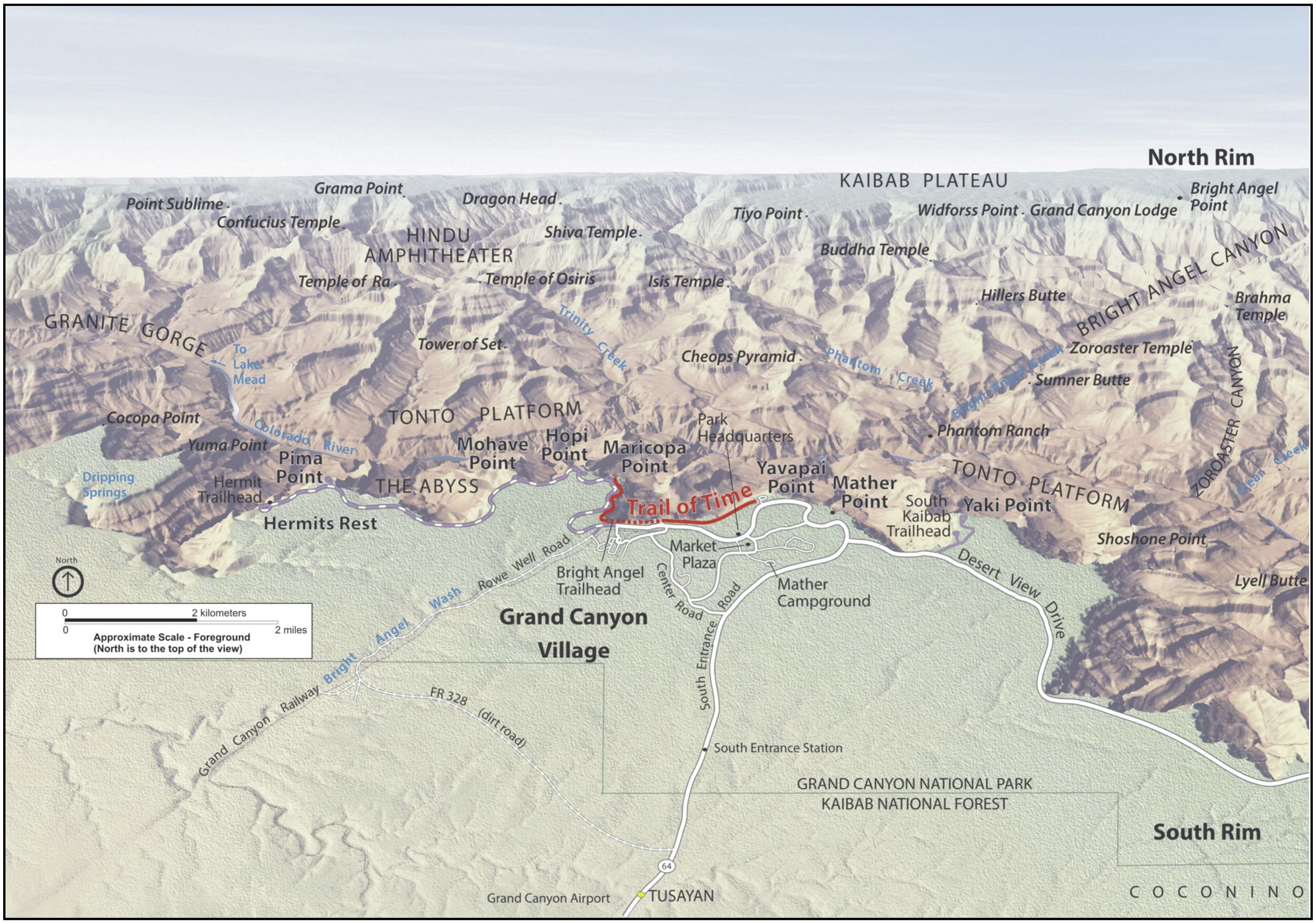


Figure 14. Perspective overview from the South Rim. See if you can spot the temples and towers and other features of the inner canyon. The Trail of Time (red) is located in the main visitor areas at Grand Canyon's South Rim. The young end (the "Today" bronze marker) is near Yavapai Geology Museum; the old end (the 2000 million year bronze marker) is near Verkamps Visitor Center in Grand Canyon Village. Parking and shuttle bus stops can be found at the Visitors Center, Yavapai Museum, and Grand Canyon Village.

of Grand Canyon's rock layers. Notice the three prominent sets of rocks: the basement block, the tilted Grand Canyon Supergroup strata, and flat-lying Paleozoic strata. Each of the portals has different portal elements, for example, the portal at the young end of the Trail (Fig. 18) has the youngest rocks in Grand Canyon, travertine and basalt, as seating rocks and pavers.

Million Year Trail. About 200 metres (650 feet) west from the west door of Yavapai Museum is the first Trail of Time portal and the Time Zero (Today) bronze marker that starts the Million Year Trail. This segment was designed as an 'on-ramp' to the Main Trail of Time; think of it as a 'time accelerator'. It is marked as a variable-scale timeline, starting with one metre representing one year. Find your age marker and have your group line up by age. Then, accelerate to one step equals 10, 100, 1000, 10,000, and 100,000 years. This segment has wayside signs that discuss the history of people at Grand Canyon, climate change, earthquakes and volcanoes, topics that are directly relevant to the geologically brief human timeframe. The "Magic Meter" at the end of this segment (Fig. 19) may prompt you to think about all the things that can occur in a million-year timespan. For example, think of the approximately 50,000 human generations that lived during the past one million years. Hold that thought as you enter the Main Trail, where time passes a million years with each step.

Main Trail of Time. After you have walked a million years, you are 'ready' to enter the Main Trail of Time. This segment extends from here to Grand Canyon Village, 2 km (1.24 miles) away. This portal has Paleozoic sandstone for pavers and seating rocks. Look for trackways in the pavers from Permian mammal-like reptiles. This is a good place to get to know (or review) the rock layers in the portal as labeled in Figure 20.

1) The flat-lying sedimentary layers: The Paleozoic (ancient life) Era was from 541 to 252 Ma (~290 Ma in duration) and the 1 km (3300 foot) thickness of Grand Canyon layers record about half of this time. To

Figure 15. Yavapai Geology Museum; this building was first open to the public in 1928 and continues to fulfill the "Yavapai Concept" articulated by Edwin McKee as a goal to "*point out and interpret the outstanding and unique features of the Grand Canyon*".

remember the rock names, use this mnemonic: **K**now **T**he **C**anyon's **H**istory, **S**tudy **R**ocks **M**ade **B**y **T**ime. The first letter of each word stands for (from the top): **K**aibab Limestone, **T**oroweap Formation, **C**oconino Sandstone, **H**ermit Formation, **S**upai Group, **R**edwall Limestone, **M**uav Formation, **B**right Angel Formation, and **T**apeats Sandstone.

2) The tilted sedimentary layers are the Grand Canyon Supergroup, made up of the Unkar Group (1256–1100 Ma) and the Chuar Group (780–729 Ma), each about 2 km (6560 feet) thick; these are shown at half scale in the portals. All are sedimentary layers except the black layer, the Cardenas Basalt, which is volcanic. These strata were deposited horizontally and later were tilted into fault blocks (like in the modern Basin and Range Province). They contain the earliest life recorded in Grand Canyon – single-celled life that formed stromatolites in the Bass Formation.
3) The Proterozoic Vishnu basement rocks record the assembly of the continent 1.84 to 1.66 billion years ago. These rocks have a profound vertical metamorphic layering (foliation) and vertical intrusions. These rocks were deformed during mountain building (orogeny) in which crust was squeezed, folded, thickened, and metamorphosed in a plate collision zone during the assembly of this part of the North American continent. The basement rocks were metamorphosed at 20–25 km (12.4–15.5 mile) depths beneath now-eroded mountain tops (Dumond et al. 2007). As the mountains were eroded, rocks from the middle crust were exhumed to reach the surface by the time of deposition of the Bass

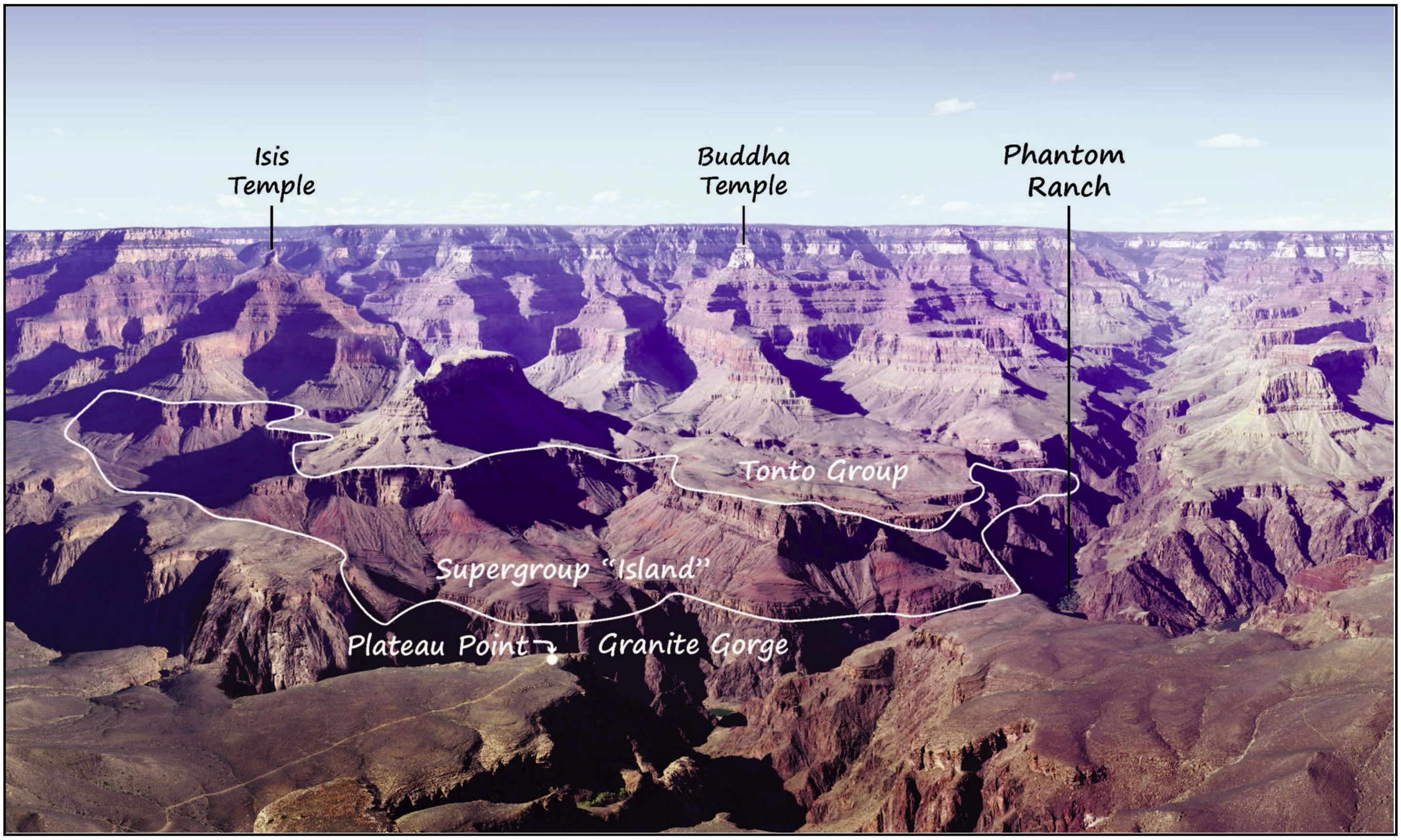


Figure 16. View from the centre window of Yavapai Geology Museum. Look within the layers to see the ancient island (monadnock) of tilted Grand Canyon Supergroup rocks that was fringed by 508 million year old beach sands of the Tapeats Sandstone and eventually got covered up by muds of the Bright Angel Formation as the Tonto Group strata accumulated.

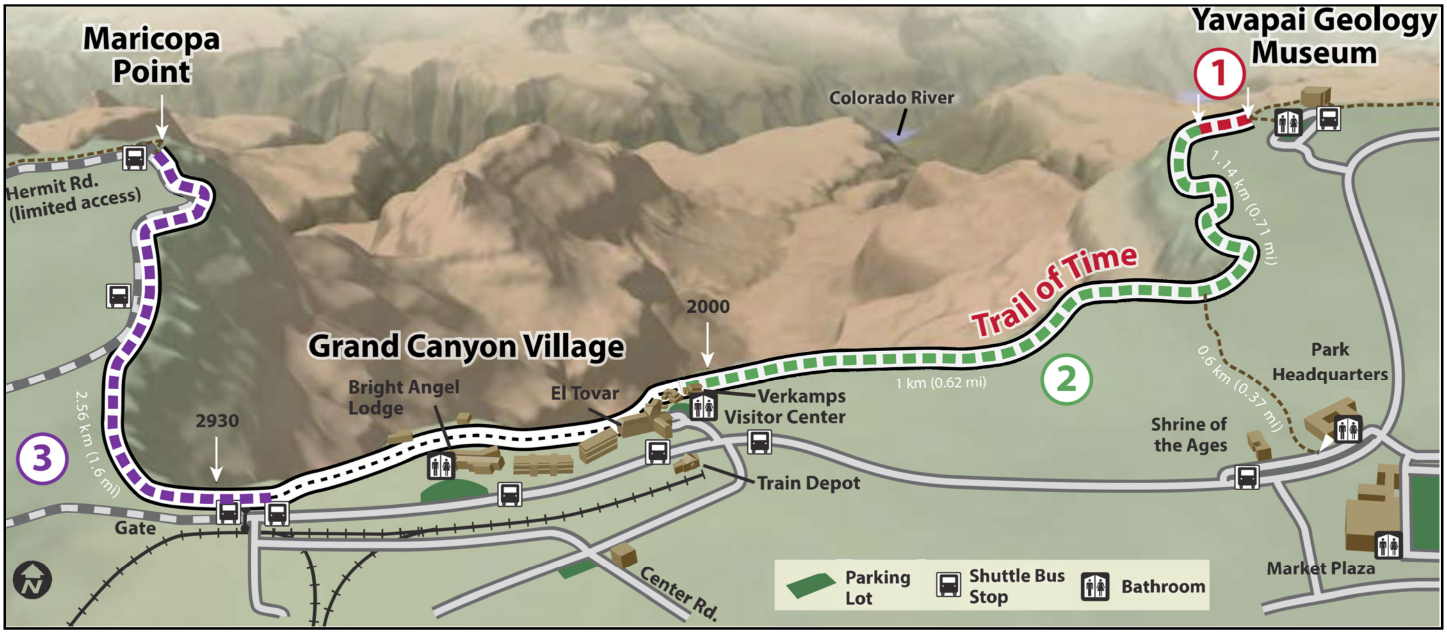


Figure 17. How to walk the Trail of Time geology timeline? It has 3 segments: 1. Million Year Trail, 2. Main Trail of Time, and 3. Early Earth Trail. The walk on the Main Trail of Time, marked at 1 m equals one million years, is 2 km long; the Early Earth Trail takes you to the age of the Earth at the 4560 million year marker near Maricopa Point.

Formation, 1250 million years ago. At this time, the mountains had been eroded flat to form the Great Nonconformity surface, and the continent may have looked a bit like modern-day Australia.

Figure 21 shows examples of some of the rocks you will see along the Main Trail of Time. Note that the history of carving Grand Canyon takes place in just the first 6 steps (6 million years) of the Main Trail of Time. You don't get to the Kaibab Limestone for 270 m. The Grand Canyon Supergroup is about one kilometre (1000 long steps) and one billion years down the timeline trail where there is a portal on the intersecting Headquarters Trail. The oldest rock unit in Grand Canyon, the Elves Chasm Gneiss, is 1840 m (1.84 billion years) away and near to the other end of the Main Trail near Grand Canyon Village. When you find yourself in long stretches of the trail where there are no rock exhibits, you are in the time of unconformities, where long portions of the geological record are missing in Grand Canyon and geologists need to go elsewhere to learn about what happened. Near Grandeur Point, near the 146 million years ago marker, take a look over at the Bright Angel Trail as it switchbacks down the Bright Angel fault (Fig. 22); this is your hike if you do Activity 3.

Early Earth Trail. The Trail of Time was not marked through the busy Historic Village area, but picks up again at the west end of the Village near the Hermits Rest shuttle bus stop. The village area has some must-see stops, including the 1905 El Tovar Hotel, 1905 Hopi House, and 1935 Bright Angel Lodge. The stone wall along the canyon rim path was built by workers from the Civilian Conservation Corps in the 1930s. En route between the Early Earth Trail and Main Trail of Time, check out Mary Colter's geological fireplace at Bright Angel Lodge

Figure 18. Entry portals for the Trail of Time Exhibit used a veneer cut from rocks collected along the river; they depict the three sets of rocks, two major unconformities, the canyon erosion profile, and the inner gorge.

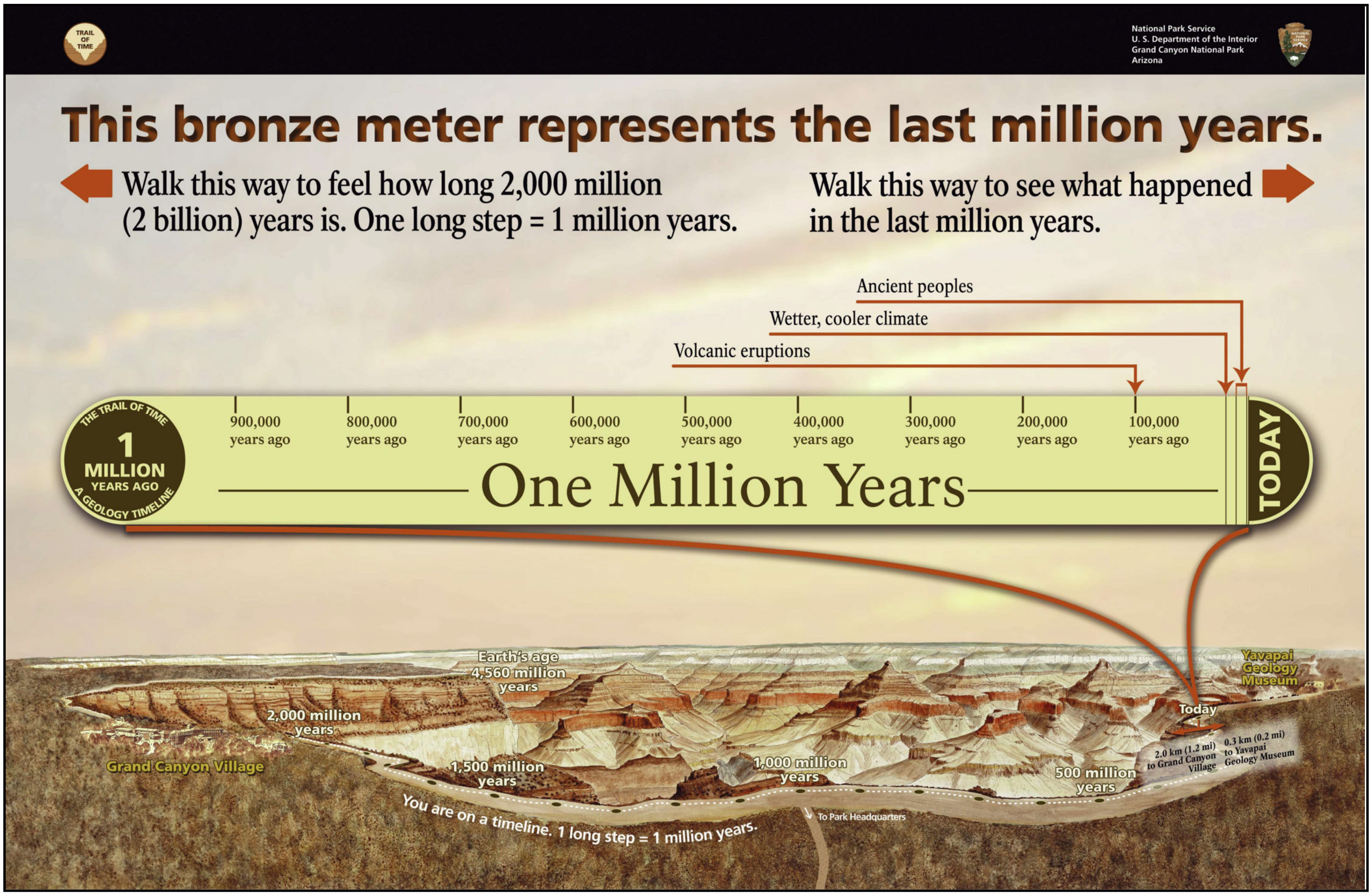


Figure 19. The Magic Meter encodes events of the past 1 million years. After walking 0.3 km (0.2 miles) west from Yavapai Geology Museum, you reach the Main Trail of Time portal. This bronze meter is inset to record the time-scale shift to the Main Trail of Time where 1 m = 1 Ma. The Magic Meter has "Today" on one end and 1 Million Years ago on the other. It has lines that show when humans arrived on the North American continent and the other events of the Million Year Trail.

(depicted in Fig. 7A). The time from 4000 to 2930 Ma predated any Grand Canyon rocks, but Vishnu Schist contains mineral grains this old. This steeper section of the Trail of Time is not fully accessible to wheelchairs and not as heavily visited as the Main segment. The views are spectacular. Numbered bronze trail markers designate the timeline every 10 m extending to a 4560 million year marker near Maricopa Point (Fig. 23). To get back to the Village from Maricopa Point, either walk back on the Early Earth Trail about 1.6 km (one mile) or walk farther on about 600 m (0.37 miles) to Powell Point, where you can take a shuttle back to the Village (except in winter months). The earliest history of the Earth involved such intense meteorite bombardment that Earth's crust was continually remelted and reworked. Because of this, the oldest rocks found on Earth (that are *from* Earth) are about 4 billion years old (4 Ga). The oldest rocks *on* Earth came from the solar system in the form of meteorites. From radiometric dating of meteorites, we know that the Earth and solar system are 4.56 Ga. A fitting rock for the end of the Trail of Time (not yet obtained) would be a meteorite such as the Diablo Canyon meteorite that made Meteor Crater. A bronze marker for the age of the Universe (13.75 billion years ago) was installed at Pima Point; you can find it if you take the Hermits Rest bus farther west.

A Fossil Walk would not seem to 'belong' along the Early Earth part of the timeline trail because animal life did not develop on Earth until 630 Ma, and the first shelled fossils developed about 540 million years ago. However, there are some excellent fossils exposed in the Permian Kaibab Limestone (Fig. 24) near the 3150 Ma marker on the Early Earth Trail. You can look (and think back) to the 270 Ma marker and the Kaibab Limestone where these would fit on the Main Trail of Time timeline. See how many different types of fossils you can find, such as brachiopod shells, sponges that have been variably turned to chert nodules, corals, disk-shaped crinoid stem segments, and web-like bryozoans. These animals were mostly filter feeders that lived and died in the Permian oceans about 270 million years ago. Less than 20 million years later, at 252 Ma, about 95% of all these marine species went extinct during the largest global mass extinction, called the "Great Dying" (e.g. Benton and Twitchett 2003). One of the biggest changes was that clams, snails, and advanced corals came to dominate the seafloor instead of brachiopods, bryozoans and crinoids. The likely cause of this extinction was massive volcanism in Siberia that altered global climate and ocean chemistry.

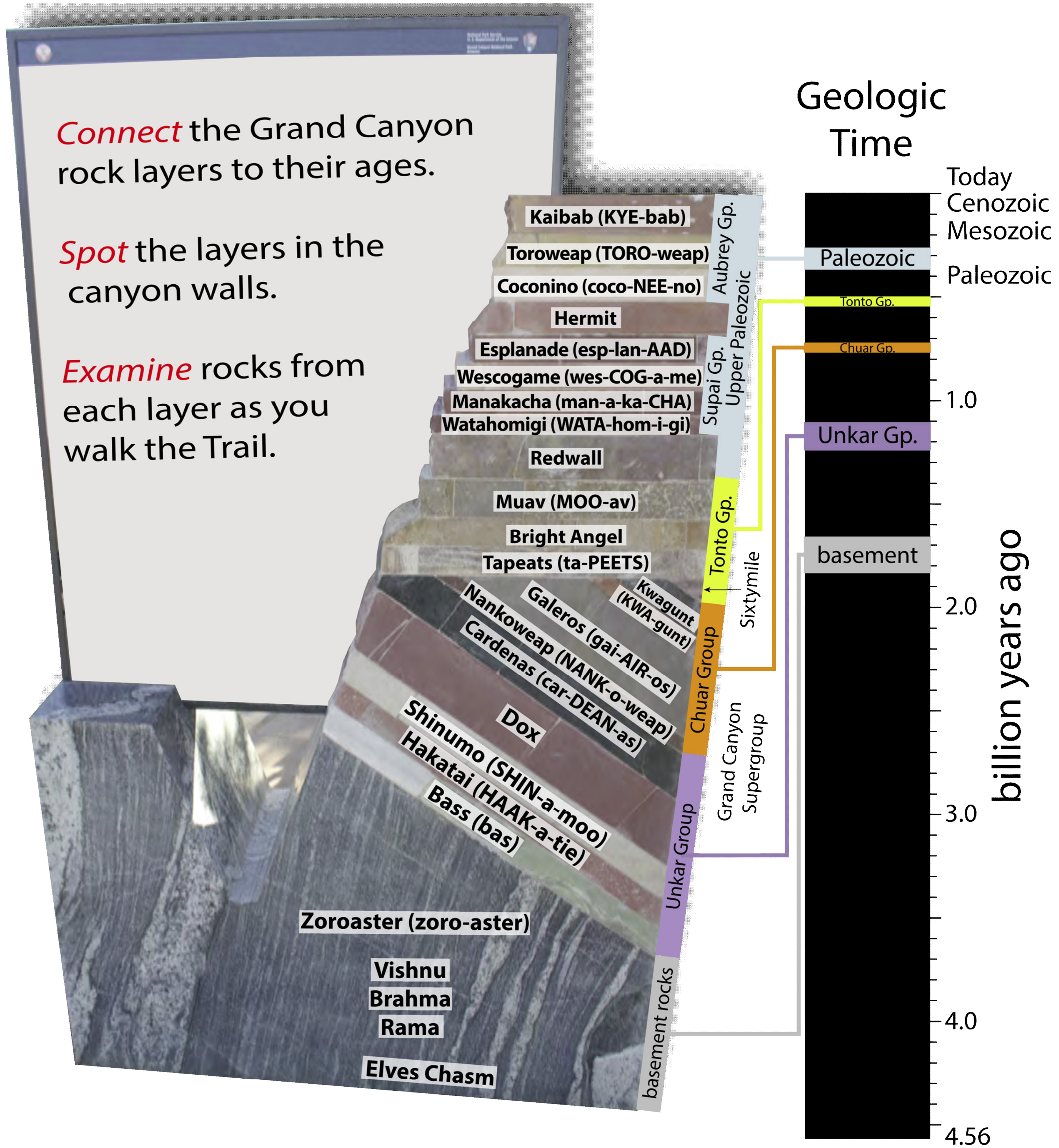


Figure 20. Connect with, touch and examine time and rock – the rock column in Grand Canyon looks amazingly complete (a vertical mile of rock), but the time column shows that there is more time 'missing' (black) across unconformities than is recorded by rock. To estimate what fraction of Earth history is recorded here; calculate what percentage is not black.

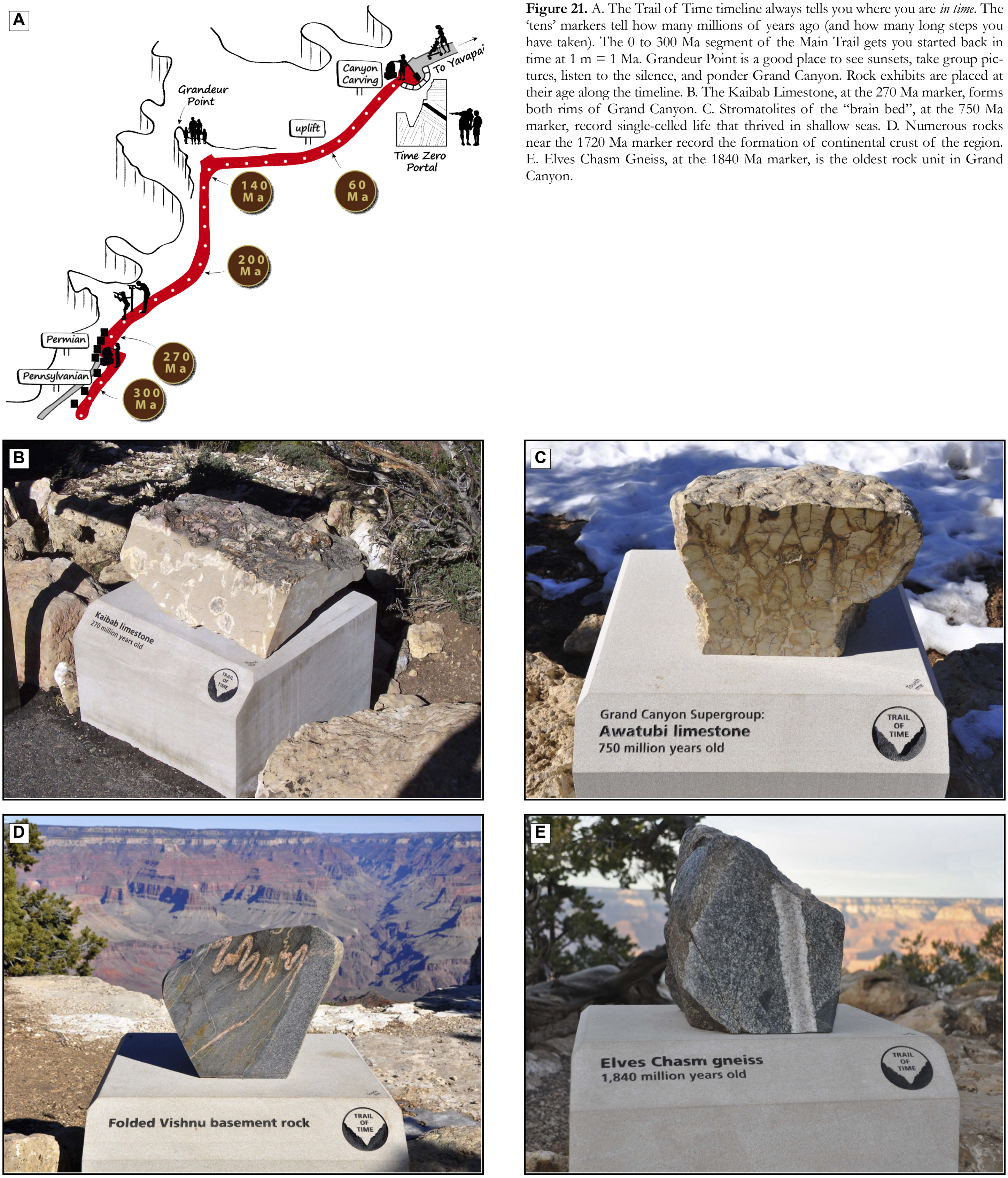


Figure 21. A. The Trail of Time timeline always tells you where you are *in time*. The 'tens' markers tell how many millions of years ago (and how many long steps you have taken). The 0 to 300 Ma segment of the Main Trail gets you started back in time at 1 m = 1 Ma. Grandeur Point is a good place to see sunsets, take group pictures, listen to the silence, and ponder Grand Canyon. Rock exhibits are placed at their age along the timeline. B. The Kaibab Limestone, at the 270 Ma marker, forms both rims of Grand Canyon. C. Stromatolites of the "brain bed", at the 750 Ma marker, record single-celled life that thrived in shallow seas. D. Numerous rocks near the 1720 Ma marker record the formation of continental crust of the region. E. Elves Chasm Gneiss, at the 1840 Ma marker, is the oldest rock unit in Grand Canyon.

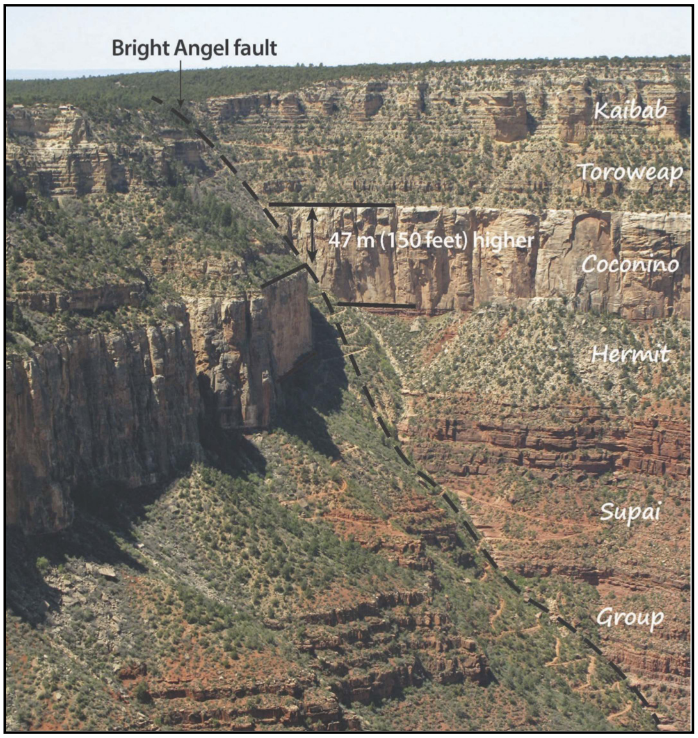


Figure 22. Bright Angel fault as seen from Grandeur Point on the Trail of Time (Fig. 21A) has about 93 m (150 ft) of southwest-side up movement. This is the net offset of the Paleozoic strata, but there has been a long history of prior movements as you can see from stop #10.

ACTIVITY 3: DOWN THE BRIGHT ANGEL TRAIL

The Bright Angel Trail follows a route that was long-used by Native Americans as they walked into and out of the Grand Canyon. It was improved by Ralph Cameron in the early 1900s who charged a $1 toll for visitors to use it before the Park acquired it in 1928. The trail switchbacks down through the steep areas where there are natural breaks in the usually insurmountable Coconino and Redwall cliffs. These breaks are made by the Bright Angel fault, as seen in the geologic map (Fig. 25) and in the view from the Main Trail of Time (Fig. 22). The trail-head is located at the west end of Grand Canyon Village (#1 of Fig. 25). No matter how far down you go, you'll get a new appreciation of Grand Canyon. A rule of thumb for many hikers is that it takes twice as long climbing out as it took walking down. Take pictures and sketches, but don't take any samples in the National Park.

Figure 24. There are great fossils in the Permian Kaibab Limestone near marker 3150 Ma on the Early Earth Trail. They do not 'belong' at this place in the timeline, but you can look/think back from here to their place on the timeline at the 270 Ma marker.

Stops #1–5: Depending on your hiking speed and amount of time you take geologizing and taking pictures, you should be able to get down to stop #3 at the formation contact between the Coconino Sandstone and Hermit Formation and back up

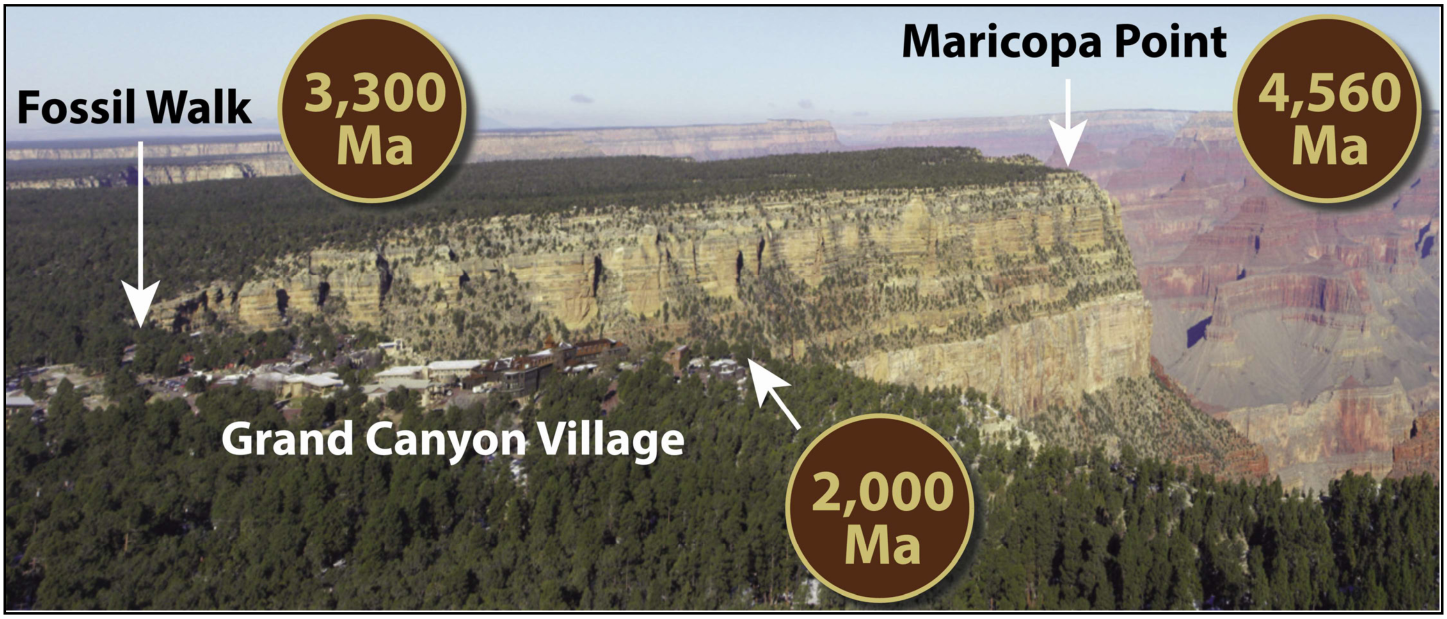


Figure 23. What went on in Earth's history before the oldest Grand Canyon rocks? The Early Earth segment of the Trail of Time is marked from the Hermit Transfer shuttle bus stop at the far west end of the historic village area and continues north to Maricopa Point.

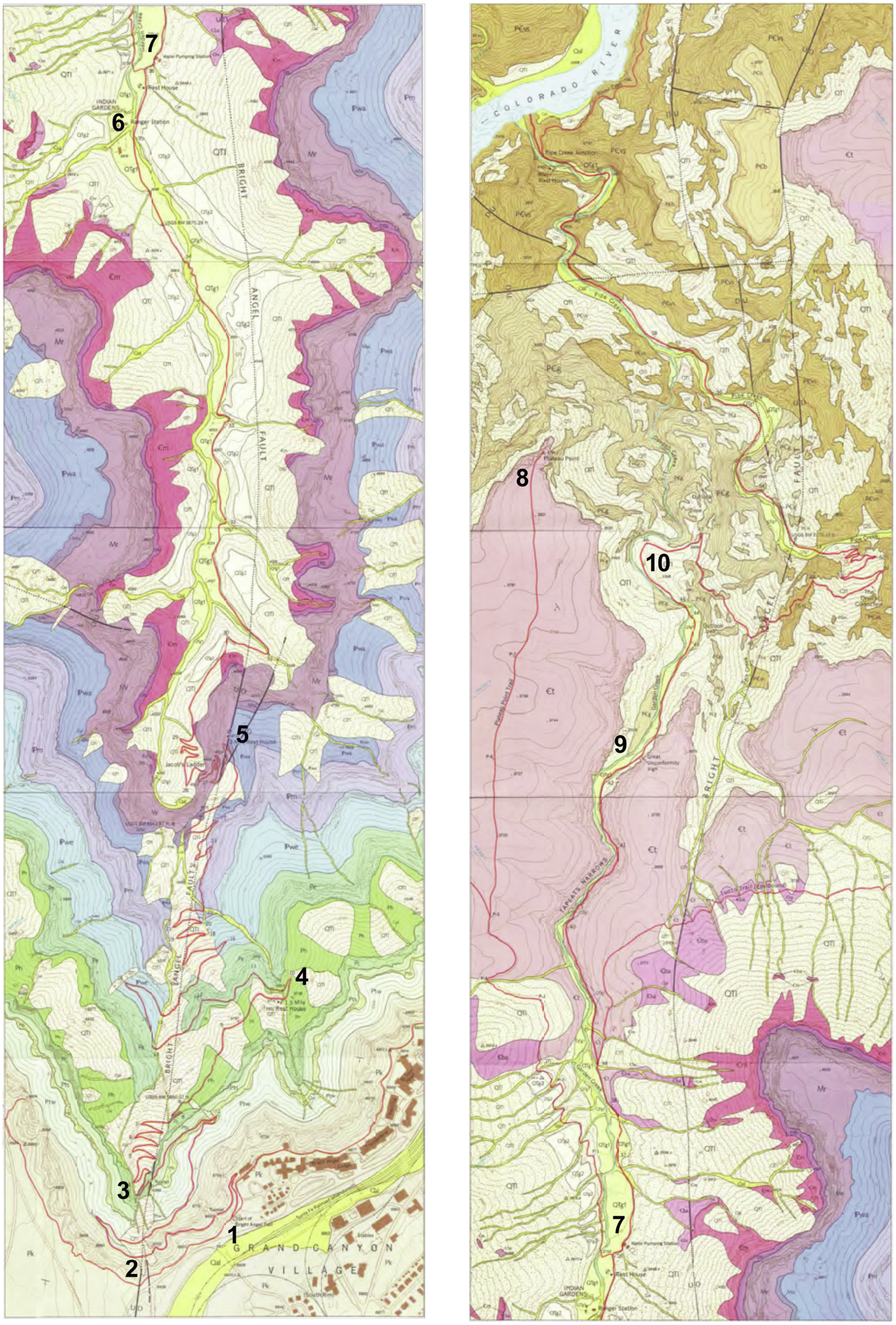


Figure 25. Geologic map of the Bright Angel Trail (Billingsley and Breed 1986) with numbers corresponding to features and sights discussed in the text.

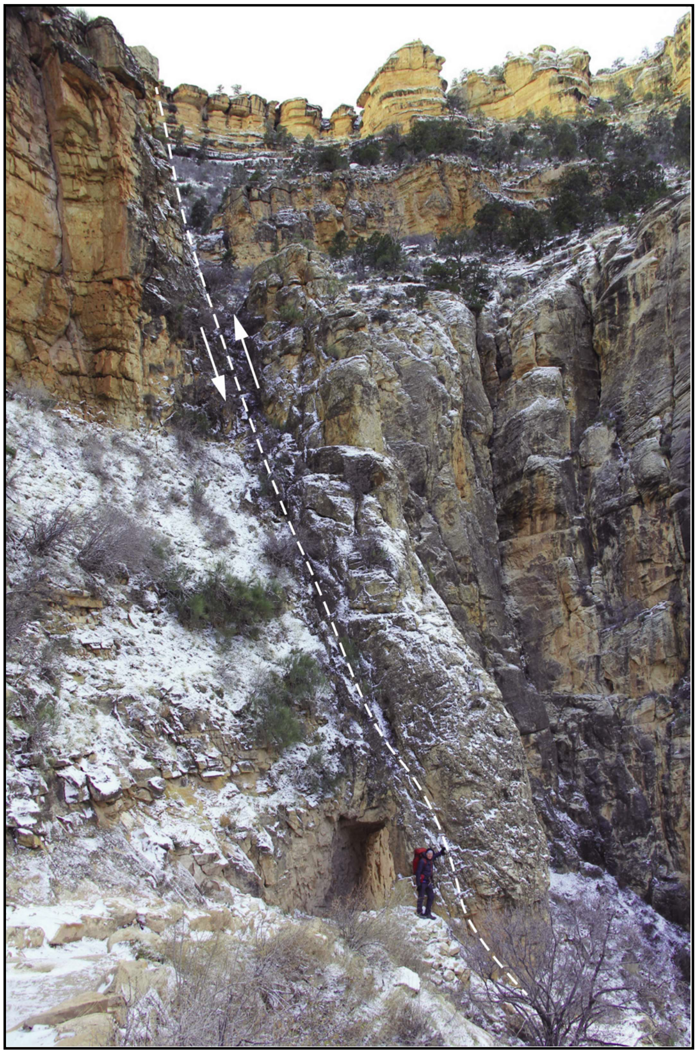


Figure 26. Stop #2: near the second tunnel along the Bright Angel Trail, allows you to put your hand on the Bright Angel fault zone. You can see numerous small faults and breccia zones in this area of the trail and in the tunnel.

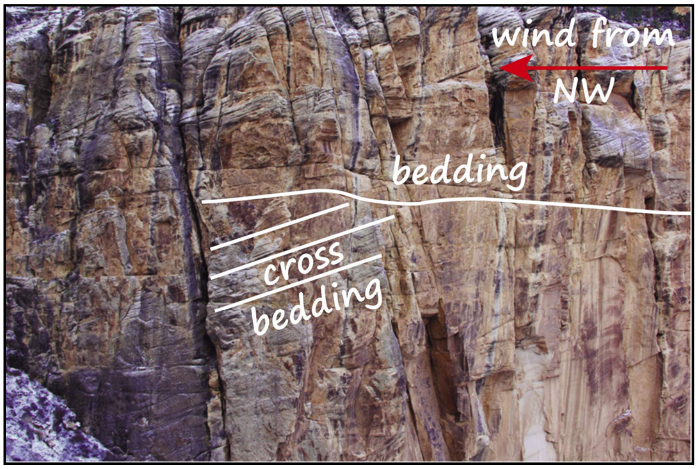


Figure 27. Stop # 3: the dipping foreset beds of large cross-bed sets in Coconino Sandstone were once the steep downwind face of huge sand dunes; they tell us that the winds were blowing from the northwest (present coordinates) 280 million years ago.

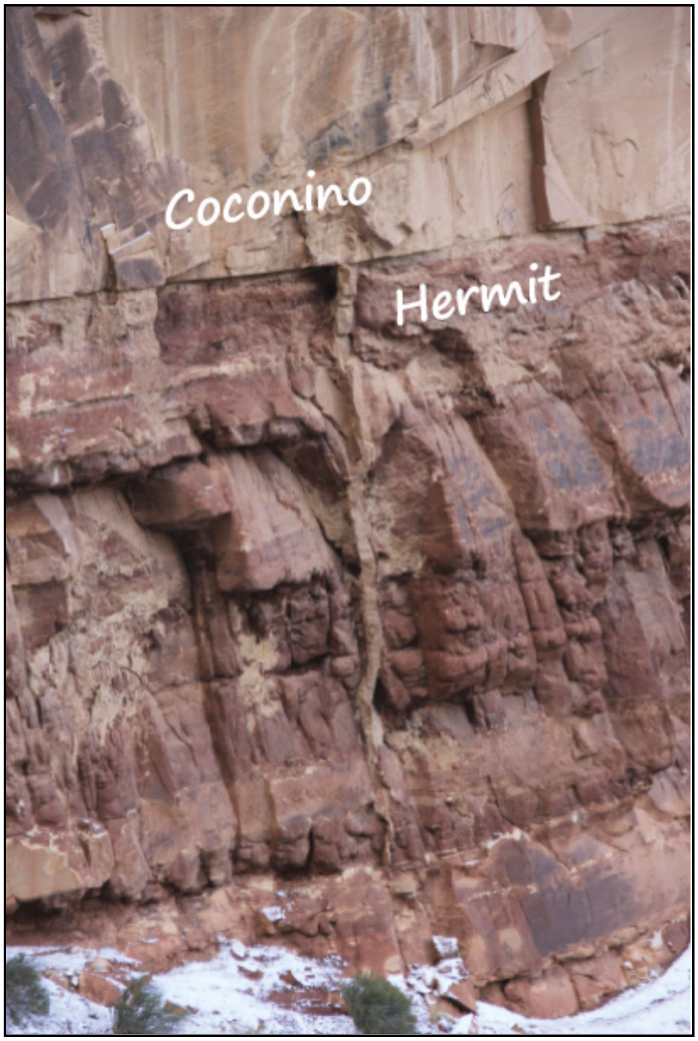


Figure 28. Stop #3: the sharp contact of the 280 million year old Coconino Sandstone with the underlying 285 million year old Hermit Formation shows deep cracks in the underlying unit that were filled with sand as dunes migrated across the older mudflat deposits.

in 1–2 hours. You can get to stop #4 at 1.5 Mile (2.4 km) Resthouse, and back in 2–3 hours. Getting to stop #5 at 3 Mile (4.8 km) Resthouse and back may take you about 4–5 hours. If you descend to stop #5, it is a 9.6 km (6 mile) round trip with a 350 m (1150 foot) vertical elevation drop. You cross the Bright Angel fault many times but it is only well exposed at the second tunnel (stop #2) and on the ridge and trail near 3 Mile Resthouse. Look for numerous breccia outcrops and fault planes in these areas (Fig. 26). Get to know the Permian strata (labeled on the map and in Fig. 22) as you walk through millions of years of time in which the rising Permian shallow seas (Kaibab Limestone) transgressed across evaporite shoals (Toroweap Formation), coastal dunes (Fig. 27; Coconino Sandstone), and mudflat (Hermit Formation) deposits (Fig. 28).

Stops #6–8: Hiking to stop #6 (Indian Gardens) is 933 vertical metres (3060 feet) and 7.2 km (4.5 miles) from the rim; it takes many hikers 6–8 hours to go down and back. At stop #7, under a large cottonwood tree, you have a decision to make.

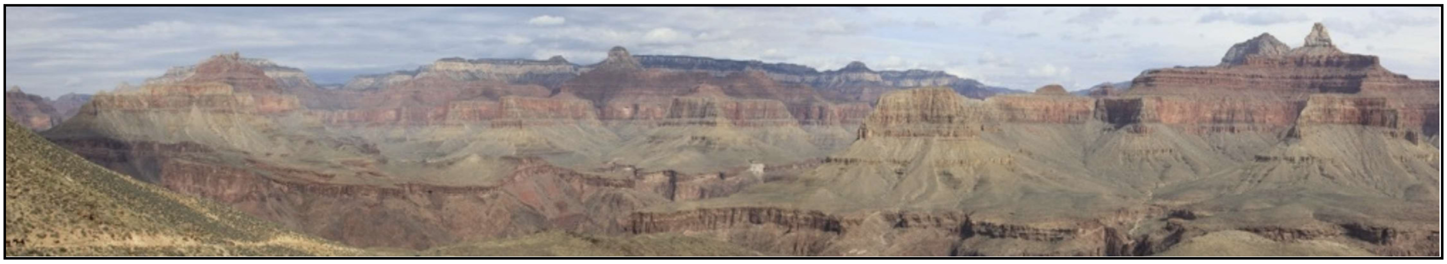


Figure 29. View of the North Rim and temples from the Plateau Point Trail between Indian Gardens and Plateau Point. One can see, from right: Zoroaster Temple, with Brahma Temple behind it; Buddha Temple in the centre, and Cheops Pyramid with Isis Temple behind it.

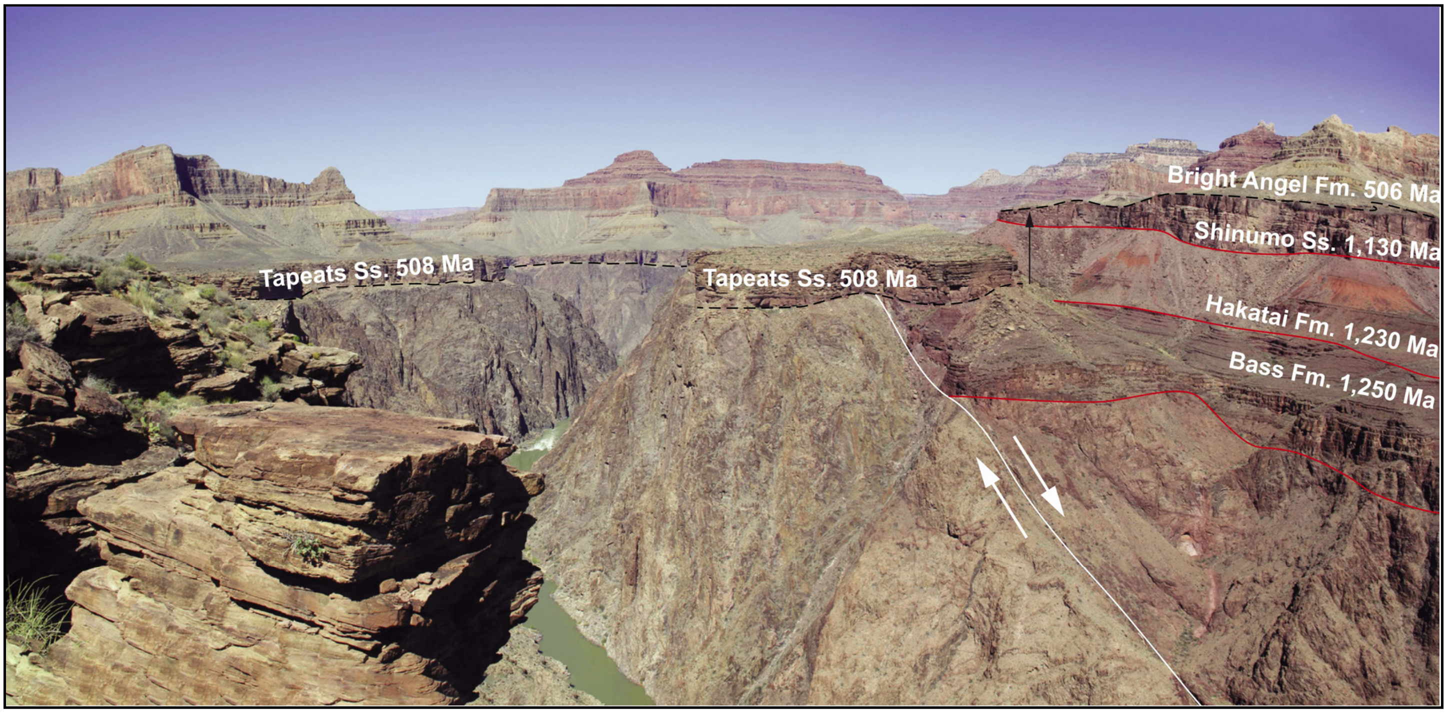


Figure 30. Stop #8: at Plateau Point you can sit on the Tapeats Sandtone and view some intricate geology across the river. Vertically foliated basement rocks form the Vishnu basement rocks of the Granite Gorge. The lowest red line is the Great Nonconformity where Bass Formation was deposited on schist and granite that had been exhumed from the middle crust. The Unkar Group of the Grand Canyon Supergroup (red lines) was deposited and tilted by normal faults (white). Then, the continent was eroded nearly flat to form the Great Unconformity (black dashed line). Beach sands of the Tapeats Sandstone lapped around paleo-islands formed by the resistant Shinumo Sandstone that stuck up several hundred metres above the sea (black arrow); the island was eventually covered over by mud of the Bright Angel Formation. Horn Rapids is seen downriver.

Starting back may make sense. Heading to Plateau Point (#8) is another 5 km (3 miles) round trip but the trail is relatively flat across the Bright Angel Formation that is exposed on the Tonto Platform and you get spectacular views of the North Rim, the Colorado River, the Vishnu basement rocks, and the Great Unconformity (Figs. 29, 30).

Stop #9: Alternatively, starting down Garden Creek you can get a hands-on look at basement rocks and the Great Unconformity (Fig. 31). Hiking all the way to Colorado River (13 km, 8 miles from the rim) and back is not recommended as a one-day trip. The Great Nonconformity, where Tapeats Sandstone rests with nonconformity on Proterozoic granite, is right along the trail. Some of the lower beds are conglomeratic and contain fragments of the underlying granite. Detrital sand grains in the basal sandstone were dated with U–Pb zircon techniques, and the youngest population is 508 Ma. The overlying Bright Angel Formation and the Muav Formation contain trilobites that correlate with 505 and 500 million year biozones, respectively. Hence, the Tonto Group marine transgression, Grand Canyon's record of the global Sauk transgression, took place between 508 and 500 Ma, more quickly and more recently than previously thought (Karlstrom et al. 2018).

Polished basement rocks beneath the nonconformity can be examined in Garden Creek where you can see vertically foliated schist and gneiss (Fig. 32). The Vishnu Schist, Brahma Schist, and Rama Schist are 1750 million years old and were metamorphosed at depths of 20 km (12 miles) beneath the summits of the now-eroded Vishnu Mountains. The intense folding and vertical foliation are the middle crustal expression of the NW–SE compression caused by plate collisions that formed high mountains. If you can imagine the mountain tops 20 km (12 miles) above you, and the time it took to erode those mountains down to sea level, then the flooding of the conti-

Figure 31. Stop #9: look around near this spot to find a place to put your hands on the contact where ~ 1200 million years of time is missing across the Great Unconformity. You can also see an Ancestral Puebloan granary where people stored corn and other crops about 1000 years ago; what a time juxtaposition!

nent by advancing seas to deposit the Tapeats Sandstone, you begin to grasp the Great Nonconformity and the dramatic changes that occurred between 1750 and 508 Ma.

Stop #10: Intrusive granite and pegmatite can be seen at stop #10. Granite in the Canyon ranges from 1740 to 1660 Ma. The granite at stop #10 has not been dated, but the megacrystic character and lack of strong foliation suggest it may be like the 1660 Ma Phantom Granite that is exposed across the river.

If you look to the north, on the east side of Pipe Creek (Fig. 33), you can piece together some evidence for what went on during the ~ 1200 million year time gap you saw at stop #9. The 1250 Ma Bass Formation of the Grand Canyon Supergroup rests on the Great Nonconformity as shown by the lowest red lines (Fig. 33). Bass Formation was deposited in shallow seas and contains Grand Canyon's oldest fossils, single-celled stromatolites. The contractional faults in this view strike northeast and dip southeast, whereas the extensional faults in Figure 30 strike northwest. The NW-compression, with NE-extension at right angles, were due to the "Grenville" continent–continent plate collision going on to the south. After this deformation, the upper several kilometres of the Grand Canyon Supergroup were eroded away before the deposition of the 508 Ma Tapeats Sandstone. Thus, the sub-Tapeats unconformity at this location represents only several kilometres of erosion (instead of 20 km) and a time gap of 'only' 742 million years below the Tapeats (across the dashed part of the black line in Fig. 33) instead of 1242 million years missing as seen at stop #9. The southeast side-up faults in Figure 33 are Mesoproterozoic in age; they are within the broad "Bright Angel fault zone", but they represent movements that predated deposition of the Paleozoic rocks. In continental crust, older weak zones (seen here) commonly get reactivated and can slip again under different stress conditions. This helps explain the southeast side-up slip during Unkar time as seen in Figure 33 versus the southeast side-down faulting of Permian rocks seen high in the canyon (stop #2, Fig. 26) along the same general zone of weakness.

VIRTUAL GRAND CANYON FIELDTRIPS

For those seeking online geological information before or after their visit, or who plan to bring kids and classes to South Rim, we recommend taking the virtual field trips offered by the University of Arizona (https://vft.asu.edu/). We helped film

Figure 32. Stop #9: if you descend into the polished basement rocks in Garden Creek, you can see vertically foliated Vishnu basement rocks intruded by granite beneath the Great Unconformity. The darkest rocks are the Brahma Schist, and the dark grey rocks are the Rama Schist, both are 1750 Ma metavolcanic rocks. The light pink/grey rocks are foliated granitic gneiss, likely from the same magmatic arc where the volcanic rocks originated. The folded veins of pink granite represent the youngest melts to crystallize.

some of these from a river trip, so you'll get bottom-up views and commentary that complement the Trail of Time and your top-down hiking. These virtual experiences can enhance geoscience learning and motivate students to see and experience Grand Canyon directly with both boots on the ground and hands on the rocks.

CONCLUSIONS: ONGOING GRAND CANYON GEOLOGY RESEARCH AND ITS GLOBAL REVERBERATIONS

One of the motivations for building the Trail of Time was to make more direct links between geoscience research progress (new knowledge), public geoscience interpretation (science literacy), and how the knowledge gets used (e.g. Park resource

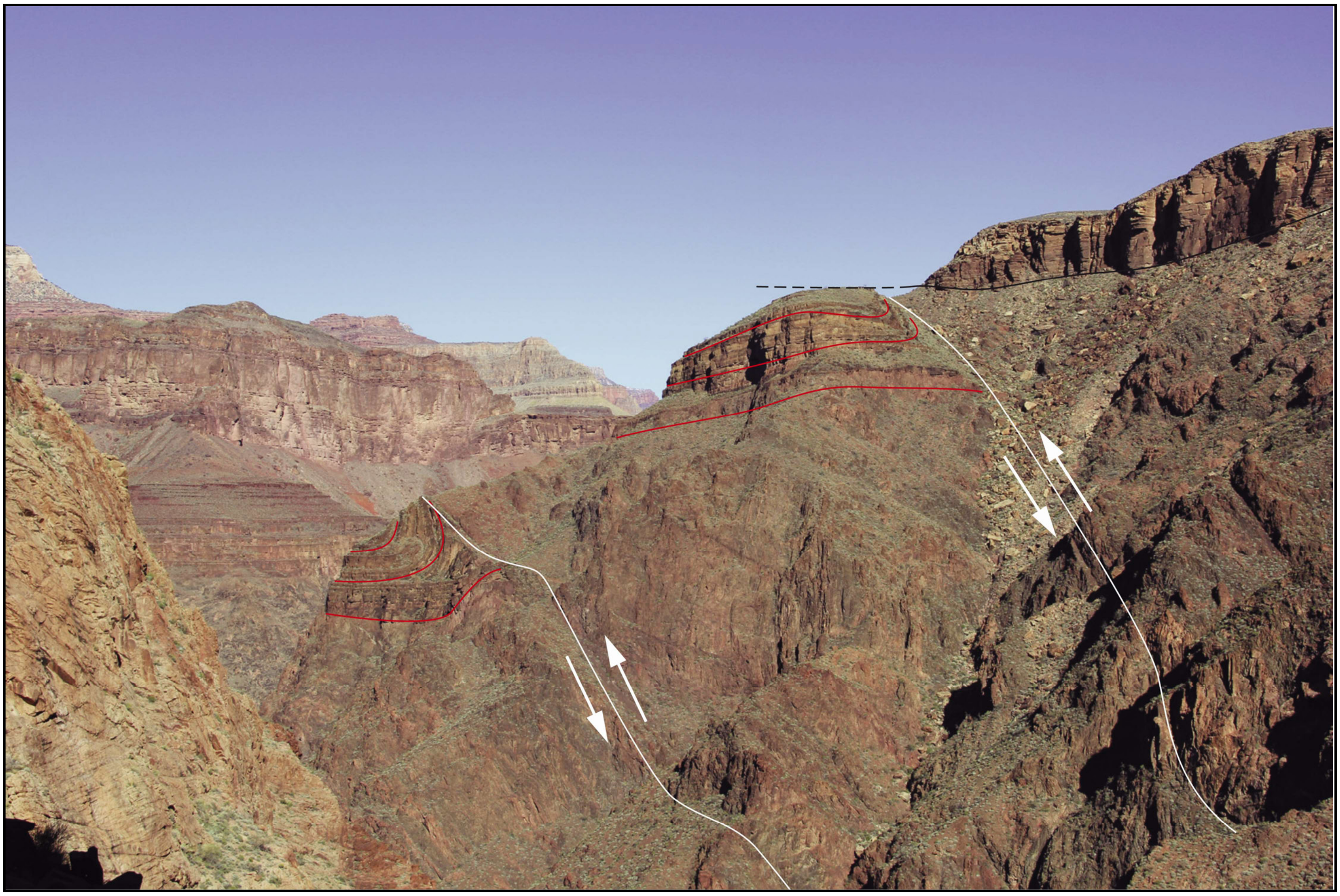
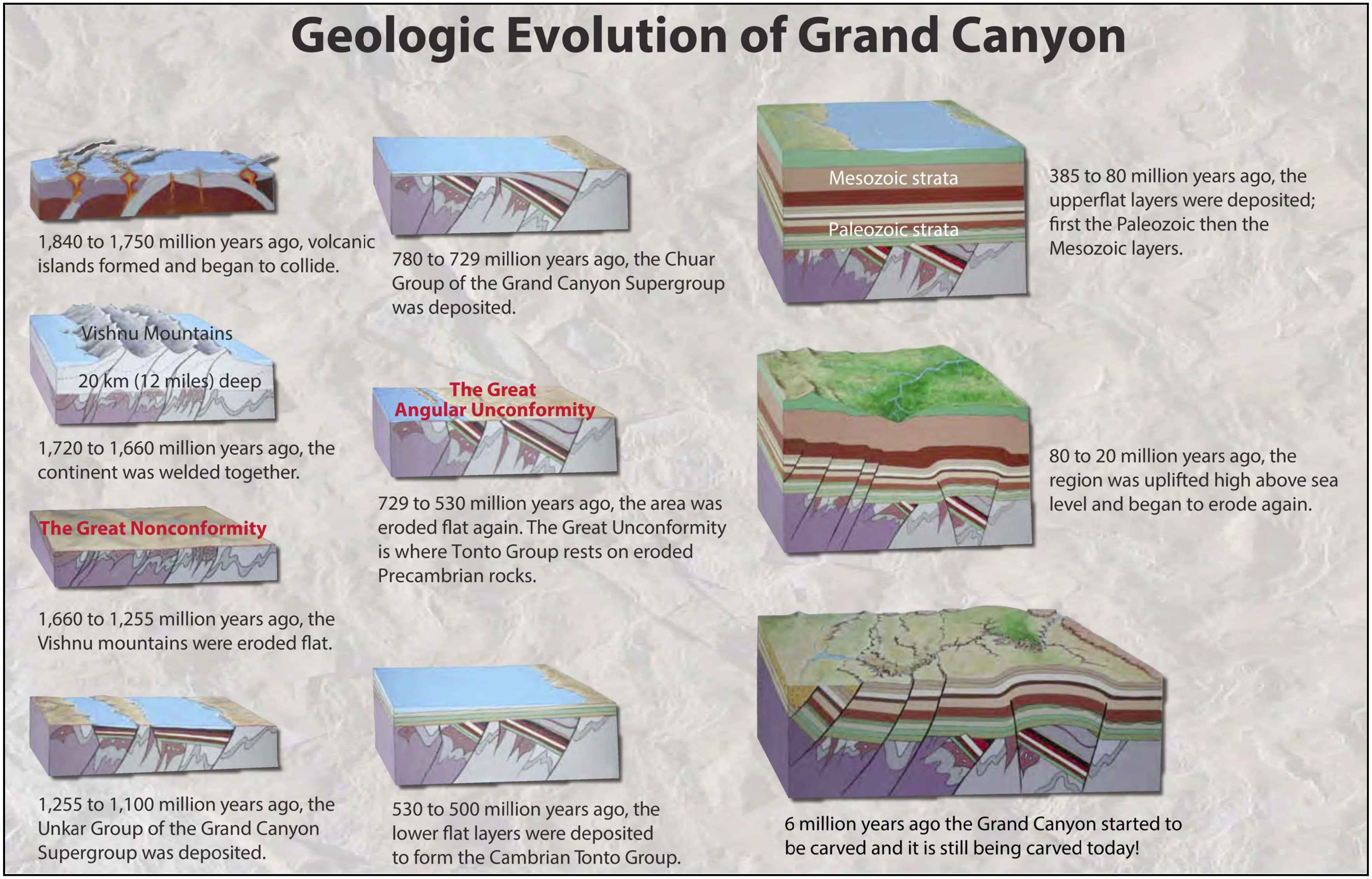


Figure 33. Stop #10: this view, looking north from stop #9 shows the 1250 Ma Bass Formation (upper red lines) that rests on an erosion surface cut into exhumed basement rocks, the Great Nonconformity (lowest red line). Basement was unroofed from 20 km (12 mile) depth to the surface between 1750 and 1250 Ma. The Bass Formation and other units of the Grand Canyon Supergroup were then deposited, folded and faulted by two contractional faults (white lines) that, in two steps, thrust basement up and over the Bass Formation. After this deformation, the upper several km of the Grand Canyon Supergroup were eroded away at this location before the deposition of the 508 Ma Tapeats Sandstone. This view shows multiple periods of erosion as also noted by Powell's two unconformities (Fig. 3).

management). You might think Grand Canyon geology would be entirely figured out by now, 160 years after the early geological studies. But, while the main geological framework is well established, there are many ongoing areas of research and many mysteries remaining to be solved. As has been true throughout the past 160 years, Grand Canyon rocks and landscapes provide one of the best geological laboratories in the world and promise many future research discoveries. Grand Canyon National Park's role in the realm of public education is also important. With over 6 million annual visitors, many from other parts of the world, this may also be one of the best locations to focus on several important aspects of science literacy, especially geologic time and natural resources as they pertain to societies. There are many current topics where research about Grand Canyon's rocks and landscapes are entwined with globally important debates about Earth science, geologic time, Earth processes, and sustainability.

Many questions remain partially unsolved. Working back in time: will there be enough groundwater in the face of future climate change to continue to supply Park visitors? What is the future of the dams on the Colorado River? How old is Grand Canyon and how will it change in the future? When and how was the Colorado Plateau uplifted and is it still going up? What caused past mass extinctions like the one at the end of the Permian and how vulnerable is our species to future extinction? What did the Great Unconformity and the Tonto Group marine transgression have to do with the emergence of diverse animal life in the Cambrian? How did climates change through geologic time and how fast can extreme climate changes take place on Earth? How do continents form and how are they reshaped by plate tectonics and the supercontinent cycle?

Geologic time and different time scales are difficult concepts for many visitors. The Trail of Time gives information about the different time scales and the stories told by each rock layer. This exhibit tries to emphasize that the rocks are very, very old (the Trail is long), whereas the canyon and the landscapes are geologically young (just six steps to carve the Grand Canyon). Figure 34 provides a visual summary of Grand Canyon geology. The last two block diagrams (in the lower right) are devoted to uplift and resulting erosion of the land-



1,840 to 1,750 million years ago, volcanic islands formed and began to collide.

1,720 to 1,660 million years ago, the continent was welded together.

1,660 to 1,255 million years ago, the Vishnu mountains were eroded flat.

1,255 to 1,100 million years ago, the Unkar Group of the Grand Canyon Supergroup was deposited.

780 to 729 million years ago, the Chuar Group of the Grand Canyon Supergroup was deposited.

729 to 530 million years ago, the area was eroded flat again. The Great Unconformity is where Tonto Group rests on eroded Precambrian rocks.

530 to 500 million years ago, the lower flat layers were deposited to form the Cambrian Tonto Group.

385 to 80 million years ago, the upperflat layers were deposited; first the Paleozoic then the Mesozoic layers.

80 to 20 million years ago, the region was uplifted high above sea level and began to erode again.

6 million years ago the Grand Canyon started to be carved and it is still being carved today!

Figure 34. Block diagrams showing the geological evolution of Grand Canyon rocks and landscapes.

scape, and the first 8 block diagrams depict the stories told by the rocks. These rock stories, worded as if told by the rocks themselves, are also presented in Karlstrom and Crossey (2019), with references to peer-reviewed published literature. There are puzzles left to be solved for each panel and we look forward to future scientific progress over the next century even as we celebrate the past 160 years of geoscience research.

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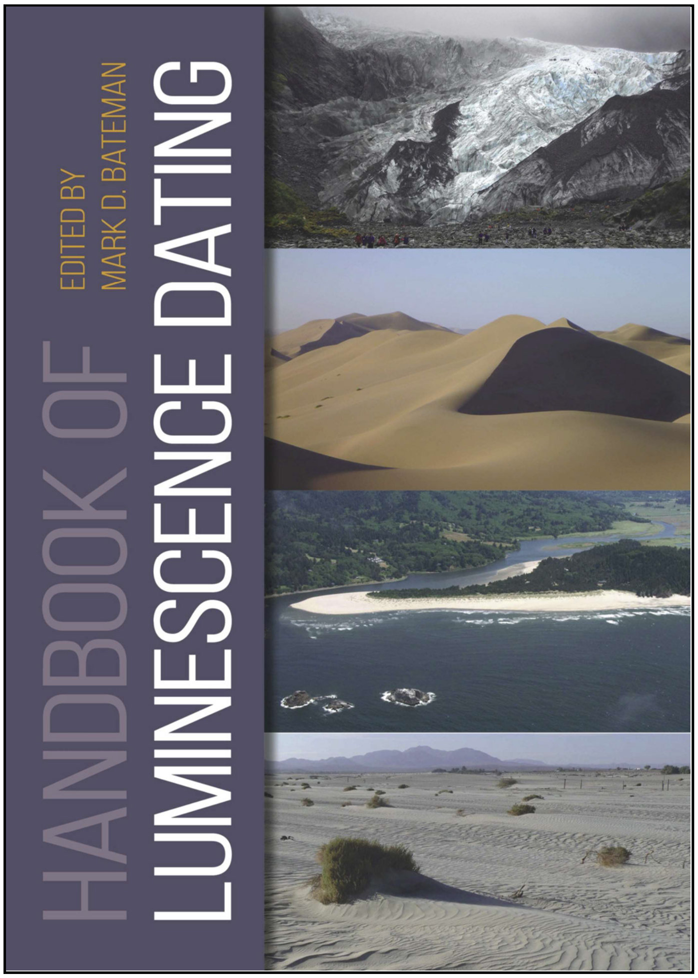

Handbook of Luminescence Dating

Mark D. Bateman, *editor*

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Luminescence dating techniques, including optically and infrared-stimulated luminescence and thermoluminescence, have been widely applied in the past 20 years. Formerly 'undateable' Quaternary sediments and successions can now be assessed chronologically, allowing interpretation of aeolian, fluvial, glacial, coastal, mass movement, and tectonic features, in addition to archaeological materials. For Quaternarists not directly involved in the luminescence community, knowledge of the evolving techniques and understanding of the current (and previous) limitations and future possibilities is important. The volume is aimed at professional and academic Quaternary geoscientists, and graduate and senior undergraduate students, looking to engage with the background, techniques, and applications of luminescence dating.

The *Handbook of Luminescence Dating* contains 12 chapters written by authors based in nine countries. Reflecting the history of luminescence, particularly optical, dating, many of the authors have ties to the University of Oxford and/or Royal Holloway University London. However, the authors represent a cross-section of researcher efforts across the spectrum of luminescence studies.

The opening chapter by Mahan and Dewitt introduces the principles and history of the various forms of luminescence dating, which provide chronological data for materials ranging from approximately 780,000 a to the last 100 years. Applications outlined include medical uses, assessment of prehistoric wildland fire events, dating of archaeological ceramics, and authentication of the age of artworks. Terminological definitions and analytical techniques, often not included in professional articles written by luminescents for luminescents, are introduced for the benefit of non-specialists. Discussion of accuracy, precision, and reproducibility allow readers to understand the parameters necessary for understanding the reported chronological data.

Bateman discusses the processes from sampling to data reporting. Sampling technique is critical to the production of usable chronological data. As many samples destined for luminescence are collected by Quaternarists not directly associated with dating laboratories, understanding what, where, and how to sample is critical. This is probably the most important chapter in the volume and would be the first that I would recommend that field researchers should thoroughly digest. Bateman's recommended procedures are easily understood, and will save much future uncertainty and grief.

Clark-Baysan outlines the role of Bayesian analysis in the production of chronometric frameworks. This chapter includes discussion of Bayesian techniques in general, expand-

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ing beyond luminescence analyses, concluding with archaeological and glacial chronological case studies.

Luminescence applications in aeolian environments are discussed by Fitzsimmons, who focuses on sandy sediments. Difficulties relating to pedogenesis, partial bleaching, low dose rates, and moisture content are considered. The second half of the chapter discusses application of the techniques to investigation of dune sequences as climate archives.

Loess is probably the most commonly dated material using optically stimulated luminescence. Stevens outlines the issues involved in loess dating, with consideration of the use of loess deposits as testbeds for luminescence techniques. The importance of loess-palaeosol sequences as climate archives, and the very limited possibilities of dating pre-MIS 5e deposits with other techniques, have made luminescence dating an essential element in palaeoclimate analysis in many locations in Europe, China, and elsewhere. Continued development of infrared-stimulated luminescence has allowed dating of mid-Quaternary successions.

Bateman considers applications in glacial and periglacial environments. These regimes demand care in sampling technique and interpretation of results, requiring analysis of small aliquots or (ideally) single grains. Application of statistical techniques can improve accuracy. Applications in fluvial and hillslope environments are considered by Fuchs. Variations in dose rate and sunlight exposure in these environments are common, requiring careful consideration.

Cunningham et al. discuss the application of luminescence dating to coastal and marine environments. Although some researchers might initially consider coastal deposits to be unsuitable, the combination of high proportion of quartz and exposure to sunlight through reworking allow luminescence dating to be applied effectively. Greater challenges exist in attempting to date estuarine, lagoonal, deltaic, and prodelta deposits. Complications resulting from the presence of U-series nuclides are also discussed.

Rhodes and Walker discuss applications of luminescence dating to active tectonic regimes. This chapter highlights the use of Quaternary research for a practical purpose – assessing the frequency of earthquake activity. Quaternary research ideally should contribute to society as a whole, and not only provide interesting things for Quaternary researchers to do. Luminescence dating provides an important context in hazard assessment.

Bailiff discusses archaeological applications of various forms of luminescence dating. Thermoluminesecence, less emphasized in the preceding chapters, is employed in archaeological investigations, and is well-treated here. King et al. focus on the use of luminescence techniques for dating exposed rock surfaces in chapter 11. In the final chapter, Wallinga provides insight on the potential future evolution of luminescence analysis.

Together, the twelve chapters in this volume provide a succinct summary of the techniques, applications, limitations, and future of luminescence analysis. This volume is recommended as a useful acquisition for senior undergraduate and graduate Quaternary programs.

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