The Trail of Time icon gives a cyclic view of rocks, time, and erosion at the Grand Canyon

The Grand Canon at the foot of the Toroweap- looking east. Lithograph by William Henry Holmes from Clarence E. Dutton, Tertiary History of the Grand Cañon District with Atlas, 1882

GRAND CANYON GEOLOGY AND GEOSCIENCE EDUCATION PUBLIC SYMPOSIUM, April 18-20, 2019

In honor of Grand Canyon National Park's 2019 Centennial celebration, Earth Day 2019, and the 150th anniversary of John Wesley Powell's 1869 pioneering Colorado River expedition.

Conveners

Karl Karlstrom, University of New Mexico (Grand Canyon geology and tectonics)
Laura Crossey, University of New Mexico (hydrochemistry and hydrology)
Steven Semken, Arizona State University (geoscience education and ethnogeology)
Todd Stoeberl, Chief of Interpretation, Grand Canyon National Park
Jeanne Calhoun, Chief of Science and Resource Management, Grand Canyon National Park

Objectives

The Grand Canyon is one of the world's iconic geologic laboratories and has long served as a centerpiece for geoscience education and science literacy. This symposium honors 100 years of geoscience education at Grand Canyon National Park and 150 years of Grand Canyon geology research. The objective is to provide an update on geologic research and on innovations in geoscience education that have taken place at Grand Canyon. The goal is to promote the next century of geologic research and outreach in this iconic region. The symposium is open to the public as well as the geoscience community. There is no formal registration or fee for the meeting.

Agenda

Thursday April 18, 2019: Speakers and participants arrive and check in (Albright Center for accommodations; Mather Campground for camping)
Friday April 19, 2019: Geology of Grand Canyon 8:30-5:00 PM.

Saturday April 20, 2019: Geoscience Education at Grand Canyon (8:30-12:00), and walk the Trail of Time (2-5 PM) with geologists.

Attendees and Estimated Costs

The meeting sessions will be held at the Shrine of the Ages Auditorium near the Park Headquarters. They are free to the public and Saturday is a no-fee entrance day to the Park. Camping at Mather Campground group site (free) is available for speakers and those who register in advance (email kek1@unm.edu). Speakers will give ~15 minute presentations and facilitate 10 minutes of Q and A about their topic.

Program: Geology and Geoscience Education at Grand Canyon

Thursday, April 18 at Mather Campground, Sage Loop site 6: 7-9 PM – group welcome and ice breaker around the campfire.

Day 1: Friday, April 19

8:15: Welcome by Grand Canyon National Park Division of Science and Resource Management- Jeanne Calhoun

8:30: Grand Canyon Geology Debates and Their Global Reverberations – Dr. Karl Karlstrom, University of New Mexico

9:00: The Vishnu basement rocks: Formation of continental crust and its relationship to the supercontinent cycle - Dr. Mark Holland, University of New Mexico

9:30: Snapshots from the Great Unconformity found in the Grand Canyon Supergroup: The Unkar Group - Dr. Michael Timmons, New Mexico Bureau of Geology

10:00: Break

10:30: The Neoproterozoic Chuar Group of Grand Canyon: A gem of unique scientific discoveries - Dr. Carol Dehler, Utah State University

11:00: Tonto Group: What can really old layers of sand, mud, and lime tell us? - Dr. James Hagadorn, Denver Museum of Nature and Science

11:30: The oldest vertebrate trackway in Grand Canyon and the dawn of reptiles- Dr. Steven Rowland, University of Nevada Las Vegas

12:00-1:30: lunch on your own

1:30: Source regions for Paleozoic sedimentary rocks: Dr. George Gehrels, University of Arizona.

2:00: Uplift and age of Grand Canyon and Grand Staircase - Carmen Winn, University of New Mexico

2:30: Where was the downstream end of the pre-Pliocene Colorado River - Dr. James W. Sears, University of Montana

3:00: Break

3:15: What a conflict of fire and water! – Lava Dams in Grand Canyon - Dr. Ryan Crow, United States Geological Survey

3:45: The Bouse connection and controversies - Dr. Phil Pearthree, Arizona Geological Survey

4:15: The shape of water - Dr. Laurie Crossey, University of New Mexico

4:45: The Coconino and Redwall-Muav aquifers of the Grand Canyon region and their importance for people and ecosystems - Dr. Abe Springer, Northern Arizona University

Day 2: Saturday, April 20

8:15: Welcome by the Park Division of Interpretation - Todd Stoeberl

8:30: Place-based geoscience education, interpretation, and ethnogeology at Grand Canyon - Dr. Steven Semken, Arizona State University

9:00: Engaging the Public in Geology and Geoscience: Techniques Learned Using the History of Ideas on the Origin of Grand Canyon, Wayne Ranney

9:30: Implications of Learning Outcomes of In-Person and Virtual Field-Based Geoscience Instruction at Grand Canyon National Park - Tom Ruberto, Arizona State University

10:00: The Old Red of John Wesley Powell: Using Geology to Solve the Historical Question of Powell’s 1869 Grand Canyon Camps - Richard Quartaroli

10:30: The Trail of Time Exhibit: - Karl Karlstrom and Laura Crossey

11:00: Brainstorming a next century of informal science education - panel

11:30: Recap and organize the ToT walk- Karl Karlstrom and Laura Crossey

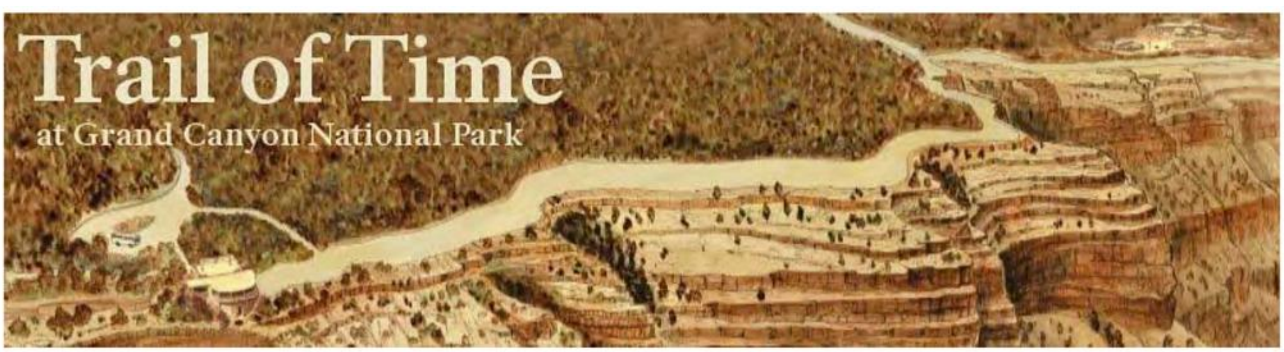
12:00 -1:30: lunch on your own

2:00-5:00: Walk the Trail of Time with geologists (in waves and small groups)

Introduction to the Symposium

Karl Karlstrom, University of New Mexico, kek1@unm.edu

Grand Canyon rocks and landscapes provide one of the best geologic research laboratories in the world. This region has served for 150 years as a place where ideas of global importance are developed, tested, and refined. Our symposium involves active researchers who will summarize for the public the present knowledge in the context of ongoing debates and future challenges. Day 1, the geology day, will present an overview of Grand Canyon geology and discuss “hot topics” that have major importance for understanding Earth history as well as Grand Canyon geology. Day 2, the geoscience education day, emphasizes the need for continued innovations in public outreach and interpretation and a close connection between scientists and society. On Saturday, we will provide geologic interpreters to walk the Trail of Time exhibit on the Rim Trail, including the originators of the exhibit. Public geoscience literacy is ever more important on our small planet of limited resources. The time perspective that geology conveys is crucial for a sustainable future as we grapple with many issues such as climate dynamism, extinctions, and resources -- including water. Grand Canyon’s 6 million annual visitors can play an important role internationally in gaining and promoting science literacy and geoscience awareness. A basic geology message for visitors is that Grand Canyon is a geologically young landscape being sculpted from very old rocks. Knowing some of the stories encoded in the rock layers and the landscapes enriches your understanding of our planet and enhances your experience at Grand Canyon.



NATIONAL PARK SERVICE

The University of New Mexico

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8:15: Welcome by Grand Canyon National Park Division of Science and Resource Management- Jeanne Calhoun, Chief, Division of Science and Resource Management, Grand Canyon National Park.

Summary of Science & Resource Management Division

Grand Canyon's Science and Resource Management Division is tasked with understanding, protecting, restoring, and communicating the park's natural and cultural resources for current and future generations. The Division's programs utilize applied science and research studies through internal and collaborative efforts for effective resource stewardship and sound decision-making. In addition to the Physical Science Program (which also encompasses Air Quality and Hydrology), the Division includes Wildlife, Vegetation, Fisheries, Cultural, Research Permits, GIS, and Database Programs.

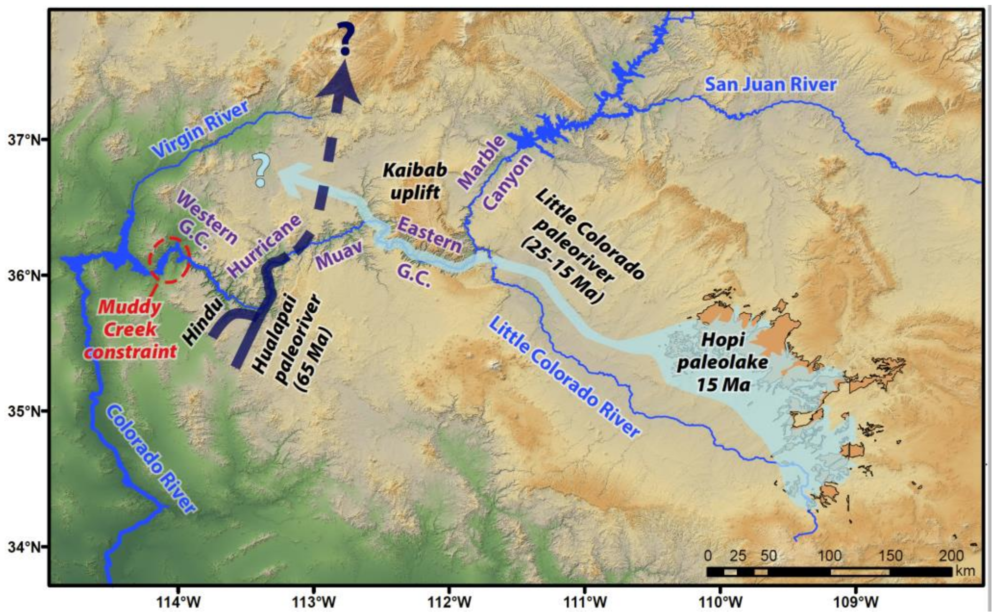
While the Physical Science Program is relatively small, it has accomplished much with collaborative efforts over the last several years. One of the greatest challenges to the management of Grand Canyon's resources is the rapid acceleration of climate change, which is affecting all of the canyon's resources, especially related to water. We have made some exciting progress recently in starting to understand the complex karst-influenced hydrologic system, especially with respect to the reliance of major springs on snow melt from the North Rim.

In addition to hydrological research, we have been synthesizing our paleontological knowledge of the Grand Canyon. This Centennial year, we are collaborating on a comprehensive paleontological survey, led by NPS Chief Paleontologist, Vince Santicci. This fossil inventory will culminate in a Paleo Blitz this fall, followed by a comprehensive report.

8:30- 9:00 Friday April 19: Grand Canyon Geology Debates and Their Global Reverberations, *Karl Karlstrom, University of New Mexico, kek1@unm.edu.*

I'll present two debates from different parts of the geologic timescale—one on "young" landscapes and the "Age of Grand Canyon"; the other on deep time and "THE Great Unconformity".

The Age of Grand Canyon: This has been debated for over a century! The map shows that the south-flowing river (from Colorado and Wyoming), makes a right hand turn to the west across the Kaibab uplift; then it makes a hard left turn after Hoover Dam and heads to the Gulf of California. Above Lees Ferry (RM=0) there is no Grand Canyon- this is Zion/Canyonlands/Grand Staircase country of red rocks that preserves the 2-3 km of rocks that have been stripped back from the rims of Grand Canyon. Grand Canyon has an amazingly abrupt end where the Colorado River emerges from Grand Canyon at Grand Wash cliffs (RM 280) and crosses from the Colorado Plateau to the Basin and Range near upper Lake Mead. Paleocanyons existed and their landscape remnants are still preserved: for example a 65 Ma paleocanyon is preserved on the Hualapai Plateau (Hindu paleocanyon). Also, Little Colorado River Valley has a composite history: it was carved from 25-15 Ma to near its modern depth as shown by lake deposits of the Bidahochi Formation.

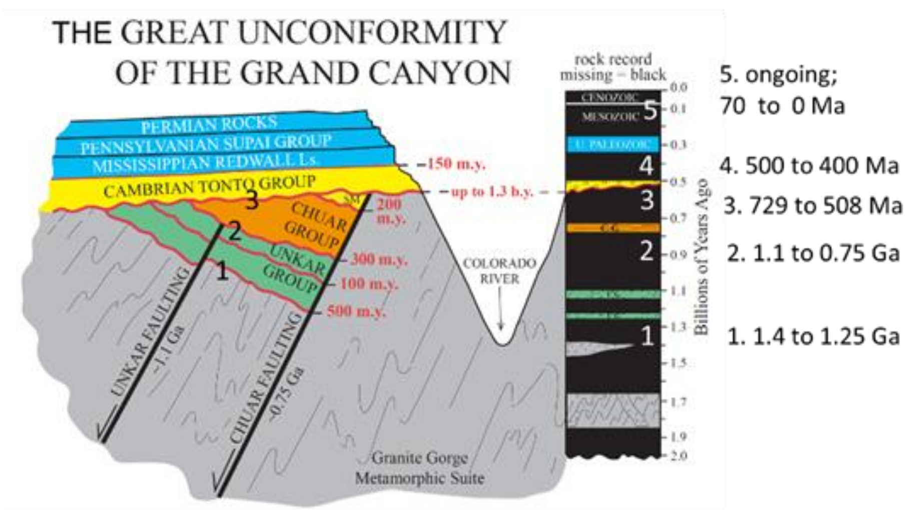


Powell (1869) envisioned that the Kaibab plateau was uplifted through an existing meandering river path (antecedence). Davis (1901) suggested that meandering river paths were established at higher (now-eroded) stratigraphic levels in Mesozoic strata and carved down through older uplifts (superposition). Blackwelder (1934) proposed that lakes on the Colorado Plateau spilled over to the Basin and Range to establish a young Colorado River (lake spill-over). Longwell (1946) established the "Muddy Creek constraint", that there was no Colorado River sediment in the current path of the Colorado River near Lake Mead until after ~6 Ma. McKee et al. (1967) proposed separate paleoriver pathways and later integration of the modern Colorado River path via headward erosion and river piracy. Hunt proposed piping of early river water under the Kaibab Plateau through caves (karst connection). Lucchitta (1989) emphasized early Colorado River pathways that were influenced by retreating cliffs (the racetrack idea).

Karlstrom et al. (2014) integrated these ideas and suggested that the Colorado River got integrated at 5-6 Ma as it found its present path from the Rockies to the Gulf of California in part through older paleocanyon segments. Earlier hypotheses for a 70 Ma "Grand Canyon" are disproved by newer thermochronology, but a N-flowing river did exist along the Hurricane fault, flowing north to the Uinta basin. A 50-25 Ma Grand Canyon is disproved as well although there was a 25-15 Ma valley carved by the paleo Little Colorado River that crossed the Kaibab uplift and then was deepened into eastern Grand Canyon after 6 Ma. But Marble Canyon and Lower granite Gorge segments were not carved until 5-6 Ma. Both groundwater and surface water move downhill and the Colorado River is envisioned to have found its path along older paleocanyon segments as it was downwardly integrated (Crossey et al., 2015). Landscapes evolve from past landscapes and hence answers to questions about the "age" of a river or canyon almost inevitably involve an evolution of paleorivers and paleolandscapes. Understanding what drove Grand Canyon to be carved in the past 5-6 million years by the Colorado River has global research importance in terms of parsing the multi-stage (and ongoing) Colorado Plateau uplift and understanding interactions of climate and tectonics in driving integration of paleoriver segments and carving of canyons.

The Great Unconformity: John Wesley Powell (1875) recognized two major unconformities, one below the Tonto Group and the other below the Unkar Group. He recognized these to be erosion surfaces of great significance that record the demise of ancient mountains before the next sedimentary layers were deposited. Clarence Dutton (1882) was the first to use the term “great unconformity”. The term now is commonly applied to the places where the flat-lying Paleozoic rocks of the Tonto Group overly Precambrian basement rocks. In Grand Canyon, up to 1.3 billion years can be missing (not recorded) at this contact, about ¼ of Earth history. Grand Canyon has an amazing rock record, but Figure 1 shows that more time is missing across unconformities (shown in black) than is recorded! Let’s number the main unconformities 1-5 (Fig. 3A), with 1, 2, and 3 all within what I’ll call THE Great Unconformity.

THE Great Unconformity encodes a composite fault-related erosion history made up from lesser but still pretty great unconformities. 1) The Great Nonconformity at the base of the Unkar Group was when the greatest basement denudation (~25 km) took place before 1.25 Ga. 2) The Great Angular Unconformity is where Tonto Group rests on Grand Canyon Supergroup rocks. This 1.25 Ga to 510 Ma time period involved the bobbing up and down of the continent, sometimes eroding sometimes developing fault-related basins. The punchline is that “many unconformities make one Great Unconformity”. We also want to know the “why” of the Great Unconformities! The Great Nonconformity records the erosional demise of the Vishnu Mountains, a high region similar to the Himalayan-Tibet region. A different explanation is needed for the Great Angular Unconformity. Here the alternating times of erosion and sedimentary basin cycles were driven by forcings at the edges and base of the plate of the Rodinian supercontinent as it was coming together at 1.1. Ga and rifting apart at 0.75 Ga. For the sub-Sixtymile and sub-Tapeats unconformities, several exciting hypotheses have been proposed. Karlstrom et al. (2018) proposed that final rifting of southern Rodinia caused uplift/erosion then flooding of the continent in the late Cambrian. Keller et al. (2019) proposed that glacial erosion cut deeply into continents globally during the 717-585 Ma Snowball Earth episodes. Peters and Gaines (2015) hypothesized that the Great Unconformity facilitated the Cambrian explosion of life and the first hard-bodied organisms. THE Great Unconformity is a globally important composite erosion surface where we can test hypotheses about the Snowball Earth, the Sauk transgression, and evolution of the earliest animal life of Earth. Different stages of the composite erosion history of the Great Unconformity are spectacularly revealed at Grand Canyon, where it was first defined.



So many rocks, so little time

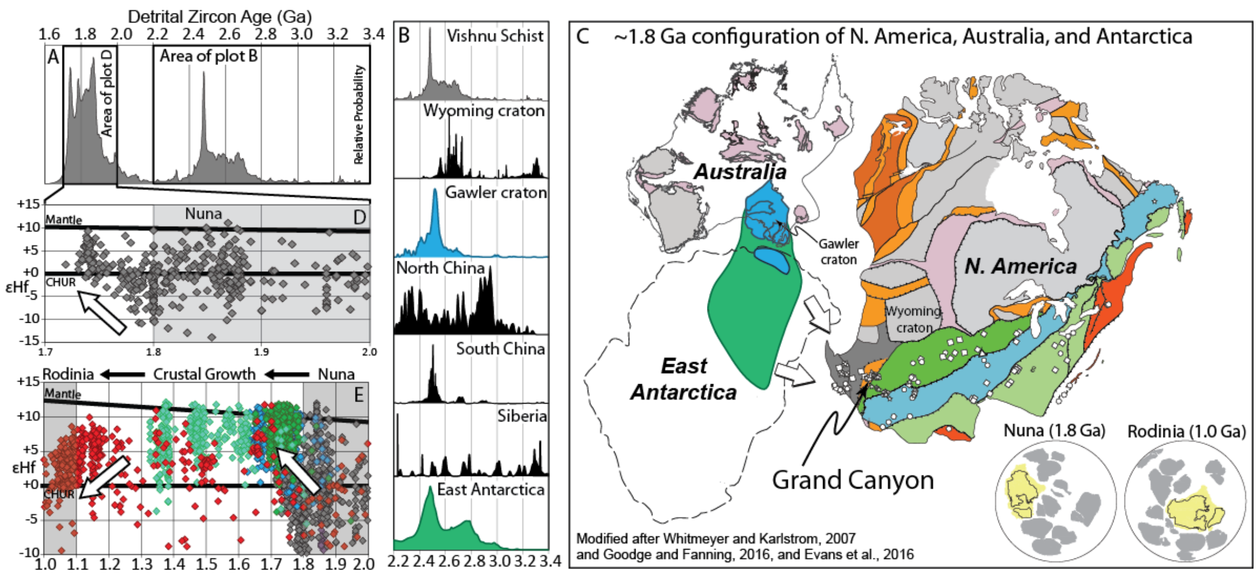
9:00-9:30 AM, Friday April 19, 2019: The Vishnu basement rocks: Formation of continental crust and its relationship to the supercontinent cycle, ***Mark E. Holland, University of New Mexico,*** ***medwardholland89@gmail.com.***

Continental crust is the archive wherein the history of Earth is recorded, and there are few places where this archive is so readily accessible as in Grand Canyon. Here, the prominently displayed layer-cake stratigraphy preserves a record of key events in Earth history like the evolution of life and global climatic changes. However, these records in sedimentary rocks are only preserved throughout deep time because of the thick, buoyant substrate of metamorphic and igneous rocks upon which they are deposited. Below the Great Unconformity, the crystalline basement rocks of Grand Canyon record the formation and evolution of the continental crust itself. New research indicates that the formation and preservation of new continental crust is intimately linked to global cycles of supercontinent assembly, breakup, and reconfiguration. From the Vishnu basement rocks to the Grand Canyon Supergroup, Precambrian rocks of the Grand Canyon contain a record of parts of two supercontinent cycles! At the bottom of Grand Canyon, the U-Pb and Hf-isotope composition of the Vishnu Schist provide clues to the timing of assembly and the configuration of a 1.8 Ga (Ga= billion year) supercontinent of Nuna, and the processes by which continents grow; whereas Grand Canyon Supergroup records the assembly and breakup of the 1.0 Ga supercontinent of Rodinia.

Basement rocks below the Great Unconformity are a complex mixture of metamorphic and igneous rocks. The metamorphic rocks are collectively known as the Granite Gorge Metamorphic Suite; the igneous rocks are named by individual intrusions (plutons). The oldest known rock unit in Grand Canyon, and the entire southwestern United States, is the 1.84 Ga Elves Chasm Gneiss – a remnant of cryptic continental crust nearly 100 Ma older than any other rock in the region. Next come the 1.75 Ga Vishnu, Brahma, and Rama Schists. Amazingly, these intensely deformed and metamorphosed rocks preserve primary structures that provide clues to their origins as volcanic and sedimentary rocks deposited at the surface of the Earth. For example, the Brahma Schist locally preserves pillow-basalt structures indicative of the rapid eruption and cooling of lava in a submarine environment, and the Vishnu Schist preserves rhythmic graded bedding typical of sediments deposited in submarine turbidity flows. Zircon U-Pb geochronology from the metavolcanic Brahma and Rama Schists indicate that they were deposited along with the Vishnu Schist between 1.75-1.74 Ga. Combined microstructural analysis and thermobarometry indicate that these sedimentary and volcanic rocks were tectonically deformed and buried as deep as 25 km in the crust during the formation of the Vishnu Mountains (Dumond et al., 2007). Prior to, synchronously, and outlasting deformation and metamorphism, the Vishnu, Brahma, and Rama Schists were intruded by granitic rocks with geochemical and isotopic characteristics typical of those found in modern volcanic arcs from 1.74-1.66 Ga. These lithologic associations and the sequence of tectonic events in the Granite Gorge Metamorphic Suite are common to basement rocks exposed across a >1000 km wide swath of crust from Wyoming to Mexico, suggesting a fundamental connection between the tectonic processes that gave rise to the Vishnu Mountains and the growth of the North American continent. An indication that these processes are related to the supercontinent cycle itself are found in detrital zircon, grains that were deposited with the original sediment that became the Vishnu Schist.

Detrital zircon grains within the Vishnu Schist are much older than the rock itself. There are two major populations of grains from 2.0-1.75 Ga and 2.7-2.4 Ga (Figure 3A). Each population of detrital zircon grains tells an important story. The oldest population indicates that the Vishnu Schist was derived in part from eroded 2.7-2.4 Ga continental crust. Intriguingly, this population of grains does not match the age of nearby crust in North America. A global survey indicates that the most likely candidate for the source of the Vishnu Schist is Archean crust that presently underlies southern Australia and Antarctica (Shufeldt et al., 2010) (Figure 3B). This link to Australia-Antarctica may provide an essential piece to reconstructing the puzzle of a ~1.8 Ga supercontinent called Nuna. Global reconstructions of Nuna differ on the precise timing of the assembly of this supercontinent, as well as the arrangement of individual continental masses within it. Our data from Grand Canyon strongly support a model where Australia was adjacent to western North America by 1.75 Ga when the Vishnu Schist was deposited (Holland et al., 2018) (Figure 3C). This new insight brackets the formation of new continental crust from Wyoming to Mexico between the amalgamation of two supercontinents: Nuna at 1.8 Ga, and Rodinia at 1.0 Ga.

Isotope data obtained from the 2.0-1.75 Ga population of detrital zircon from the Vishnu Schist indicate that the time between these two supercontinents was a globally significant pulse of continental growth. The Hf-isotopic composition of zircon can reveal whether a pluton was derived from melting of older continental crust or from "juvenile" mantle-derived rocks, the later representing new additions to the continental crust. Detrital zircon from the 2.0-1.75 Ga population in the Vishnu Schist record a progressive shift towards more juvenile compositions from 2.0 to 1.75 Ga (Holland et al., 2015; 2018) (Figure 3D). This is interpreted to reflect extensive recycling of older crust during supercontinent assembly followed by new crust formation along its margin. A continental-scale compilation of zircon from North America reveals that this trend continues from 1.8-1.2 Ga giving rise to juvenile continental crust beneath much of the present-day continental U.S. Beginning at ~1.2 Ga, Hf-isotope compositions shift progressively towards values indicative of crustal recycling, heralding the assembly of the next supercontinent, Rodinia, by 1.0 Ga (Figure 3E).

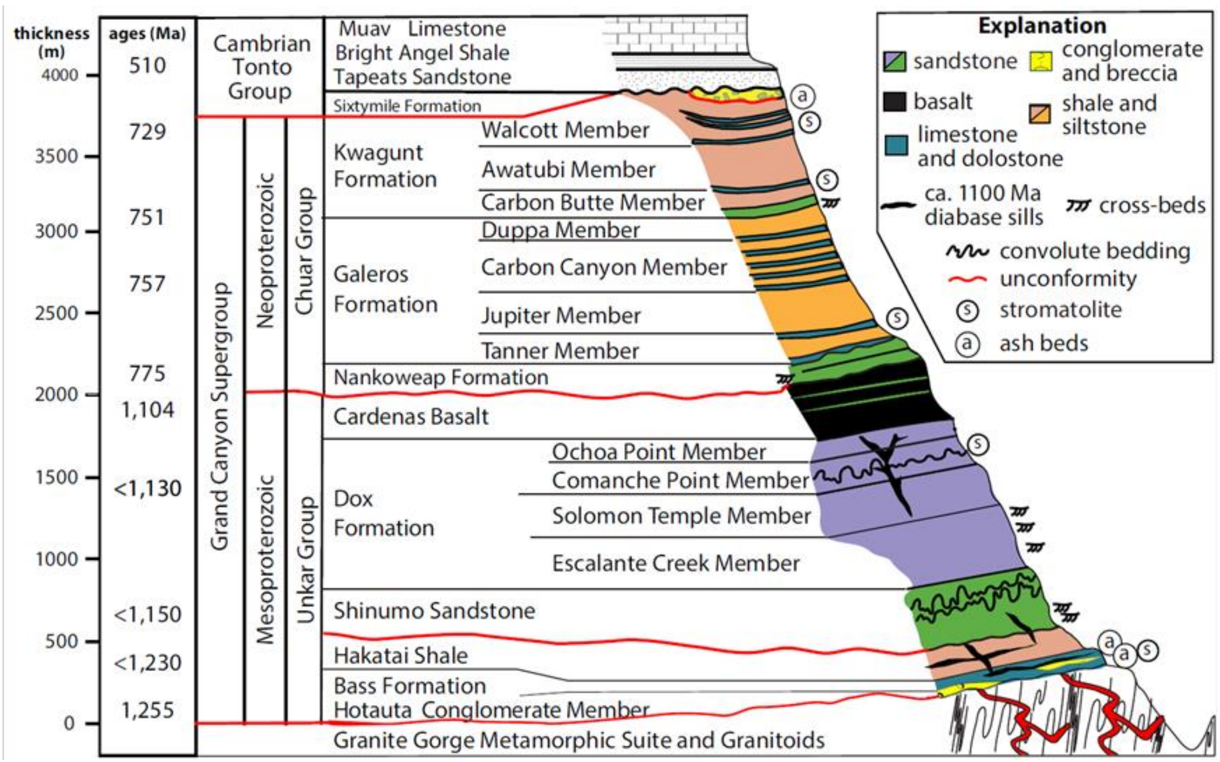


9:00-9:30 AM, Friday April 19, 2019: Proterozoic secrets from the Great Unconformity found in the Grand Canyon Supergroup-Part 1: The Mesoproterozoic Unkar Group

J. Michael Timmons, New Mexico Bureau of Geology and Mineral Resources, NM Institute of Mining and Technology, mike.timmons@nmt.edu

This presentation will be the first of two to explore the preserved Proterozoic geologic record within the Great Unconformity.

The Grand Canyon Supergroup is a nearly 4000 meter thick (12,000 feet) section of tilted layers of carbonate, sandstone, mudstone, and igneous rock that can be divided into two main groups. The older (lower) Mesoproterozoic Unkar Group (1250 to 1100 Ma (mega annum) and the younger (upper) Neoproterozoic Chuar Group (<775 million years to 729 Ma) (Figure 1). These strata lay unconformably on the crystalline basement (1800-1400 Ma), are unconformably overlain by Cambrian strata, and are only preserved in places where late Proterozoic extension 'down-dropped' them into the basement. Therefore, these groups provide unique snapshots of geologic history that are usually represented by a 1200 Ma time gap along the Great Unconformity.



The Unkar Group (the focus of this presentation) shows evidence of syntectonic deposition indicating the development of a basin far inboard of the plate margin. Sediments were transported west and north by river systems eroding a Himalayan-scale mountain range that extended from present-day Nova Scotia to west Texas (Grenville highlands). This mountain range, has long since eroded away, however researchers now recognize that these mountains formed along the boundary between colliding plates as the supercontinent Rodinia amalgamated at about 1,100 million years ago. A mountain range of this scale must have left an impressive sedimentary record, yet little of these ancient deposits are preserved in outcrop, with the notable exception of a few localities like Grand Canyon. Much of the record was lost to history by erosion of the Unkar landscape, now locally represented by a large unconformity between the Unkar and Chuar groups. About 300 million years after the Unkar Group was deposited and tilted by faulting, sediment was again blanketing the Grand Canyon region as the Chuar Group was being deposited (as discussed in the following presentation).

The approximately 2,000 m (6,500 ft) thick Unkar Group is made up of five main formations, including, from bottom to top, the Bass Formation, Hakatai Shale, Shinumo Sandstone, Dox Formation and Cardenas basalt (Figure 1; Timmons et al., 2005, Timmons et al., 2012 and references therein). The base of the group is dated by a thin ash bed in the Bass Formation, yielding an age of 1,255 million years old (and there is a new high precision CA-ID-TIMS unpublished age of 1250 Ma). The capping Cardenas basalts and associated intrusive rocks yield an age of 1,104 million years old (Timmons et al., 2005). Depositional environments within the lower Unkar Group vary from shallow marine rocks, including conical stromatolite-bearing dolomite of the Bass Formation, transitioning into marginal marine and fluvio-deltaic deposits that grade into the cyclic Hakatai Shale of marginal marine origin. An unconformity representing about 60 million years occurs at the top of the Hakatai Shale, which is in turn was covered by shoreline to riverine deposits of the Shinumo Sandstone. The last of the sedimentary record is represented by the thick Dox Formation (950 meters or 3,100 feet), which records a dramatic influx of fine grained, distally derived sands and muds in a dominantly fluvial depositional environment (Timmons et al., 2012). Detrital zircon grains within the Unkar Group indicate a mixture of potential source areas including locally derived grains from proximal basement terrains dominating the lower formations and grains from much more distal areas within the Grenville orogen heavily contributing to the upper formations (Timmons et al., 2005).

The Unkar Group is tilted and broken into symmetric and asymmetric fault-bounded basins, much like keystone blocks. These faults are northwest-striking, creating spectacular angular unconformities with the overlying Chuar Group and Paleozoic strata. Numerous subordinate structures to the northwest-striking normal faults die out within the Unkar section and others are intruded by feeder systems to the Cardenas Basalt, indicating that faults formed during sedimentation and volcanism due to extension of the Earth's crust in late Unkar time. Also observed within the Unkar Group are northeast-striking, northwest convergent monoclines that either die out within lower strata or are truncated by deposition of the Tapeats Sandstone, indicating a Precambrian age for these structures. Field observations suggest that the monoclines were developing during deposition of the lower Unkar Group, marked by abrupt facies changes and soft sediment deformational features consistent with syn-sedimentary deposition (Timmons et al., 2005; Lathrop, 2018).

The combined observations of the Unkar Group provide important insight into part of the Great Unconformity both within Grand Canyon and beyond. Far field stresses related to the developing convergent margin marked by the Himalayan-scale Grenville orogen had profound effects on the continental interior (Mulder, et al, 2017). The development of northwest-vergent monoclines early in Unkar time suggest that compressional forces were transmitted hundreds of kilometers into the continental interior, similar in style to monoclines that developed during the Laramide orogeny in the latest Mesozoic. Perhaps coincident with and outlasting compressional deformation, extensional deformation along northwest-striking normal faults developed during late Unkar time ultimately preserving the Unkar Group in the downthrown blocks. Coeval structurally-controlled orogen-perpendicular intracratonic rift basins developed in the continental interior, some of which are still preserved in subcrop (Central Basin Platform, Mid Continent rift, etc.). Massive river systems transported detritus from the Grenville orogen into the continental interior and likely blanketed much of the continent at that time. However, most of that history was stripped away during the late Precambian, setting the stage for Paleozoic deposits on crystalline basement rocks.

9:30- 10:00 AM, Friday April 19, 2019: Proterozoic secrets from the Great Unconformity found in the Grand Canyon Supergroup-Part 2: The Neoproterozoic Chuar Group

Dr. Carol Dehler, Utah State University, Logan, Utah, carol.dehler@usu.edu.

Geologic studies on the Chuar Group began in the late 1800s, when C. Doolittle Walcott and burro sifted through the fossiliferous shales that comprise most of the 1700 m thick group of strata. Originally thought to be Cambro-Silurian in age (Walcott, 1883), as many Precambrian units in the western US were, the microfossils and stratigraphic relationships required an older history, later understood to be framed above by Cambrian rocks, and below by the thick Unkar Group and crystalline basement. Although this rock unit only covers ~150 km^2 of exposed strata in the remote eastern Grand Canyon, it draws interest from the global scientific community for many different reasons.

The CG has one of the best-preserved assemblages of Precambrian organisms in the world (e.g., Porter and Riedman, 2016). It contains a plethora of acritarchs (organic-walled microfossils of probable eukaryotic origin). Interestingly, there are two different examples of the earliest known predation: 1) tiny drill holes in acritarchs indicate a tiny vampyrid predator (Porter, 2016); and 2) the testate amoebae fossils (vase-shaped microfossils, some of which have markings indicating cannibalism) (Porter et al., 2003). The careful work by Susannah Porter's research group has shown that food web complexity, predation, and carnivory were all happening as far back as Chuar Group time.

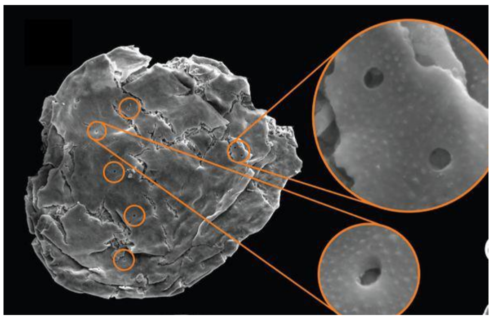


Fig. 1. Tiny drill holes in acrtitarch indicating eukaryotic predation. Acritarch is 50 microns in width. (Porter, 2016)

How old is the Chuar Group and what amount of time does is represent? We can say now that the Chuar Group strata is between <775 Ma and 729 Ma. This equals about 45 million years of time in 1700 m, which yields a sedimentation rate of <1 mm/year. This is a slow sedimentation rate, which is consistent with the sedimentology of the unit, although inevitably there must be subtle unconformities lurking in the strata, likely forming during the lowering of sea level and the passive tectonism provided by the Butte Fault and other structures, especially the Chuar Syncline (Timmons et al., 2001).

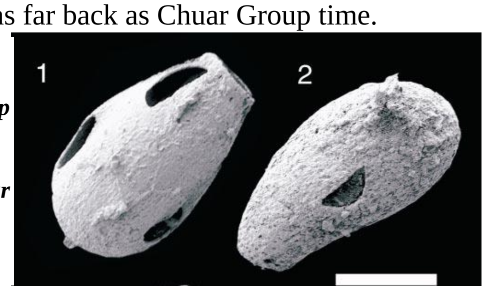


Fig. 2. 'Bite marks' on testate amoebae fossils from the Walcott Member, Chuar Group (vase-shaped microfossils) indicating predation and possibly cannibalism. Scale bar is 50 mm for 1; 35 mm for 2. Porter et al., 2003).

In studying the Chuar Group, its stratigraphic boundaries, and its various datable materials, it has become apparent that the underlying Nankoweap Formation (previously thought to be unrelated to the Unkar Group below or the Chuar Group above), is related to, and is now the oldest formation of, the Chuar Group. U-Pb analyses on detrital zircons in the Nankweap Formation are what provide the basal age of 775 Ma+/- 0.27 Ma age on the Chuar Group (U-Pb CA-ID-TIMS) (Dehler et al., 2017; Bullard, 2017). This requires a long duration of 300 Ma along the unconformity between the Unkar and overlying Chuar groups. This same unconformable relationship is also observed not too far westward, in the Pahrump Group of California (Mahon et al., 2014; Bullard, 2017). The ash at the top of the Chuar Group, in the Walcott Fm, originally discovered by Don Elston, was dated to be 742 +- 6 (TIMS age using upper intercept and air abrasion; Karlstrom et al., 2000), with a more recently reported weighted mean age of 729 +-0.9 Ma (TIMS using ion dilution-chemical abrasion) (Rooney et al., 2018). SW Laurentia (modern day coordintes) drifted from 2˚S to 18˚N during deposition of Chuar sediments (Weil et al., 2004).

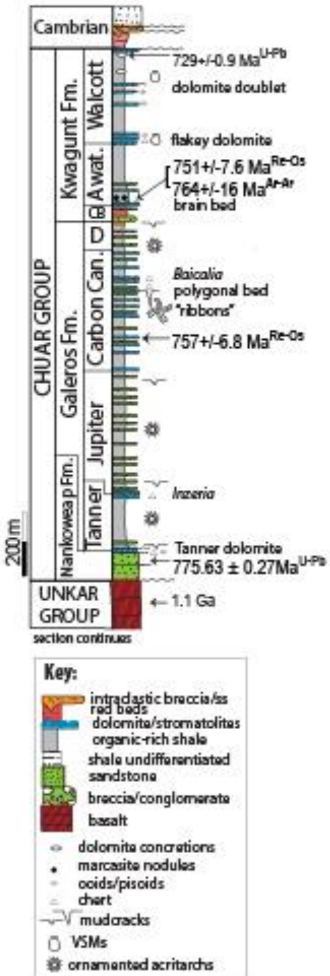


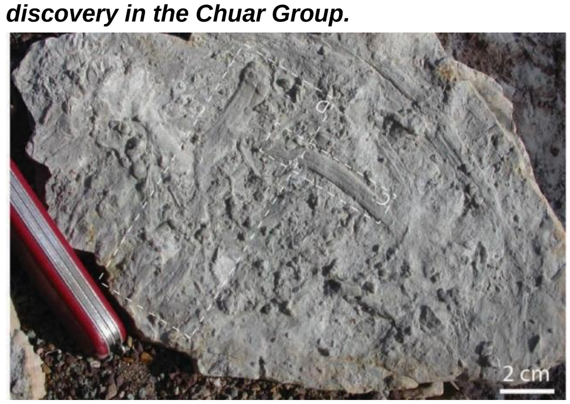
Fig. 3. Updated age model for Chuar Group. See references in text.

The fortuitous age brackets at the base and the top of the Chuar Group make it one of the best dated middle Neoproterozoic records in the world. Further exploratory work on more unusual dateable material (such as organic matter in dolomite and marcasite nodules) using less conventional dating techniques (such as Rhenium-Osmium and Argon-Argon dating) has further shed light on Chuar sedimentary and biologic tempos. The Re-Os age on an organic-rich dolomite from the Carbon Canyon Member is ~757 +/- 6.8 Ma, and the unusual marcasite nodules in the lower Awatubi Member are ca. 751+/-7.6 Ma and 764+/-16 based upon both Re-Os and Ar-Ar analyses, respectively (Dehler et al., 2017; Rooney et al., 2018).

Cosmopolitan stratigraphic studies on the Chuar Group have documented the amazing variegated and organic rich shale, making up most of the unit, along with spectacular stromatolites, other carbonate types, and sandstones (e.g., Ford and Breed, 1973; Dehler et al., 2001). Being riddled with mudcracks, especially in the middle Chuar Group, the Chuar sea was never far from a shore line, although the Tanner and Walcott member black shales indicate relatively deeper water conditions. Especially in the middle Chuar Group, the facies that stack and repeat on a meter-scale are interpreted as expressing orbital forcing mechansims such as eccentricity. The carbon, oxygen, and sulfur chemostratigraphy of the Chuar Group indicates high variability in the carbon cycle in an epieric sea where the water chemistry ranged from oxic, to ferrugenous, and rarely euxinic.

The new ages from the Chuar Group place it into two important geologic frameworks. The first is that not only the Chuar Group, and the middle Pahrump Group of California show basin initiation at ca. 775 Ma (and have similar microfossils), but so does the Uinta Mountain Group in northern Utah. Detrital zircon TIMS ages from basal sandstones from all three of these units have a maximum depositional age of ca. 775 Ma, suggesting a ChUMP interior seaway at this time, not unlike the western interior seaway of Cretaceous North America (Bullard, 2017). A new unpublished Re-Os age of ca. 763 Ma from the Visingso Group in Sweden, which shares amenities with the ChUMP strata, indicates co-eval organic-rich sedimentation on a different paleocontinent (Baltica) and that the "ChUMP" basin was likely a global transgressive phenomenon related to the rifting of Rodinia (Pulsipher and Dehler, 2018). The second geologic framework comes from the new 729 Ma age at the top of the Chuar Group. This age is ~12 million years prior to the onset of the first of two global glaciations (Snowball Earth) and therefore is a record of Earth Systems conditions during the time leading up to global glaciation.

Figure 4. New Problematica macrofossil discovery in the Chuar Group.



The Chuar Group is far from being 'overstudied'. Just recently, ribbon-like 'sea grass' impressions were discovered in the Carbon Canyon Member that remain a paleontologic enigma. The Chuar Group is the unit that keeps on giving!

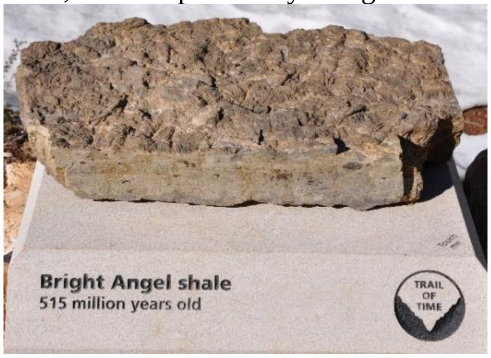
10:30-11:00 Friday April 19: Tonto Group: What can really old layers of sand, mud, and lime tell us? ***Dr. James Hagadorn, Department of Earth Sciences, Denver Museum of Nature & Science, Denver, CO 80205, jwhagadorn@dmns.org.***

About 500-550 million years ago, long before land was covered in vegetation, nearly every continent was blanketed by thick packages of sand—much like northern Africa is today. Those 'blanket' sands were reworked as seas rose and fell, as continents moved into different climatic zones, and as rivers, winds, and waves transported sand elsewhere. On every continent, sandstones from this interval are overlain by thin packages of mudstone and limestone that contain fossils and other evidence of early animal life from land and from shallow seas. This characteristic succession of sandstone-mudstone-limestone is known to geologists worldwide, but is perhaps best exemplified by the Tonto Group of the Grand Canyon, composed of the Tapeats Sandstone, overlain by the Bright Angel Shale, which is in turn overlain by the Muav Limestone. Earth scientists have learned much about how the chemistry of ancient oceans changed by studying the composition of these ancient limestones, and have gained insights into the diversification of life in the sea from the fossils found in these ancient strata. Trackways like the one above represent some of the first steps animals made on land, as they began to crawl out of the oceans and colonize land ~510 million years ago.

Yet we are just beginning to tap into clues hidden in these Tonto-like packages of rock. New techniques have allowed us to date these sandstones better, and when paired with improved understanding of the environments in which they were deposited, are allowing us insights into how ancient continents formed, broke up, and when and where they moved on their plate tectonic journey.

For example, the Grand Canyon's Tonto Group records a globally important marine flooding of the continent called a transgression. Across the U.S. this has been called the Sauk transgression. Our research team has recently learned that this marine flooding involved not only the Tapeats Sandstone, but another "hidden" rock unit in the Canyon, called the Sixtymile Formation. We dated this rock by bracketing its age with different geological chronometers, including sand-sized zircon crystals that undergo radioactive decay, and fossils whose ages are known based on documenting their sequential appearance in strata worldwide. In the case of the Tonto Group, we were surprised to learn that it contains more strata in it, and more time, than we previously thought!

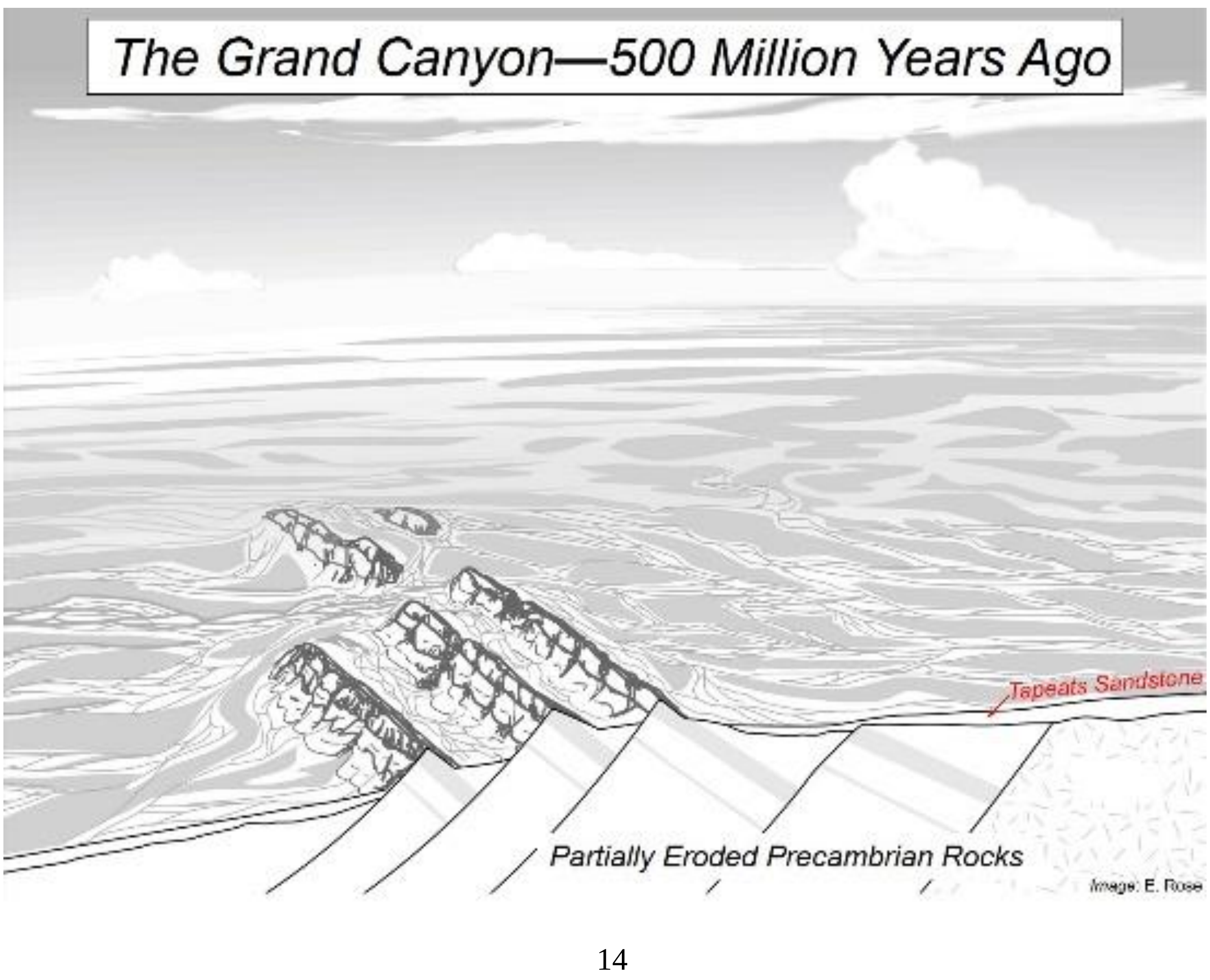
The enigmatic Sixtymile Formation, previously considered to be as much as 700 million years old, contains crystals that indicate it was deposited between 530 to 508 million years ago, as miniature bays and ocean basins were forming in this region (Karlstrom et al., 2018). New data from zircons in the overlying Tapeats Sandstone, and from fossil trilobites from the overlying Bright Angel



Shale, suggest something even more remarkable. They suggest that this portion of the Tonto Group, representing the worldwide buildup of Sauk-style sediments, occurred incredibly rapidly—sometime between 508-500 million years ago. This is much faster than we had previously thought.

Toward the end of this massive flooding event, the seas laid down thick layers of lime and reef-like sediment, forming the Muav Limestone. Nearly 75 years ago, Eddie McKee identified something unusual in the western Grand Canyon – there was more of this limestone than originally thought. A lot more. And it looked funny, like layers of slimy microbes had built dome-shaped reefs in it. He called this layer above the Muav the "undifferentiated dolomite", but never quite figured it out. Renewed research on this unit in this region and near Las Vegas, indicates it is part of the same transgression as the rest of the Tonto Group, and may represent the last hurrah of sedimentation in the Sauk Sea. Best represented by exposures at Frenchman Mountain, Rowland and Korolev (2011) propose calling it the Frenchman Mountain Dolomite. Given these new discoveries, in forthcoming scientific papers, we will be proposing that the Tonto Group should include not only the Tapeats-Bright-Angel-Muav, but these two "new" units, the Sixtymile and Frenchman Mountain formations.

Improving our understanding of the Tonto Group is relevant not just to the academic enterprise of understanding our planet's history, but because such rocks are sensitive indicators of greenhouse conditions – after all, warming climates melt ice, oceans then fill, and continents get flooded, just like they did during the Sauk transgression. Finally, elsewhere in the world, Tonto Group-type rocks are important aquifers, petroleum reservoirs and archaeological sites—but nowhere are such rocks as amenable to study as in Grand Canyon National Park.



11:00-11:30 Friday April 19: The Oldest Vertebrate Trackway in Grand Canyon and the Dawn of Reptiles, Dr. Steve Rowland, University of Nevada Las Vegas, *steve.rowland@unlv.edu.*

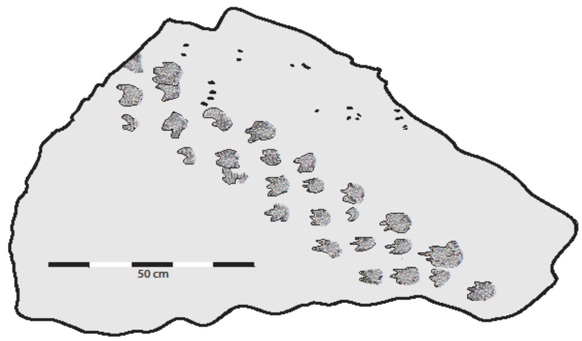
A recent rockfall along the Bright Angel Trail, about half a mile up the trail from 3 Mile Rest House, produced a jumble of sandstone blocks from the Manakacha Formation—second oldest formation in the Supai Group. Two of the blocks contain corresponding upper and lower surfaces of a conspicuous vertebrate trackway. The black-and-white stick in this photo is 1 meter long, divided into 10-cm (4-inch) increments. This trackway was a surprise because no fossil footprints (either vertebrate or invertebrate) had previously been reported from the Manakacha Formation. It is by far the oldest vertebrate trackway known in Grand Canyon.

My colleagues and I have been researching this trackway, with the goals of (1) figuring out how old it is, (2) determining what sort of animal made it, (3) reconstructing the weird gait it left us to puzzle over, and (4) evaluating its significance, locally and globally.

The age of the trackway is the easiest question to answer. The Manakacha Formation is well established to be Pennsylvanian (Upper Carboniferous) in age. More specifically, this formation is about 316 million years old at the bottom and about 312 million years old at the top. The Bright Angel Trail trackway occurs about three quarters of the distance from the base of the formation to the top. So, if we assume that the rate of sedimentation was roughly constant, our trackway is about 313 million years old.

The question about what kind of animal made this trackway is more complicated. At the time the trackmaker was making this trackway, a group of animals called amniotes had recently evolved from amphibians. Amniotes are animals such as reptiles that lay eggs with a tough shell that protects the developing embryo from drying out, as opposed to amphibians, whose eggs don't have a tough shell and must be laid in water to survive. So, in determining the identity of the Bright Angel Trail trackmaker, the first question that needed to be addressed is whether the tracks were made by an amphibian or an amniote. Amphibians typically have four widely-splayed, stubby digits on their front feet, and they don't usually occur in sand dunes. Our trackway does not display four widely-splayed, stubby digits on any of its feet, and it occurs in sandstone that was deposited by the wind, so we rejected the possibility that the trackmaker was an amphibian. Therefore, it must have been an amniote.

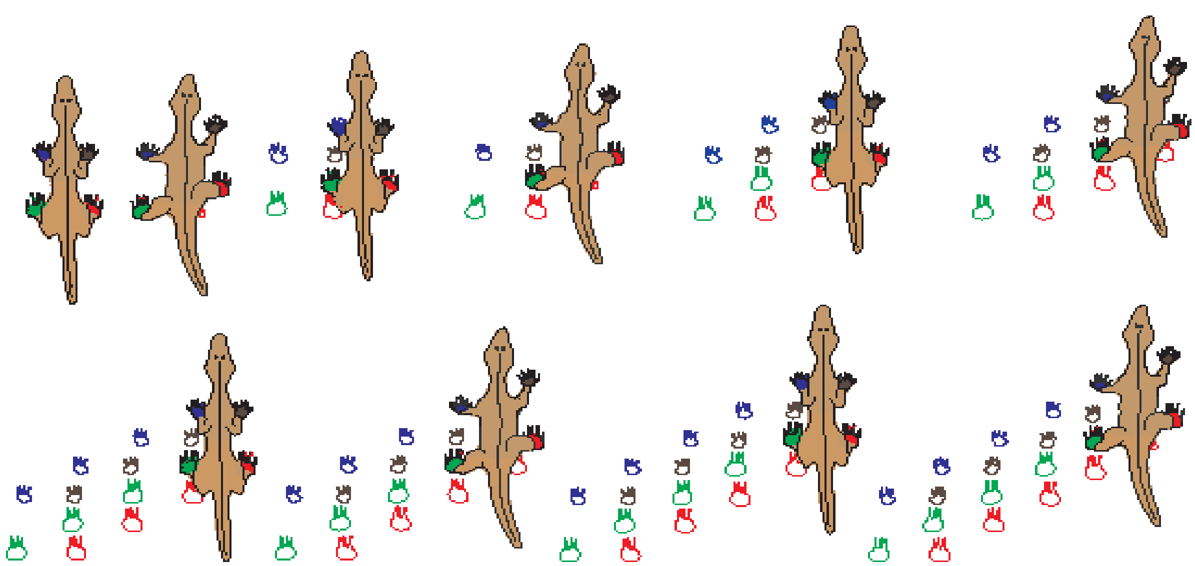
The earliest amniotes include reptiles, but they also include a disparate group of animals called pelycosaurs. The most famous pelycosaur is *Dimetrodon,* which lived later, in the Permian Period. In an evolutionary sense, humans are also amniotes because we evolved from pelycosaur ancestors. Based on footprints alone, it is not possible to distinguish between early reptiles and early pelycosaurs. We can say with confidence that the Bright Angel Trail trackway was made by a basal amniote, but we can't be sure whether it was a reptile or a pelycosaur.



Next we need to address the question of the weird gait that is recorded in the Bright Angel Trail trackway. In the drawing on the right, the tracks are pointed to the left, so that's the way the animal was facing. But the trend of the trackway is 40 degrees to the right of the direction that the animal was facing. The tracks occur in rows, with four tracks in each row. Each row is offset about 8 cm to the right, in comparison to the previous row.

At first glance it looks like this trackway may have been made by two animals walking together or in succession. But the series of sketches below shows my locomotion model; I'm sure that it was a single animal doing a two-step shuffle to the right. Biomechanically this is called a lateral-sequence walk, offset to the right. No one has ever reported a fossil trackway like this one, so it is definitely unusual.

The global significance of the trackway is that it is the oldest known example (by about 10 million years) of an amniote in a sand-dune setting. It documents the early adaptation of amniotes to the dunefield biome. And that is globally significant!



1:30- 2:00, April 19, 2019: Source Regions for Paleozoic Sedimentary Rocks, ***Dr. George Gehrels, Department of Geosciences, University of Arizona, ggehrels@gmail.com.***

As part of the Trail of Time project, U-Pb ages of detrital zircons have been determined from several dozen samples of sandstone collected from Paleozoic sedimentary layers in the Grand Canyon (Gehrels et al., 2011). These ages are used to reconstruct sedimentary source regions and transport mechanisms as follows:

- U-Pb ages are determined on a large number (e.g., 100-300) of zircon crystals from a ~10 lb sample of sandstone
- the measured ages are compared with ages of rocks in source regions (mountain ranges) that existed at the time
- pattern-matching determines which regions were important sources of sediment
- analysis of intermediate sedimentary units allows reconstruction of dispersal pathways and transport processes

These analyses reveal a surprising history which demonstrates that the sedimentary layering in the Grand Canyon is a direct result of global tectonic processes (e.g. collision of continents) and as well as patterns of global climate. First-order conclusions are as follows:

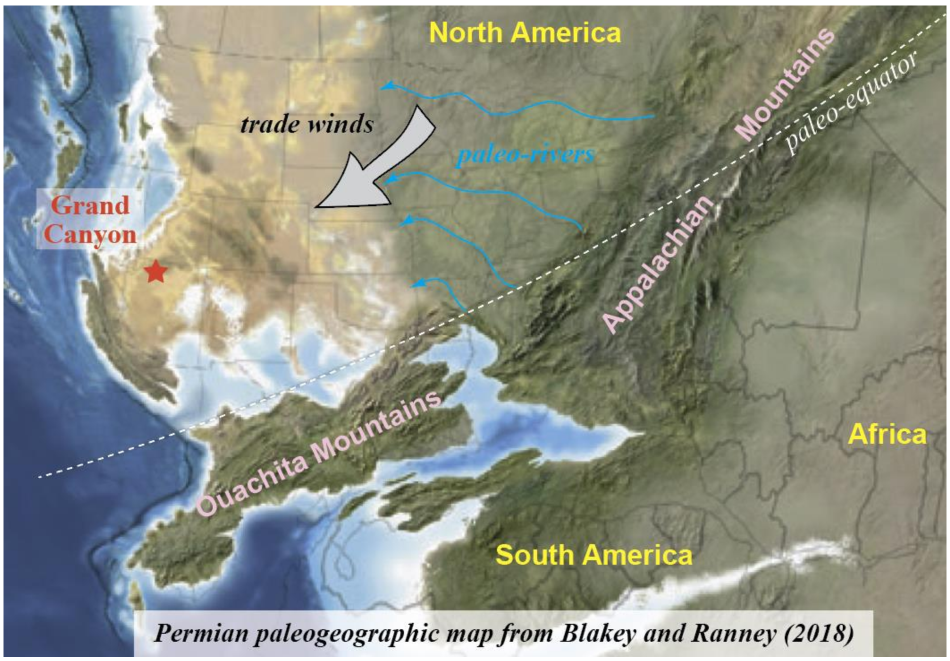
During **Cambrian** time, sandstones of the Tapeats and Bright Angel formations confirm traditional views (dating back to John Wesley Powell) that sediment was shed from nearby mountain ranges which exposed older Precambrian basement (e.g., Vishnu Schist, Zoroaster Granite). These mountain ranges were remnants of the continental collisions that first formed the North American continent ~1.7 billion years ago, and extensional events that fragmented North America and produced the Unkar and Chuar sedimentary basins.

Beginning in **Devonian** time, sandstones of the Temple Butte Formation record the first arrival of sediment derived from the Appalachian orogen – a conclusion that would have astonished the pioneers of Grand Canyon geology! Zircon grains of ~600-400 Ma record the successive collision of island arcs that formed in the Iapetus Ocean and collided with the eastern margin of North America during initial assembly of the Pangea supercontinent.

Mississippian sandstones of the Surprise Canyon Formation really are surprising, as they are dominated by sediment derived from the Appalachian orogen! This conclusion is completely counter to the traditional view that these sediments were shed from the nearby Ancestral Rocky Mountains. Imagine instead that rivers were carrying gravel-size sediment from what must have been Himalaya-size mountains in eastern North America!

Pennsylvanian sandstones of the Supai Group document continued derivation of sediment from the Appalachians, with transport processes that record a fascinating connection between tectonics, climate, and Grand Canyon stratigraphy. During Supai time, eastern North America was located along the paleo-equator, with high rainfall enabling Amazon-size river systems to carry sediment across the North American continent. The interlayering of sandstone and mudstone, which produces the stair-step topography of the Supai, records rapid changes in climate and sea level that correspond to cyclic changes in the size of southern hemisphere ice sheets. Next time you are climbing up through one of the Supai sandstone layers (especially if during the summer), imagine that your struggles are directly connected to the growth of this giant ice sheet!

Permian strata cap the amazing history (and scenery) of the Grand Canyon, with sandstones that record the final assembly of the Pangea supercontinent and the aridification of North America as it migrated northward out of tropical latitudes. The Coconino Sandstone, with its world-class cross beds and ripple marks, results from the final collision of eastern North America with Africa, with some sediment actually derived from the African continent. This sand was carried westward largely by the trade winds, resulting in a blanket of sandstone that accumulated in a Sahara-like desert. These strata and overlying sandstones of the Toroweap and Kaibab formations record an additional influx of sediment from the Ouachita Mountains, which formed due to the collision of southern North America with South America.



Permian paleogeographic map from Blakey and Ranney (2018)

1:30-2:00 PM, April 19, 2020: Uplift and age of Grand Canyon and Grand Staircase, ***Carmen Winn, University of New Mexico, c.winn264@gmail.com.***

The story of this iconic landscape begins with the Colorado Plateau and Rocky Mountains near sea level at 70 Ma (milli-annum, or million years ago), while Nevada, California, and central Arizona formed highlands similar to the Andes and the Altiplano today. This interior seaway deposited shales and sandstones that today can be seen in the Four Corners region and Black Mesa today, but once extended to cover the Grand Canyon, atop approximately 3 km of rock layers that were deposited over the 180 Ma. of the Mesozoic era.

In order to determine when rock layers are eroded from the landscape, we rely on a technique called low-temperature apatite thermochronology. Apatite, which is the same mineral the enamel of your teeth is made of, is a common trace mineral in igneous rocks and can also be found in sedimentary rocks sourced from older igneous rocks. This mineral acts like a temperature-sensitive radiometric clock, where the daughter products of radioactive decay are preserved in the crystal only once it has cooled through certain temperatures. For apatite, these temperatures range from 120-40 °C. Ideally for the Colorado Plateau, these temperatures correspond to burial depths of >1 to nearly 4 km if we assume a surface temperature (usually ~20 °C) and a rate of warming as you move deeper, which is called a geothermal gradient(25 °C/km). Notice that these depths are similar to the thickness of rock layers burying the Colorado Plateau at 75 Ma. We can use computer modeling of thermochronologic data to generate a continuous temperature history through time, and then relate those temperatures to burial depths through time. This technique, verified with geologic observations, is how we've reconstructed the history of the landscape of the southern Colorado Plateau, including the Grand Canyon, over the last 70 Ma.

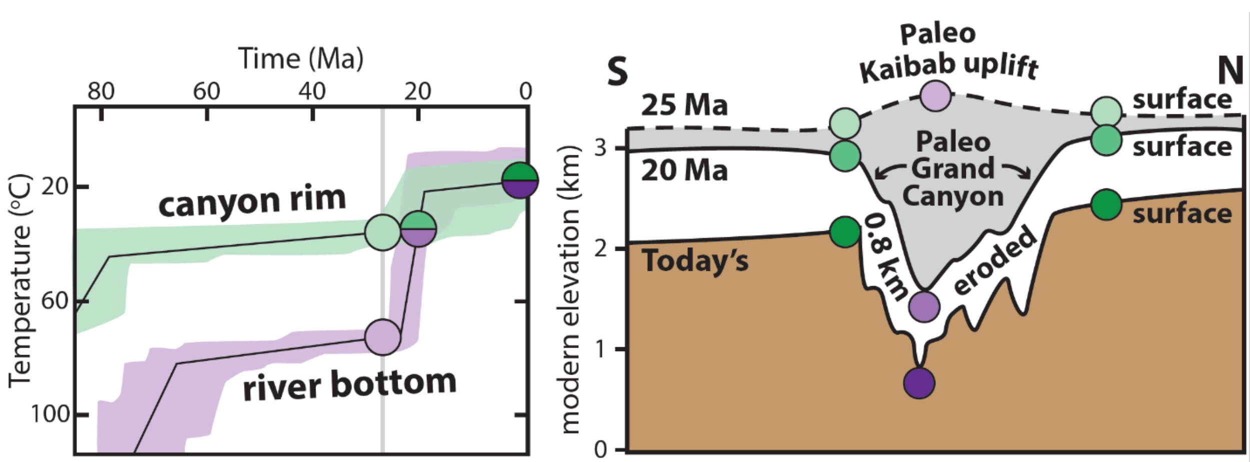
As the land began to rise during the Laramide orogeny (the building of the Rocky Mountains about 65 Ma) due to a flat oceanic plate bulldozing its way underneath the North American plate, the sea retreated and north-flowing rivers began to drain from the central Arizona Mogollon highlands. One of these rivers carved a ~1 kilometer scale canyon along the Hurricane Fault zone and Diamond Creek, and deposited tens of meters of river gravels, named the Music Mountain formation, along this paleovalley (Young, 2001). While this ancient river may have carved partway below the rim of this stretch of the Grand Canyon, it probably only flowed parallel to this north-south section of the Colorado River (Karlstrom et al., 2014 and Winn et al., 2017). Imagine if you were standing on the modern rim of the Grand Canyon near Toroweap - the ancient canyon rim would be a thousand meters above your head while the bottom of the canyon at that time would be near your feet. We think this river existed between 65-55 Ma and flowed north to an enclosed basin in northern Utah (Davis, 2010). As these rivers cut down through the landscape, they exposed weak rock layers under stronger sandstones. Erosion of these weaker layers undercut the stronger cliff-forming layers, causing the cliffs to retreat while the rivers carried this material north.

Near the end of Laramide times, around 40 Ma, the climate began to shift to warmer temperatures and localized basins and uplifts formed, interrupting and drying out these north-flowing rivers. This led to a quiet period on the landscape, where no material was being removed by major rivers and new weak layers weren't being exposed, so the rates of cliffs retreating slowed down. Local basins like the Claron basin filled with lakes, forming the beautiful white and pink layers of the Claron formation seen today in and around Bryce Canyon National Park.

Around 30 Ma, the flat oceanic plate stuck to the base of western North America began to separate and sink into Earth's mantle. This caused the hot material underneath it to well up and begin to melt the lower parts of the North American plate, causing huge outbursts of volcanism and the collapse of the highlands in central Arizona and Nevada over the next 10-15 Ma. Remnants of these volcanoes can be seen today in the San Juan mountains in southwestern Colorado, the Mogollon-Datil area near the

Arizona-New Mexico border. This warming of western North America probably caused the Colorado Plateau region to rise again, and the collapse of the highlands to the west created big valleys. Rivers once again integrated across the landscape, draining to the northwest into these valleys. This time, a major river flowed along the modern path of the Little Colorado River (Karlstrom et al., 2017) carving a kilometer-scale paleovalley above the modern Grand Canyon from the Little Colorado River to Kanab Creek between 25 and 15 Ma. This paleovalley was carved partway below the rim, at most to the top of the Supai Group, and its ancient rim was in rocks that have since retreated to the Vermillion Cliffs (Lee et al., 2013). It is very likely that a tributary to this river also flowed north through the western paleovalley carved 25 Ma earlier. This tributary deposited younger gravels on top of the older Music Mountain formation and is called the Buck and Doe conglomerate. These rivers caused another big pulse of cliff retreat and removed a huge amount of material from the southern Colorado Plateau before dying out around 15 Ma.

During the last 10 Ma, further uplift of the Rocky Mountains driven by dynamic mantle forces drove the downward integration of the modern Colorado River (Karlstrom et al., 2012). The Colorado River integrated through the Grand Canyon region at 5-6 Ma, stitching together pre-existing valleys and dropping in to the Grand Wash basin (Karlstrom et al., 2014). The low elevation of the river's mouth relative to the Colorado Plateau, once it reached the ocean at 5.3 Ma (Dorsey et al., 2012), and a transition to a cooler, wetter climate drove the river to rapidly carve the modern Grand Canyon, including the stretches between the paleovalleys such as Marble Canyon, the Muav Gorge, and the Westernmost Grand Canyon (e.g. Winn et al., 2017). The Colorado River and its tributaries have removed about 340,000 km^3 of rock from the Colorado Plateau and the Rocky Mountains in the last 10 Ma (Dorsey and Lazear, 2013). Much of this material has been removed by vertical downcutting of the rivers, but some has been removed by the lateral retreat of cliffs, particularly near the Grand Staircase of southern Utah, which was originally described by Clarence Dutton in 1882.



Apatite thermochronology: Tracking past landscapes: Two samples were taken on the rims of Grand Canyon and one at the bottom. Their cooling history (at left) reveals, 25 million years ago, they were at different temperatures, hence different depths below the paleo Kaibab uplift (dashed line). By 20 million years ago the samples were all about the same temperature, hence same depth, indicating that a paleo Grand Canyon had been carved (solid line). In the past 20 million years, an additional ~0.8 km of erosion occurred, deepening Grand Canyon. In contrast, Marble Canyon and western segments are younger, and were carved in the past 6 million years (from Karlstrom and Crossey, 2019).

2:00- 2:30 PM, Friday April 19, 2019: Where was the downstream end of the pre-Pliocene Colorado River? ***Dr. James W. Sears, University of Montana, james.sears@umontana.edu***

The modern Colorado River empties into the Gulf of California, a geologically young feature that opened as Baja California rifted away from mainland Mexico. The oldest sediments in the Colorado River delta only date back about 5 million years (Dorsey et al., 2005), when the modern version of Grand Canyon likely became integrated (Karlstrom et al., 2014). Perplexing evidence reported by Rebecca Flowers and colleagues at Caltech, however, indicates that the Colorado River may have begun to excavate parts of Grand Canyon in Oligocene and Miocene time, more than 20 million years earlier than establishment of the modern delta, and that erosion may have cut down to middle levels of the canyon before 6 million years ago (Flowers et al., 2008). But how and where could the early Colorado River have reached the sea?

Canadian geologists have mapped remnants of the ancient, Amazon-scale, "Bell River" system in Canada (McMillan, 1973; Figure 1). The paleoriver fed an enormous, now abandoned and submerged delta in the Labrador Sea **-** the largest sedimentary depocenter on the Atlantic seaboard of North America (Balkwill et al., 1990). Continental glaciation destroyed the Bell River system in Canada during the ice ages and beheaded its giant delta at Hudson Strait.

The headwaters of the Bell River drained the Rocky Mountains of Canada and Montana. In Montana, they included Missouri River tributaries that reach the Continental Divide between SW Montana and Idaho. That part of the Continental Divide dates back only a few million years, to middle Miocene and Pliocene time (Pierce and Morgan, 1992), when faulting related to the Yellowstone Hotspot and Basin-Range Province cut off the southern headwaters of the Bell River.

Oligocene and Miocene fluvial sediments with possible provenance in the volcanic terranes of southern Nevada and Utah fill tributary paleochannels of the Bell River system in the SW Montana Rockies (Sears, 2013). The paleochannels occupied the northern end of a rift valley that extended from Montana to SW Utah, where Oligocene and Miocene volcanic flows fill a large, deep paleovalley that is uplifted and dissected in the Bull Valley Mountains on the edge of the Colorado Plateau. Detrital zircon dates from the Montana fluvial sediments (Link et al., 2008) may indicate an Oligocene through middle Miocene fluvial connection along the rift valley from the Bull Valley Mountains to SW Montana.

I suggest that the ~ 25-15 Ma Colorado River may have flowed into a rift system that extended from SW Utah to Montana. It joined the trunk of the Bell River system in southern Canada, and eventually flowed into the Labrador Sea. Its ancient path was defeated by late Miocene and Pliocene tectonics and volcanism, and Pleistocene glaciation. The Colorado River may have integrated and carved modern Grand Canyon when it turned south ~ 5 million years ago, shortening its path to the sea from 5500 km (to the Labrador Sea) to 500 km (to the Gulf of California).

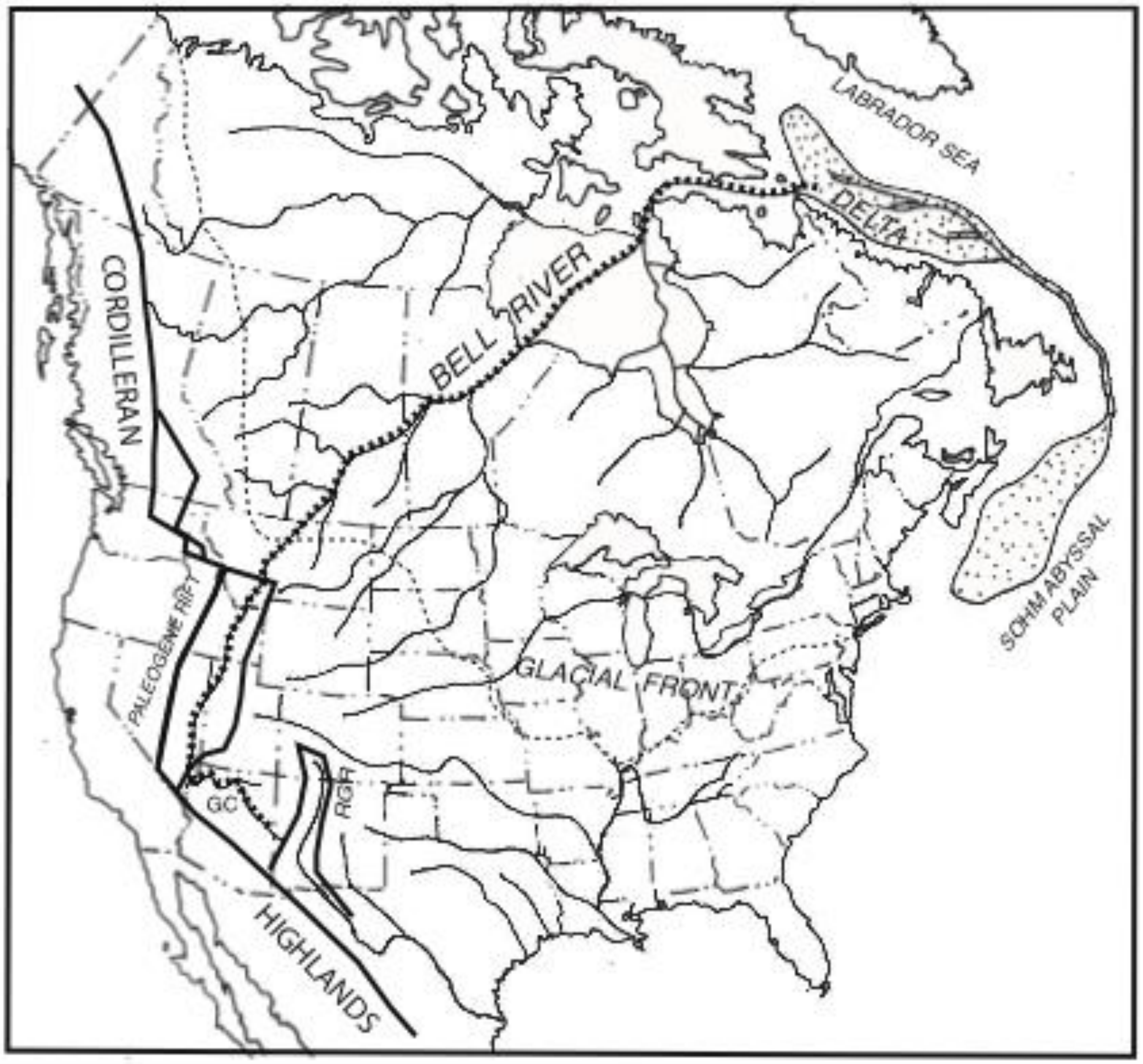


Figure 1. Bell River system of Canada may have had headwaters in Grand Canyon before destruction by tectonics, volcanism and glaciation. GC-Grand Canyon. RGR- Rio Grande Rift (After Sears, 2013).

2:30-3:00 PM, April 19, 2020, What a conflict of fire and water!" – Lava Dams in Grand Canyon, ***Dr. Ryan Crow, United States Geological Survey, Flagstaff, Arizona, rcrow@usgs.gov.***

Did you know that a series of lava flows poured into western Grand Canyon, about 90 km (55 miles) from the Grand Canyon Village? Floating on a raft in western Grand Canyon or from Toroweap viewpoint on the north rim it is easy to imagine, as John Wesley Powell did in 1869, "…a river of molten rock running down into a river of melted snow." Basalt clinging to the canyon walls, lava frozen in descent, provides a dramatic and very visual record of the lava dams that must have formed there, but many questions about the area's most recent volcanic history remain incompletely answered: When did these eruptions occur? What was the structure and extent of the different lava dams? How did the dams fail? Here I summarize recent efforts to answer these and other questions published in (Crow et al., 2015).

Some uncertainty about the extent and structure of the lava dams exists because the Colorado River removed much of the dams soon after their formation. However, many volcanic features remain, offering important clues into the area's past. Both high on the rim and down in the canyon, cinder cones record the locations of volcanic vents— the source of lava flows. Dikes, plugs, and sills remain as the crystallized plumbing that fed those vents. Lava cascades show where lava flows poured off the rim and into the canyon. Horizontal flow remnants at the canyon's bottom are the remains of dissected lava flows that traveled downstream, confined to the river corridor; it is these flows that created the lava dams.

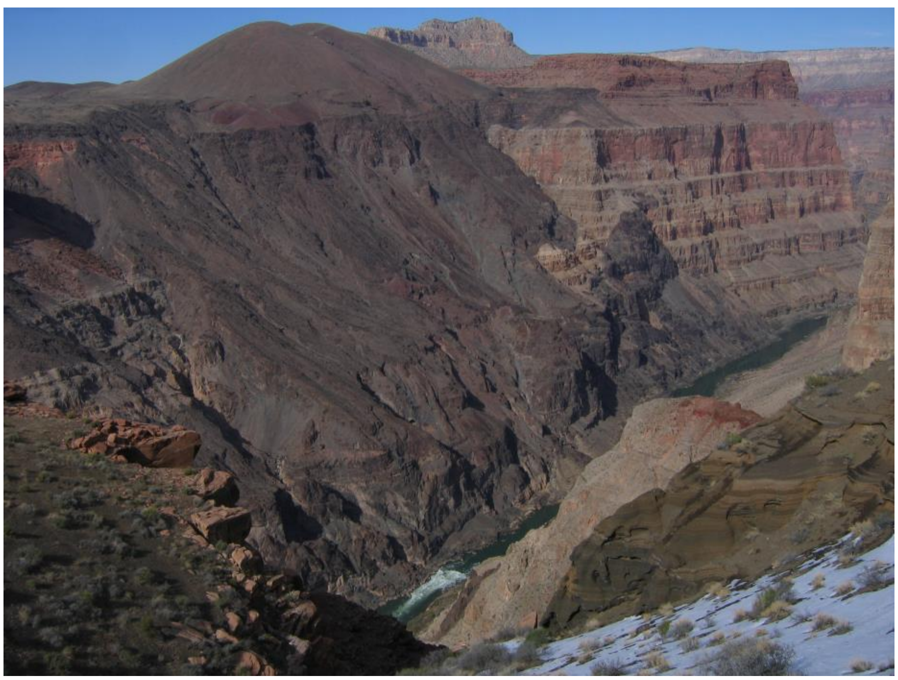


Figure 1. View of Vulcan's Throne (cinder cone), lava cascades, and horizontal flow remnants at the canyon's bottom near Lava Falls rapid. The photo was taken from a cinder cone fragment on the south rim.

An important first step in unraveling the area's volcanic history was the correlation of these features to reconstruct the lava dams and their probable sources. To do this, the canyon's volcanic features were mapped in three-dimensions, they were dated using a naturally-occurring radioactive "clock" (Ar-Ar dating), and "fingerprinted" using their geochemical and paleomagnetic signature.

The dating of the volcanic features and lava dam remnants helped identify about 17 damming events. Little is known about the source of the oldest dam, which formed approximately 850,000 years ago. Between 600,000 to 400,000 years ago a series of at least 10 damming events occurred in the Lava Falls area. Lava poured into Grand Canyon from both rims and erupted within the canyon at places like Vulcan's Anvil, a lava plug that still protrudes from the river. Eruptions that vented directly into the canyon like Vulcan's Anvil, produced some of the longest flows. Some traveled at least 135 km (80+

miles) downriver, choking the canyon with lava and cinders. Another lava dam formed around 320,000 years ago when a flow entered the canyon near Lava Falls. Between 250,000 and 200,000 years ago a series of eruptions occurred in Whitmore Wash, about 10 river miles downstream from the Lava Falls area. Multiple flows traveled down and filled that side canyon, and partially filled the Grand Canyon. Between approximately 200,000 and 100,000 years ago, the youngest known lava flows entered the canyon from the north rim. Cinder cones between Lava Falls and Whitmore Wash erupted, sending lavas cascading into the canyon at multiple locations.

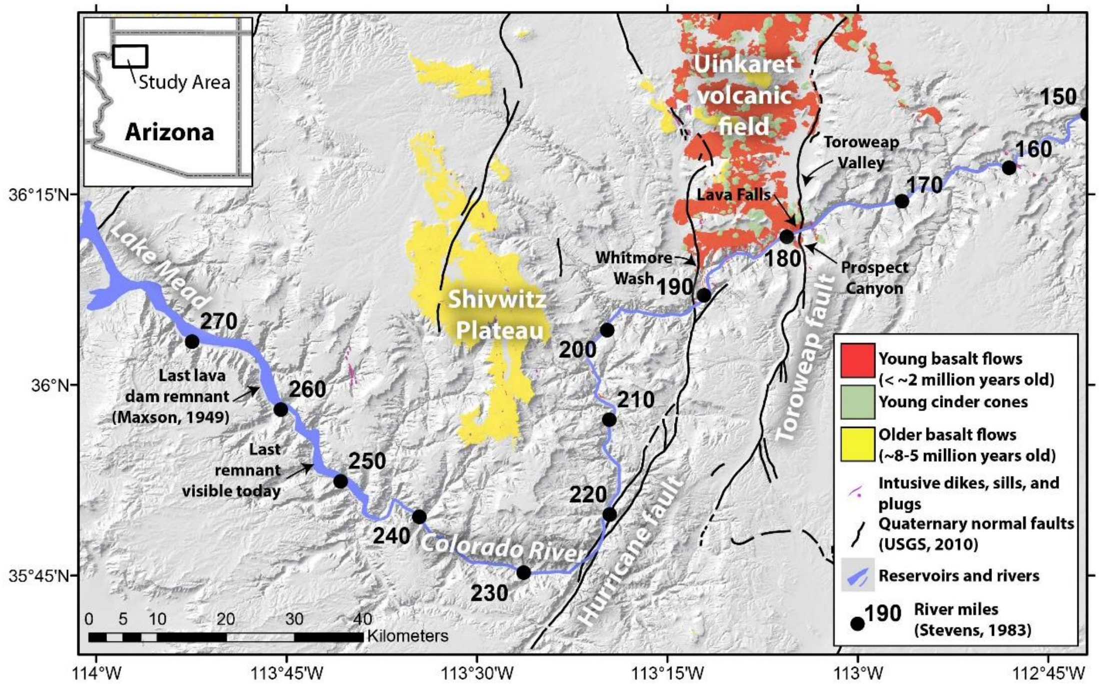


Figure 2. Simplified geologic map of western Grand Canyon showing the Uinkaret volcanic field, from which the lava flows that produced Grand Canyon's lava dams were erupted (modified from Crow et al., 2015).

Many, including Powell, have wondered how these dams interacted with the river and how long it took for the Colorado River to remove them. Clues lie in the structure of the dams and the deposits that overlie them. Most lava dams only show evidence for lava-water interactions in their upstream-most parts, indicating that they backed up river water quickly. Columnar cooling structures present within almost all Grand Canyon's lava dams also indicate that dams were overtopped by the Colorado River soon after emplacement and that the river flowed on top of them for months to years as they solidified. Outburst-flood deposits indicate that parts of some dams failed catastrophically. However, in contrast to earlier models, this new study suggests that these flood deposits were in many cases deposited on top of the still stable downstream section of the same dam. The relative stability of the far-traveled part of lava dams is expected because they likely flowed down a mostly dry river bed and would have been less fractured. A lack of verifiable lake deposits and the lack of far-traveled gravel on top of most lava dams suggests that many dams were removed by abrasion and hydraulic plucking of columns before the lakes behind them were completely filled with sediment. Based largely on historical sedimentation rates, the longest dams may have persisted as a convexity in the river profile for hundreds to thousands of years, whereas smaller dams were likely removed in tens to hundreds of years. Read the much more detailed Geosphere article for more details.

3:00-3:30 PM: The age and origin of the Colorado River below Grand Canyon: Recent advances and continuing controversies, *Dr. Philip A. Pearthree, Arizona Geological Survey, Phil.pearthree@azgs.az.gov.*

Deposits exposed in the lower Colorado River Valley (LOCO) downstream from Grand Canyon contain abundant information about the initial arrival of the river and subsequent river evolution. Basic elements of the story have been known for decades. Researchers in the 1960s debated the implications of the “immovable object” of the late Miocene Hualapai Limestone, which was deposited in several basins immediately west of Grand Canyon and contains no clear evidence of Colorado River (CR) water and sediment. In the LOCO south of Hoover Dam, investigators described the late Miocene to Pliocene Bouse Formation consisting of marl, travertine/tufa, and calcareous sandstone (basal carbonate) overlain by much thicker clay, silt and sand beds (siliciclastic deposits) (see photo below). These deposits record gradual inundation of Basin and Range landscapes. The entire Bouse Formation was interpreted as a marine or estuarine deposit based on a small number of species considered to be diagnostically marine, although they are found only in its southern extent. Because Bouse deposits are currently at elevations as high as 555-560 m above sea level (masl), tectonic models postulated subsidence along the LOCO to allow for a marine incursion, followed by hundreds of meters of northward-increasing uplift during the Pliocene and Quaternary. Bouse deposition was succeeded by accumulation of a thick sequence of quartz-rich sand and far-travelled, rounded gravel deposits that were clearly transported by the early CR (later named the Bullhead Alluvium). Age constraints on all these deposits were quite broad and imprecise.

A new wave of research began in the mid-1990s, when analyses of strontium (Sr) values from basal carbonate outcrops were used to argue that the Bouse Formation was deposited in a series of lakes fed by the river, each lake eventually spilling downstream until the river reached the northern Gulf of California. Recent efforts to describe the nature and extent of these deposits, understand their depositional environments, document syn- and post-depositional deformation, and develop tighter age constraints have substantially refined our understanding of the processes of river formation. With this new research has come new controversies regarding the details of the age of river development and the depositional environment of the Bouse Formation. These are some highlights:

Figure 3. Greenish siliciclastic deposits and white basal carbonate over fine locally derived gravel near Parker, AZ

Spatial distribution of deposits. Recent mapping and reconnaissance observations indicate that basal carbonate is found through the full elevation range of Bouse deposition in each basin, maximum elevations of siliciclastic deposits typically decrease from north to south in each basin, and the highest elevations of basal carbonate deposits in each basin rise in a series of steps from south to north. These relationships are consistent with the downstream-spilling lake hypothesis. Discovery of basal carbonate deposits much farther west near Amboy, CA, implies that the southern Bouse water body covered much of the eastern Mojave Desert – an extensive marine incursion or vast, river-fed saline lake? In the LOCO, Bullhead deposits are inset deeply into Bouse deposits and Hualapai Limestone deposits, indicating that substantial erosion occurred all along the river valley after Hualapai and Bouse deposition and prior to major Bullhead aggradation.

Sediment character. Sedimentary structures in basal calcarenite deposits in the southern basin have been interpreted as definitively tidal, but travertine/tufa deposits in the same general area appear more likely to be lacustrine. A continuing conundrum. Dating of detrital zircon grains from Bullhead and Bouse sand deposits indicates that both were primarily supplied by the CR. The obvious river deposits of the Bullhead Alluvium were derived from a watershed very similar to the modern CR. Siliciclastic Bouse deposits were almost certainly supplied by a slightly earlier version of the developing river system; they are predominantly fine-grained because they were deposited in standing water.

Deformation. Pre-, syn-, and post-Bouse and Bullhead deformation has occurred in the LOCO. Based on the elevations of the highest Bullhead deposits found along valley margins throughout the LOCO, there is clear evidence of uplift across faults in the central and eastern Lake Mead region but not elsewhere. The Bullhead/Bouse contact – earliest evidence of a through-flowing river – is up to 100 m below sea level in parts of the Blythe basin, and the base of the Bouse is much deeper in these same areas. Since rivers don't flow uphill, post Bullhead/Bouse subsidence must have occurred in these areas. Structural and geodetic evidence suggests that the LOCO region is undergoing slow transtensional strain accommodated by NW-striking faults and subsidence of N-trending basins (as just described). Isostatic responses to temporary or permanent loads of water and sediment enhanced subsidence in the basins, and uplift due to erosional removal of material likely occurred in adjacent mountains. These effects have resulted in somewhat exaggerated modern elevation ranges of Bouse and Bullhead deposits.

Figure 4. Cross bedded rounded exotic gravel and quartz-rich sand of the Bullhead Alluvium, Tyro Wash, AZ

Age constraints. Tremendous strides have been made in dating deposits related to the development of the lower CR in the past 20 years. Tephra deposits found in the Hualapai Limestone constrain the arrival of CR water and sediment to <6 Ma. Downstream in Cottonwood Valley, 5.6 Ma and 5.35 Ma tephra beds have been found in sediments beneath the basal Bouse carbonate. Paleomagnetic analyses of these pre-Bouse sediments there indicate that Bouse deposition began in Cottonwood Valley sometime after a geomagnetic reversal at 5.24 Ma. Any Bouse deposition in the LOCO related to the CR would have to be younger than this. In the southern Bouse basin, dates of last occurrence for 1-2 foram species have been used to estimate an age of >6 Ma for basal carbonate near the basin axis. In the same basin, a 4.9 Ma tephra interbedded with basal carbonate at ~300 masl implies that the maximum inundation in the southern basin occurred shortly after that time. Recent precise dating of sanidine grains from a key section of CR deposits in the Salton Trough indicate that river sediment could not have arrived before 4.8 Ma. This is not consistent with the previous 5.3 Ma estimate for the first arrival of CR sediment there, but it is consistent with all upstream constraints except the foram-based dating. Bullhead aggradation was underway in the Lake Mead area by 4.5 Ma and culminated before 3.5 Ma.

Zero, one, or two marine inundations? There is a robust, on-going debate about the depositional environment of the southern Bouse Formation – marine, estuarine, saline to freshwater lake, or some combinations of these environments. Recently a new wrinkle was introduced, not one but two marine inundations separated by ~400,000 years. This novel idea is not consistent with the new age constraints for the 1st arrival of CR sediment to the Gulf of California. In addition, the sediments interpreted as evidence for a 2nd inundation more likely record the gradual decline of the water level in the southern Bouse basin.

4:00-4:30, April 19, 2019: Hydrochemistry at Grand Canyon: Who Knew Groundwater Hydrology Could Be So Complicated? ***Dr. Laura Crossey, Birdsall Dreiss Distinguished Lecturer (Hydrogeology Division, GSA 2019), University of New Mexico, lcrossey@unm.edu***

Springs and associated riparian environments provide critical habitats for both aquatic and terrestrial wildlife in the Grand Canyon region. Springs also provide drinking water for Grand Canyon National Park (GCNP). Grand Canyon springs are fed by world-class karst aquifer systems (both shallow and deep) on the Colorado Plateau, but increasing pressure on groundwater resources from climate change, mining and other development activities pose major challenges to resource managers. The shallow and deep karst systems of the region interact with other flow systems in complex ways as revealed by recent studies. General hydrologic models for the Colorado Plateau aquifers highlight the importance of recharge areas ('springsheds') for water supply. Ongoing work by several groups and agencies is helping to quantify these complex relationships using multiple tracer methods, both natural tracers like stable isotopes, solutes, and gases carried in the groundwaters; and through artificial manipulations such as dye tracers (Crossey and others, 2006; Tobin and others, 2018; Jones and others, 2018). Figure 1shows identified flow paths throughout the canyon corridor (combines results of this work as well as Jones and others, 2018). A robust monitoring and geochemical sampling program is needed to provide data for understanding the sustainability of spring-fed water supplies for anthropogenic use. Our ongoing geochemical studies of spring waters (including dissolved gases) have identified the importance of mantle-derived volatiles and CO_2 that contribute dissolved salts and other products of water-rock interactions at depth to the regional aquifer systems (Crossey and others, 2006, 2009 & 2016). Faults are important conduits for fluid transport and mixing and hence impart a tectonic influence on water quality. The combined results show that Grand Canyon's aquifers involve a multi-component system resulting from variable ages and mixing of meteoric recharge, karst system transport, matrix sandstone transport, fault connectivity, and deeply-sourced tectonic inputs. Quantitative forecasting of the effects of climate change on water quality depends on our understanding of all of these inputs, for example because deep and old waters will become more influential with diminishing surface flows and slower recharge rates and as aquifer recharge flowpaths and quantities change. Results from Grand Canyon and other spring-supported stream systems in the western U.S. indicate the need for development of hydrologic baselines that recognize these complexities. This can be accomplished through use of both natural and artificial tracers to unravel mixing and expanded use of environmental sensors to monitor real time changes. These investments are needed to inform water management decisions that address societal and ecosystem needs.

A currently urgent resource problem for the Park is to develop ideas to assure into the future drinking water for both Rim areas of the Park. The current transcanyon water delivery system has been in place for decades. Our work shows that this system has affected the hydrology of this part of the canyon (see Figure 2). The measurement of distinctive stable isotope signatures of north versus south rim waters allows quantification of the anthropogenic delivery of billions of gallons of north rim water which have been infiltrating back to the groundwater system on the south rim over decades.

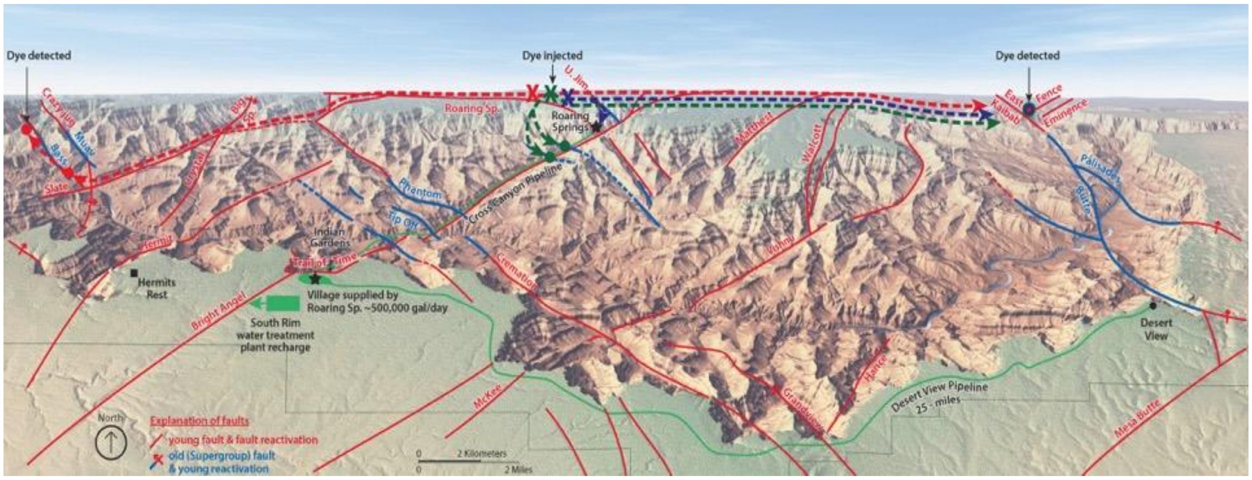


Figure 1. View looking north across Grand Canyon from Grand Canyon Village. Dashed lines indicate inferred groundwater flowpaths based on NPS dye tracer experiments from North Rim sinkhole injection sites (X) and receptor locations to the east and west (filled circles) demonstrating connectivity on a less than two year timescale. Also shown is the Transcanyon Pipeline, and fault systems which are interpreted to serve as major conduits for the hydrologic system.

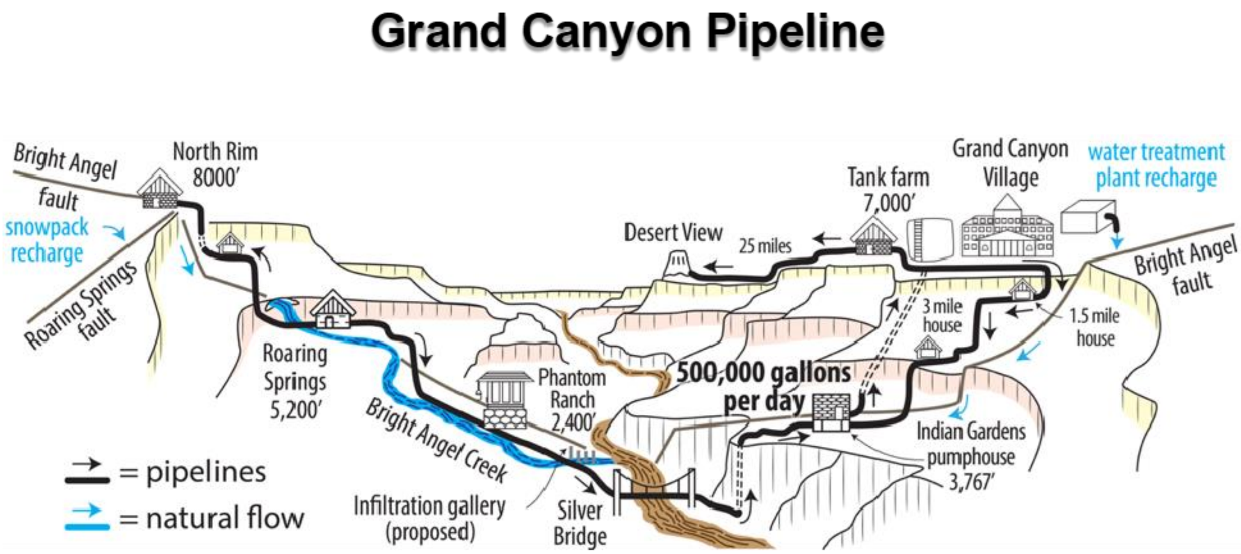


Figure 2. Schematic of the Transcanyon Pipeline (from Karlstrom and Crossey, 2019).

4:30- 5:00 Friday April 19: The Coconino and Redwall-Muav aquifers of the Grand Canyon region and their importance for people and ecosystems, ***Dr. Abe Springer, Northern Arizona University, abe.springer@nau.edu.***

There has been a significant recent revival of active research into the hydrogeology of the shallow (Coconino aquifer) and deeper (Redwall-Muav) aquifers of Grand Canyon National Park (GRCA). Because of the aging infrastructure of the Transcanyon water supply system, there are planning efforts to change the point of diversion for the pipeline from Roaring Springs cave to the alluvial fan at Phantom Ranch. Studies have been conducted to determine the impacts of this change in point of diversion on natural resources and the actual physical availability of a supply from a shallow well in the alluvium.

GRCA contains the second largest surface area of karst landscape in the National Park system, behind only the Everglades. More than one million of the park's hectares are classified as karst or possible evaporate karst (Weary and Doctor 2014), providing an excellent laboratory to study karst aquifers. Drinking water for the park visitors and staff is sourced entirely from Roaring Springs. Roaring Springs and every other spring-fed tributary of the Kaibab Plateau provides significant base flow to the Colorado River and supports riparian zones along these tributary canyons. The tributary canyons support many springs-dependent species. Springs in the greater Grand Canyon ecoregion support nearly 50 % of the plant species in the region (Sinclair 2018).

Roaring Springs discharges from the unconfined, karstic, R aquifer in the Kaibab Plateau, Arizona and is over 1,000 m below the Kaibab Plateau. The R-aquifer is regionally extensive and bisected by the Colorado River in the Grand Canyon giving separate groundwater systems with similar geologic characteristics (Tobin et al. 2018). The largest R-aquifer springs in Grand Canyon are on the North Rim and include Roaring Springs. All water discharged from the aquifer on the North Rim is relatively young and susceptible to rapid impacts from land-use activities on the Kaibab Plateau. Climate change and high-severity wildfire have the potential to lead to forest turnover and significant hydrological changes from the Kaibab Plateau (O'Donnell et al. 2018).

The Kaibab Plateau is a classic representation of a snowmelt-dominated karst aquifer system. Snowmelt runoff and precipitation infiltrates the Kaibab Plateau rapidly via sinkholes, faults, and fractures and slowly through diffuse infiltration. Once in the subsurface, it travels hundreds of meters vertically before moving laterally through the karst system in the North Rim's R-aquifer. There are approximately 7,000 sinkholes on the Kaibab Plateau with a sinkhole density ($5/km^2$) similar to south-central Kentucky (Jones et al 2017).

Recent dye tracer studies and hydrograph analyses from Roaring Springs have helped understand the timing and response of recharge on the Kaibab Plateau to springs in the Canyon. Most precipitation (~60%) falls during the winter (November through March) as snowpack and subsequently melts during spring (March through May), when low temperatures, minimal plant use, and saturated conditions in the vadose zone allow more water to recharge the aquifer system. Roaring Springs requires most of the winter snowpack to sustain perennial flow as little recharge occurs during the summer monsoon (mid-July through September). Significant precipitation or snow melt events can cause a discharge increase at Roaring Springs within three days.

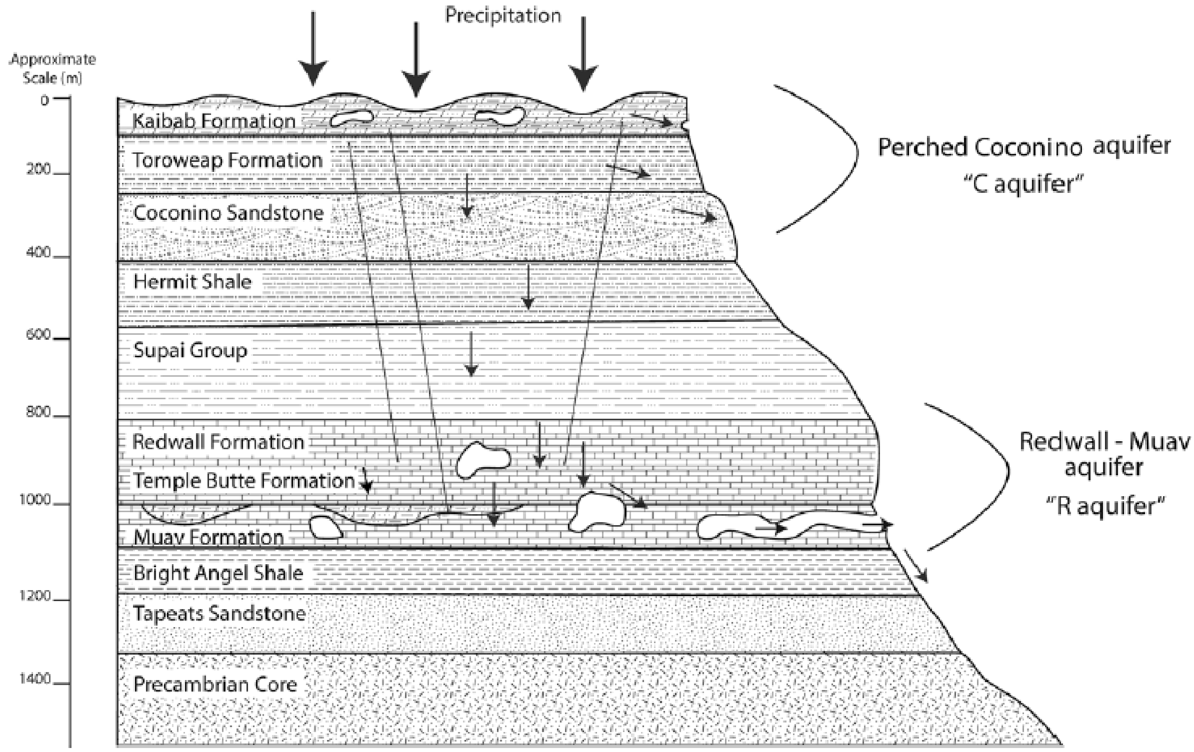


Figure 1. Idealized conceptual hydrogeologic profile of the Kaibab Plateau (Jones et al. 2017).

8:30-9:00 April 20, 2019, Place-based geoscience education, interpretation, and ethnogeology at Grand Canyon, *Dr. Steve Semken, Arizona State University, semken@asu.edu.*

Grand Canyon is a dynamic natural landscape that encodes nearly two billion years of geological history, and manifests many active geological, hydrological, and ecological processes today. Interwoven and thoroughly interconnected with this natural landscape is a *cultural* landscape constructed of the names, experiences, livelihoods, histories, and structures of diverse peoples who have inhabited it through time. Grand Canyon National Park epitomizes a *place*: any locality (landscape, environment, community, site, or even a smaller feature therein) that people have invested with meanings and personal attachments through real or vicarious experiences there (e.g., Tuan, 1977).

As sublime, as long-inhabited, as popular and beloved, and as pedagogically powerful as Grand Canyon is, it has accrued an especially rich and diverse assemblage of meanings, and it has evoked deep emotional attachments from nearly all who have spent any time there, and many who have only viewed it through images or text. The *sense of place* is a concept from geography and environmental psychology that can be defined as the set of all meanings and attachments an individual or a group hold for a given place. Sense of place can be measured by numerical and textual methods alike (Semken et al., 2017), and thus serves as a useful means of defining and understanding how people connect with a place such as Grand Canyon. This knowledge can in turn be applied to teaching, stewardship, planning, and so on.

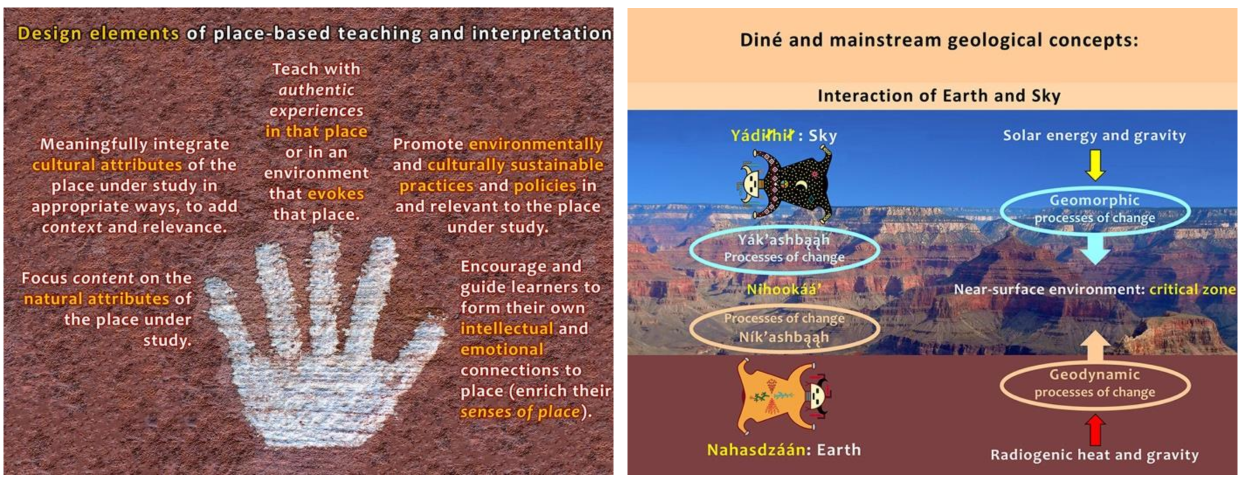
A *place-based* approach to teaching is one in which the topics or subject matter are predominantly drawn from and relevant to a place (or places), instruction is done experientially in and by means of the place, and the goal is to expand learners' knowledge of and personal connection to the place (e.g., Sobel, 2004; Gruenewald and Smith, 2008). Sense of place is an expected and assessable learning outcome of the approach (Semken and Butler Freeman, 2008). Different disciplines are engaged to study place, and natural and cultural knowledge are integrated so that each provides relevant and illustrative context for the other.

The traditional, localized teaching philosophies and methods of indigenous and other deeply-rooted peoples such as Native Americans are the original examples of place-based education (e.g., Cajete, 2000), but the approaches have seen increasingly wider use because of greater interest in teaching that promotes environmental and cultural sustainability in contested places (Semken and Brandt, 2010; Gosselin et al., 2016) and greater equity and diversity in the scientific community (Ward et al., 2018). *Interpretation,* the educational approach native to National Parks and many other free-choice learning settings, has the goal of revealing meanings and relationships (Tilden, 1957) that enable visitors to form their own intellectual and emotional connections to a place, site, or feature therein (National Association for Interpretation, 2012). By all definitions, interpretation is clearly a richly place-based form of free-choice education. Interpreters and place-based formal educators have closely aligned interests, and much to share with each other! The Trail of Time Exhibition (Karlstrom et al., 2008), which introduces millions of visitors to Grand Canyon geology each year, is one example of the beneficial outcomes of synergy among interpreters, place-based formal educators, and geoscience researchers in bringing the pedagogical power of places to the public.

There are many ways to teach or interpret using a place-based approach, but multi-year and multi-institutional surveys of the practice have consistently pointed to a set of core characteristics (Semken et al., 2017) that can also be thought of as "design elements" for the implementation and evaluation of future programs, resources, or curricula. These are depicted graphically in the illustration at lower left.

Among these "design elements" is the meaningful and appropriate integration of culturally based attributes of the place under study. It is understood that knowledge obtained in the place(s) of study through mainstream methods of scientific inquiry is a necessary component of place-based science education. But to render such teaching more authentically place-based, context-rich, and most relevant to diverse learners, it is also important to find ways to meaningfully integrate (as shown in the image at lower right) the body of local and traditional knowledge of Earth features and processes accrued by peoples indigenous to the place of study, won through generations of empirical observation and reasoning, and ultimately tested and proven through survival in environments often very challenging to life and sustainability! The young science of *ethnogeology,* defined as the scientific study of geological knowledge and Earth-system interactions of cultural groups such as indigenous peoples (e.g., Londoño et al., 2016), can be used to inform and guide such integration. Ethnogeologic research combines methods of field geology and field ethnography, typically conducted by researchers within, with permission from, under supervision of, and in collaboration with specific cultural groups or communities (i.e., it is a form of community-based participatory research). Such community collaboration and oversight are needed to ensure indigenous cultural protection and intellectual-property rights.

Although geoscientific interpretation at Grand Canyon National Park is strongly place-based, to date there has been little infusion of ethnogeologic or ethnogeographic knowledge of the many Native American nations and tribes that consider Grand Canyon part of their ancestral homeland. With increasing collaboration between the National Park and the Tribal communities, and greater participation of indigenous scientists and educators in Park management and interpretation, there are opportunities for more effective infusion of ethnogeological knowledge of the Colorado Plateau into future interpretive resources and programs, as well as place-based curricula and instruction focused on Grand Canyon developed and offered by other members of the geoscience and natural-science education community.



Left: The five design elements of place-based teaching and interpretation, after Semken et al. (2017). Right: A comparison of Diné (Navajo) ethnogeologic and mainstream models of interacting geodynamic (e.g., tectonic) and geomorphic (e.g., erosion) processes, which can be applied to place-based geoscience interpretation or formal curriculum based on the Colorado Plateau; after Semken and Morgan (1997).

9:30-10:00 AM, April 20, 2019: Engaging the Public in Geology and Geoscience: Techniques Learned Using the History of Ideas on the Origin of Grand Canyon,
Wayne Ranney, wayneranney17@gmail.com.

For geologists the Grand Canyon is the single greatest repository of Earth history. It may also be the single best landform in which to engage the public about geology and geologic thought. When visitors peer into the Grand Canyon they typically have little or no reference for how to approach, let alone comprehend, what they see beneath their gaze and feel within themselves. For these reasons, the canyon may serve as the preeminent tool for geologists to connect with the public in bringing about a broader awareness and greater understanding of the depth and breadth of Earth history and the processes that work to shape our planet.

My four-decade career as a geoscience educator began while working as a backcountry ranger in the bottom of the Grand Canyon. Living three seasons within the canyon brought me in contact with stupendous geology and accomplished geologists. After this experience, I began leading geology-themed guided hikes and river trips and giving public lectures on the origin of the canyon and its rocks. I specifically chose this career path (in lieu of academia or industry) because of my deeply held passion for the way geology inspired non-scientists to learn more about our planet. Like any geoscience undertaking, staying current in the literature is critical in this profession since, when new findings emerge, the story must adapt and evolve as well. The evolution of ideas on the origin of the canyon from the mid-19th century to the present has allowed me to test and expand on techniques that help foster greater interest by the public in geology. After many hundreds of hikes, river trips and presentations, a historical review of emerging ideas has proven useful in creating geoscience enthusiasm in non-scientists and allows for broader geologic themes to be touched upon as well.

As an introduction to the topic, I speak of our shared ***human*** experience in coming to know the rich geologic history of the Grand Canyon. Beginning with a human and not strictly scientific story allows non-scientists to not necessarily be put off by an overtly technical topic. A review of Native American legends highlights how humans have desired to connect with and understand the Grand Canyon, even before there was science. Next, the written impressions of the first Euro-Americans to come in contact with the canyon – conquistadors, explorers, trappers, and miners – are cited, providing another familiar background for the listener. More importantly, it reveals a near universal rejection of this landscape as holding anything beneficial in the future. Examples cited are excerpts from the 1540-42 Coronado Expedition, the 1776 journals of Fray Francisco Tomás Garces and the Dominguez and Escalante Expedition, an account by American trapper James Ohio Pattie, and the report of Lt. Joseph Christmas Ives.

The narrative continues by showing how a developing geologic awareness forced an entirely new perspective on the previously disinterested population of Euro-Americans. When the first geologist visited the canyon an entirely new approach to it was attained. John Strong Newberry, ironically traveling on the same expedition in which Lt. Ives wrote that the canyon would be "*forever unvisited and undisturbed,*" wrote that "*These canyons belong to a vast system of erosion and are wholly due to the exclusive action of water… nowhere else in the world has the action of this agent produced results so surprising as regards their magnitude and their peculiar character*." In a later report he also wrote, "*Though valueless to the explorer, the miner and even the adventurous trapper, the Colorado Plateau is to the geologist a paradise*." Using his geologic training, Newberry saw that the canyon was not merely positioned along a fault or rift that the river only later came to occupy. He saw that the gorge itself resulted from the cutting power of the river. This was a revelation in its day since rivers were not generally thought of as capable of shaping landscapes to any great degree. Newberry revealed that the canyon was something much more than merely a barrier to travel – it could be a destination *because* of its spectacular scenery and the earth history it revealed. Using this historical enquiry humanizes the Euro-American experience in coming to terms with an entirely new kind of landscape.

John Wesley Powell, the next geologist to see the canyon needs no introduction, which serves in itself as another opening to geologic matters. Recalling the 1869 expedition and the travails the party encountered provides a familiar theme that is easily approached by the public (especially in this year – the sesquicentennial of the expedition). I use images from the 1983 book, *"In the Footsteps of John Wesley Powell"* by Hal Stephens and Eugene Shoemaker that use repeat photography nearly 100 years after the Powell expedition. Dissolve animations allow viewers to see the slow pace of geologic change, with some shrubs and driftwood logs from 1871-72 expedition still present on the modern-day landscape.

As time permits, other well-known 19th century geologists are entreated, including Clarence Dutton and the landscape art of William Henry Holmes, and C. D. Walcott who's 72-day mapping expedition in the area of the Butte fault is significant in challenging Powell's initial ideas. In all, eight Grand Canyon "All-Stars" from the last half of 19th century and first half of the 20th century are noted, ending with the results from the "*Symposium on the Cenozoic Geology of the Colorado Plateau in Arizona*" (1964). Dr. Edwin (Eddie) McKee summarized an original theory that posited that the modern river may have evolved from two separate and distinct ancestors. Using animation techniques developed for computerized slide presentations, this theory can be sequentially portrayed, and introduces the idea that different parts of the canyon may have separate and distinct histories. Later integration of these rivers likely stitched the separate entities together to produce the Grand Canyon.

Any number and variety of the most recent ideas may then be added to round out a typical 45-minute public lecture. These modern theories may include the evolution of the basin fill-and-spill event on the lower Colorado River (LOCO), cooling and unroofing histories that use apatite fission track dating, Grand Canyon volcanism and lava dam scenarios (always a crowd pleaser) and controversies regarding the canyon's age.

I acknowledge that the approach presented here, which is always evolving and changing, is not the only way to engage with the public and I am aware that other geoscience educators have equally successful methods to enhance a wider public acceptance of geology. I am most interested in learning from you and I am also happy to share my techniques with other geoscience educators in engaging the public about geology and its many intellectual rewards.

I believe that the sad state of scientific literacy in our country is due to misinformation about what we do and why we do it, ***and*** that scientists have for too long ignored a perceived disinterested public. One need only look at the percentage of Americans who believe the Earth is 6,000 years old to understand how we as a discipline have failed the public in this regard. Historically, geology has not offered many "rewards" to those who chose a career path of public science education. And I believe we are not so much in need of more data as we are in need of more geologists with data, who choose to share their enthusiasm and passion for geology with the general public. There is no better place for such an endeavor than the Grand Canyon.

9:30- 10:00 Saturday April 20: Implications of Learning Outcomes of In-Person and Virtual Field-Based Geoscience Instruction at Grand Canyon National Park, ***Tom Ruberto, Arizona State University, truberto@asu.edu.***

Education through field exploration is fundamental in geoscience. But not all students enjoy equal access to field-based learning because of time, cost, distance, ability, and safety constraints. At the same time, technological advances afford ever more immersive, rich, and student-centered virtual field experiences. Immersive, interactive *virtual field trips* (iVFTs; Mead et al., in press) may be the only practical options for most students and members of the public to explore and learn geoscience in pedagogically rich but generally inaccessible places (Atchison & Feig, 2011) such as the Grand Canyon backcountry.

We are conducting research on the effectiveness of iVFTs in teaching geoscience, and how they can be positioned to complement, not compete with, in-person field trips (ipFTs). An initial project in this study was done involving an introductory (non-major) geology course and an advanced (major) geology course, to measure and compare the learning outcomes of ipFT- and iVFT-based field instruction at Grand Canyon National Park done in each class. The ipFT students participated in instructor-guided inquiry hikes at the Trail of Time Exhibition (*Figure 1;* Karlstrom et al., 2008; Semken et al., 2009) along the South Rim, whereas iVFT students explored Canyon geology by means of a guided-inquiry virtual tour at river level and a guided-inquiry digital lab exercise situated in Blacktail Canyon (*Figure 2*).

The iVFT used in this study was developed by the Center for Exploration through Education (ETX) at Arizona State University (Anbar et al., 2017). It differs significantly from virtual field trips described previously in the literature. Representing the next generation of digital field experiences, the iVFT is novel in that it marries multimedia elements found in traditional VFTs with an intelligent tutoring system (ITS) that employs a combination of hardware and software tools to bring physical field locations into a virtual environment (Ben-Naim, 2010). High-resolution 360° spherical images anchor the iVFTs and serve as a framework for programmed overlays that enable interactivity and allow the iVFT to provide feedback in response to student actions. High-resolution and visually stunning multimedia components delivered to two-dimensional screens via the Internet reside within a software platform that allows students to ask and answer questions while providing them with embedded assessments and real-time feedback with intelligent tutoring. This combination of VFT and ITS has not previously been studied in the geoscience education community.

The study examined how an ipFT versus an iVFT enabled students to visualize and interpret Grand Canyon geology. Because of its geological significance and dramatic presentation, the Great Unconformity between Paleozoic and Proterozoic rocks (Karlstrom & Timmons, 2012) was selected as the experimental setting. Students in the ipFT and iVFT groups were assessed on their ability to sketch and interpret the Great Unconformity by means of concept sketches (Johnson & Reynolds, 2005) assigned to both groups shortly before and after their field trips, and scored using a common rubric. Pre- to post-trip mean scores on concept sketches increased for all groups, indicating learning in both the ipFT and the iVFT. However, the gains shown by iVFT students were three times greater than those shown by ipFT students, and were the only statistically significant gains. We attribute this in part to the outcomes-driven design of the iVFT and in part to the absence of distractions and worries often seen in novice students on ipFTs (Orion & Hofstein 1994). Other measurements done with both groups showed that both iVFTs and ipFTs engendered mostly positive emotions (motivators for learning) in students, and that completion of the Grand Canyon iVFT typically increased a student's interest in and motivation to follow it up with an ipFT to Grand Canyon in the near future.

Our findings do not suggest that iVFTs can supplant ipFTs, particularly in the training of geoscience major students. However, a thoughtfully designed and implemented iVFT can meet or even exceed the learning outcomes expected with an ipFT; it can help prepare novice students for greater success during a subsequent ipFT; and it can introduce the geology of Grand Canyon and similar pedagogically powerful places to students who are unable to explore them in person.

Figure 1. The ipFT students embark on a Trail of Time hike with their professor, including study of the Great Unconformity via two wayside panels, viewing tubes (rim level perspective), and an on-site lecture. Photo by Thomas J. Ruberto.

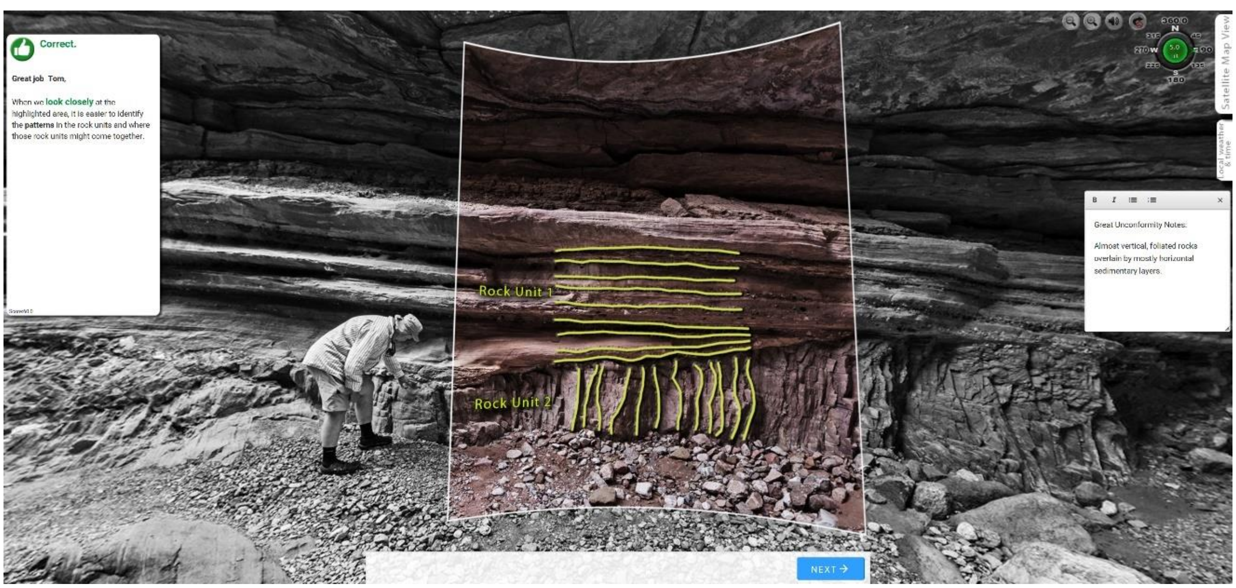


Figure 2. Screenshot from the Blacktail Canyon iVFT. Interactive features within the Smart Sparrow platform allow for overlays and annotations not possible in the field. Retrieved from http://vft.asu.edu.

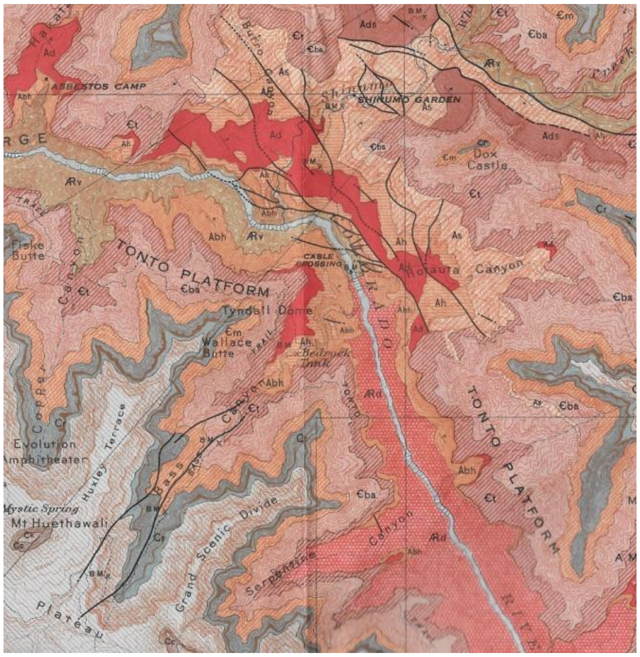
10:00-10:30 AM, April 20, 2019: The Old Red of John Wesley Powell: Using Geology to Solve the Historical Question of Powell's 1869 Grand Canyon Camps, ***Richard Quartaroli 1912 N Beaver St, Flagstaff, AZ 86001, 928-779-2687, richard.quartaroli@nau.edu.***

When John Wesley Powell led his first river trip down the Green and Colorado Rivers in 1869, much of the way was through unknown territory and along a mysterious river course. His intention was to map *terra incognita* of the Southwest including the Colorado Plateau, filling in some of the blank spots on the current maps. Only a few men kept journals and Powell's was very sketchy, though he also kept one with geological observations. A map of the river course survived, though is no longer extant, but accompanied his second river trip in 1871-72 to which the men of that trip compared and updated with new mapping.

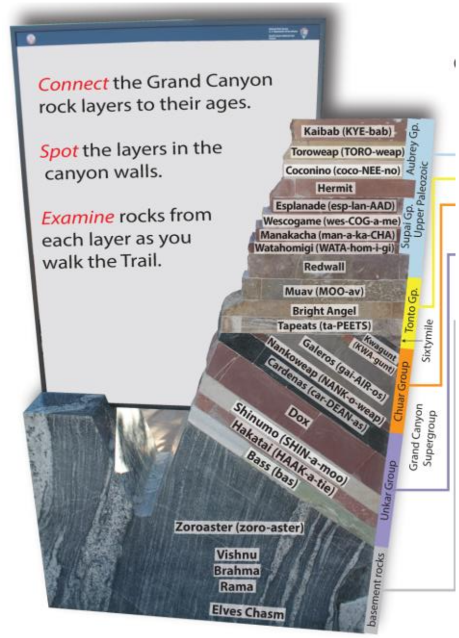
Campsite locations are of much interest to river runners, historians, and Powell aficionados. Some can be pinpointed exactly, such as the junction of the Green and Grand Rivers in Utah. The estimated mileages traveled of the three major journalists rarely agreed, and the descriptions and counts of rapids run also varied. Head boatman Jack Sumner mentioned the side of the river for camps in all but a few instances, but Powell and secret journalist George Bradley often did not. One could use botanical or archaeological descriptions on occasion, but geology often provided more clues. The night before the August 7 eclipse, they camped on the right. Bradley wrote, "We have camped in a place where the rock is so much broken…and the limestone is just in sight." Powell stated, "Upper vertical wall with many projecting points like end of wall." Now as you pass the camp on the right at river mile 22, you can look back and up to see some craggy projectiles along the skyline, to me a likely location to match Powell and Bradley.

The three men often mentioned red sandstone encountered along the way, in the Canyon of Lodore and Desolation Canyon. But it isn't until below the Little Colorado River (LCR) that the name of **"Old Red"** makes its appearance in the journals. To me their original references to **"the old red sandstone"** is directed to the Devonian rocks belonging to the sequence traditionally known by that nomenclature in Britain, that represents the angular unconformity of James Hutton's 1788 visit to Siccar Point in Scotland (Kerr, 2018). Powell stated in his geology journal, "Coming down the river below the mouth [of the LCR], rusty gray sandstone until there is 600 feet below the lowest limestones found. Then we come to the **'Old Red'** when the region is much broken up for three or four miles," between the LCR and Hance Rapid, where the Grand Canyon Supergroup first appears at what is often called "The Great Unconformity," and he names the "old red" twice more. Above Hance Rapid, Sumner said, "Ran **the old red sandstone** about four miles below the mouth." Bradley wrote, "We are now in **the red sandstone** of Lodore Canoñ." Arguably, one could choose any of the Grand Canyon Supergroup layers present at this point above Hance, but the most obvious is the red-orange Hakatai Shale. Age of all these various layers will be compared.

As the 1869 Powell party did not have any campsites between the Little Colorado River and the top of Hance Rapid, camps that are recognized as being correct (except for a discrepancy as to the side of the river), the geological descriptions here offer only reference material. When those **"old red"** descriptions reappear downstream, as do the layers, a quandary is presented as to the location of their camp in the Bass area. One of the most sought-after camps in Grand Canyon is commonly called Bass Camp, river right just above Shinumo Creek. That is the camp chosen by anyone who has ventured a guess as to where Powell and his crew camped on August 21st. That is, everyone except myself. My presentation will be as a historian using geological descriptions to speculate on an answer to a historical mystery of my own conjuring, perhaps something new and interesting to an audience of geologists.

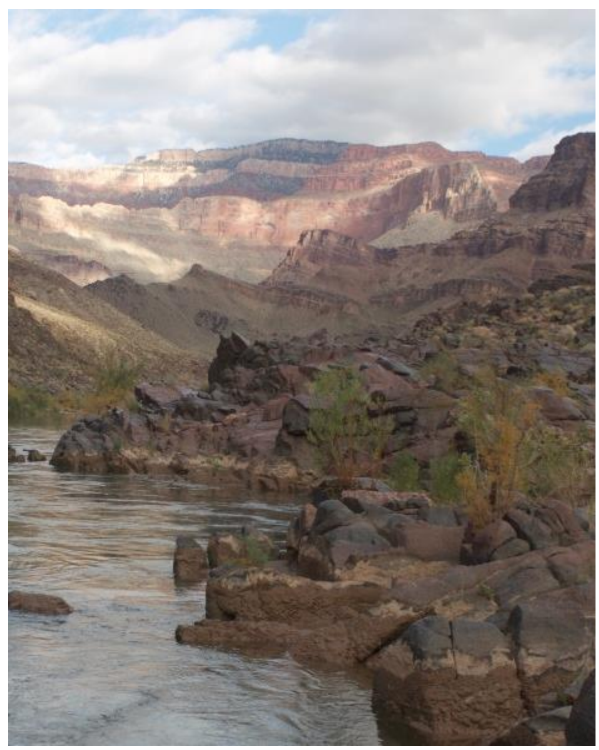


Levi Noble, The Shinumo Quadrangle, showing the Hotauta/Bass/Shinumo area.



Karl Karlstrom, "Trail of Time Portal," showing Grand Canyon rock layers.

John K. Hillers, Noon Camp at Hotauta Canyon, September 3, 1872.



André Potochnik, Hotauta Camp, 2018.

10:30- 11:00 AM, April 20, 2019: The Trail of Time Exhibit
Drs. Karl Karlstrom and Laura Crossey, University of New Mexico.

Overview: What is the Trail of Time? *It's A Geology Timeline.*

The Trail of Time is the world's largest geoscience exhibition at the world's grandest geologic landscape, Grand Canyon National Park. The Trail of Time helps you utilize the unique vistas and rocks of Grand Canyon to *ponder, explore, and understand* the magnitude of geologic time and the stories encoded by Grand Canyon rocks and landscapes. Earth is REALLY old, so geologic time is immensely long. The trail is marked every meter. At 1 meter = 1 million years it takes 4,560 long steps to walk through the 4.56 billion years of Earth's history.

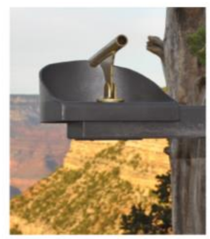
Bronze markers tell where you are in time, and divide time into million-year steps.

Start at any of the 4 entry/exit portals. These were made from the real Grand Canyon rocks.

The Trail of Time is on the South Rim of Grand Canyon National Park. It extends 4.6 km (about 3 mile) along the paved Rim Trail between the Yavapai Geology Museum on the east and Maricopa Point on the west. Most of the Trail of Time is accessible to wheelchairs and baby strollers, and convenient to shuttle bus stops and parking areas. You can park at Grand Canyon Village, Park Headquarters, Yavapai Geology Museum, or the Visitors Center, walk any segment of the Trail of Time forward or backward through time, and catch a shuttle bus back. It makes a great hike.

17 wayside panels tell about Grand Canyon's history and geologic processes.

46 rock samples were collected along the river and placed at their age along the timeline.



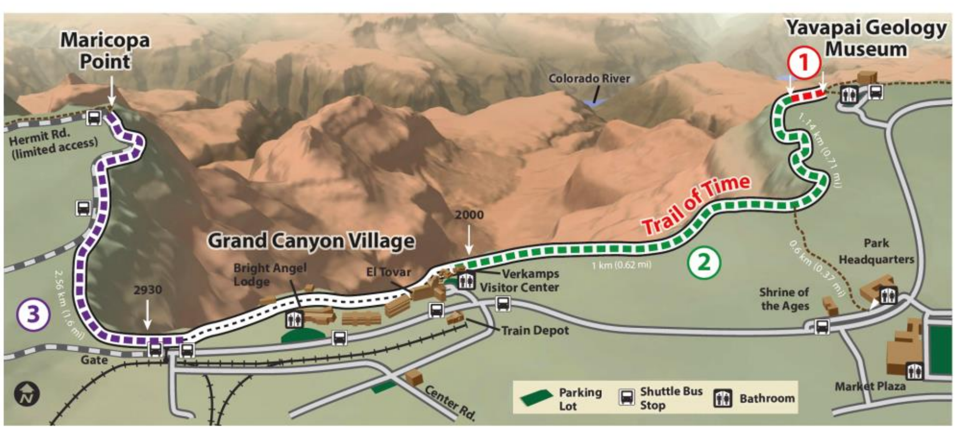
Viewing tubes show you how to connect the rocks in the Canyon walls to their place along the timeline.

How to walk the Trail of Time? It has 3 segments.

③ The Early Earth Trail picks up west of Grand Canyon Village near the Hermits Rest shuttle stop. Look for the 2,930-million-year marker and the steps to the west Rim Trail. This trail is marked every 10 meters to the 4,560-million-year age of the Earth. The Early Earth Trail is a more challenging hike with spectacular views, but it is not fully accessible. You can walk just past Maricopa Point to Powell Point to catch the shuttle bus back to the Village.

② The Main Trail of Time. On this trail, each meter (each long step) represents one million years. Your progress is shown by small bronze markers every meter and a numbered marker every 10 million years. This 2-km-long (1.24 mile) segment takes you from the carving of Grand Canyon in the past 6 million years (six steps) to the oldest rock unit in Grand Canyon, the 1,840-million-year-old Elves Chasm gneiss. If you want to walk from oldest to youngest, walk from Verkamps Visitor Center two thousand steps (2 billion years) to Yavapai Geology Museum. You can catch the shuttle bus at either end and also near the middle (with a 0.6 km (0.4 mi) walk to Park Headquarters).

① The Million Year Trail is also called the "Time Accelerator," or the "ON RAMP." From Yavapai Geology Museum, tour the museum then walk to the portal about 200 meters west of Yavapai Museum. It starts with HUMAN TIME (one step = one year), then accelerates to 1 step = 10, 100, 1,000, 10,000, and 100,000 years into deep time. On this trail, each meter is marked with a numbered disk. When you have walked a million years on this trail, you can think about how human time scales relate to geologic time.

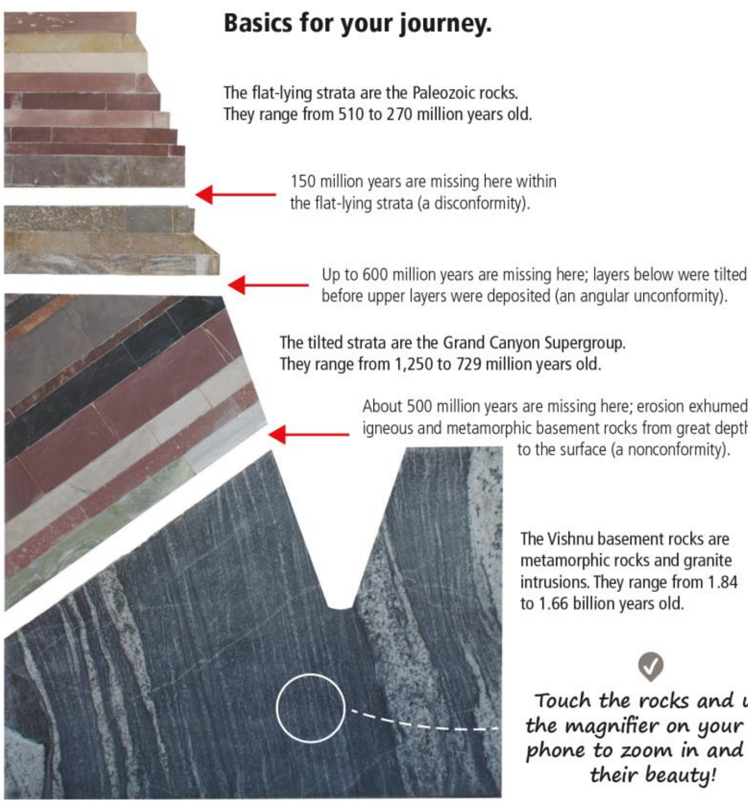


How long does it take, what will I see, what should I bring?

Time spent on the rim of Grand Canyon may be one of the best ways to spend your next hour(s). You can start at Yavapai Geology Museum (recommended) or Verkamps Visitor Center in Grand Canyon Village. After viewing the museum, head out the west door, walk 200 m (650 feet) to the first portal, then another 170 m (560 ft) to complete the Million Year Trail. It takes about an hour. This gets you thinking about geologic time and how humans fit it. The Main Trail of Time proceeds another 2 km (1.24 miles) west on the rim trail and is marked at 1 meter = 1 million years. You can exit after a billion years (1.4 km from Yavapai) at the Headquarters Trail junction OR, walk the second billion years (another 1 km or 0.6 mile) to historic Grand Canyon Village. It is another 2.5 km (1.5 miles) to the age of the Earth at Maricopa Point, but that might be another trip. If you do the Main Trail of Time (from Yavapai to the Village or vice versa) it is 2.14 km (1.3 mile) and will take 2-3 hours, you'll see all of the rock exhibits and most wayside signs, and you can catch a shuttle bus to your next destination. It is recommended to take water, a hat, proper shoes and clothes for weather changes, and a snack for along the Trail.

1,745 Ma	1,736 Ma	1,500 Ma	1,000 Ma	515 Ma	6 Ma	90,000 yrs
Spot the garnets in this metamorphic rock.	*Sketch the mingled magmas in this igneous rock.*	*Why are there no rocks near this marker?*	*Touch 1-billion-year-old fossils.*	*Look for the trilobite tracks from the Cambrian explosion.*	*Walk the 6-million-year age of Grand Canyon.*	*Find the chunks of Earth's mantle.*

Basics for your journey.



Touch the rocks and use the magnifier on your cell phone to zoom in and see their beauty!

How to Use This Companion.

Watch for italicized letters like this that mark activities, quotes, and questions to ponder.

Where we abbreviate "million years" and "billion years", we use "metric" time:
- a= annum (a year)
- ka= kilo annum (a thousand years)
- Ma= mega annum (a million years)
- Ga= giga annum (a billion years)

Rocks are dated mainly using the mineral zircon that occurs both in volcanic layers and as sand-sized grains in the sediments (see p. 120). These ages continue to get refined by new research.

Geologists are the detectives that unravel rock stories (what happened when, and how). Rocks are named for places near them. The layers are called formations (and members). Related formations are lumped into groups and supergroups (see p. 57).

Medallions in the outside corners help you relate things you see along the Trail of Time to information and stories in the *Companion*.

11:00- 11:45 AM, April 20, 2019: Brainstorming a next century of science research and education-panel discussion.

Panel: Karl Karlstrom, Steven Semken, Laurie Crossey, Abe Springer, Jeanne Calhoun, Todd Stoeberl, Andy Pearce, others, all

11:00-11:15: 1) How to integrate geoscience elements within Grand Canyon National Park (GRCA)

A. The Trail of Time
B. Yavapai Geology Museum
C. Inner Canyon Interpretation
D. Ranger talks and fossil walks
E. Ethnogeoscience
F. The Park website
G. The Park App
H. School science programs and Junior ranger
I. others

11:15-11:30: 2) How to integrate Geoscience with other GRCA science, interpretation, and resource challenges

A. Water imperatives and climate change
B. Biology/Ecology
B. Archeology/ anthropology
C. Hydrology
D. Colorado River corridor and the Dam
E. Dark Skies/ Astronomy
F. Air Quality/ Climate change
G. Increasing Park visitation

11:30-11:45: 3) How to link science literacy and resource goals to other Colorado Plateau Parks

A. Zion/ Bryce
B. Petrified Forest
C. Lake Powell/Lake Mead
E. Grand Staircase/ Escalante
F. New Mexico or Colorado Parks?
G. others

11:45-12:00 AM, April 20, 2019: Recap and organize the ToT public walk
Drs. Karl Karlstrom and Laura Crossey, University of New Mexico

Group 1: Yavapai to Verkamps: leaders:
Group 2: Verkamps to Yavapai: leaders:
Group 3: Maricopa to Headquarters (to Yavapai): leaders:
Group 4: Headquarters to Yavapai: leaders:

References Cited for these abstracts: The references are from the foundational literature and from recent peer-reviewed papers that document scientific progress. Feel free to email the authors for pdf copies of these papers if you want to dig more deeply.

Scientific testing of hypotheses and the presentation of new data is done in the context of peer-reviewed journal articles. Scientific "peers" are not the friends of the authors, but rather other experts who can make comments on the quality of the new data and ideas. The peer-review system is not perfect, and the papers that get through review and into the literature are not necessarily correct. But, speaking as a long-serving reviewer and editor for professional journals, the peer-review process nearly always results in improved papers that test alternate hypotheses with new data. Hypotheses are often more easily falsified than verified, and more than one hypothesis can have important elements such that, even after 150 years of debate, since Powell, we continue to refine and debate older ideas as we construct today's models. The references below are not a comprehensive list, but they represent some of the peer-reviewed papers that have come out in the past decades. In general, the references within newer papers will take you back through older literature on a given area or topic.

Anbar, A.D, Mead, C., Bratton, D., Horodyskyj, L. Hayes, J., Schonstein, D., Watt, S., Watt, K., Ben-Naim, D., and Leon, A., 2017, Demonstrating the value of education through exploration as a theory of digital design: *Abstract ED41B-0275 presented at the 2017 Fall Meeting, AGU, New Orleans, Louisiana, 11-15 December.*

Atchison, C. L., and Feig, A. D., 2011, Theoretical perspectives on constructing experience through alternative field-based learning environments for students with mobility impairments: Qualitative Inquiry in Geoscience Education Research, v. 44, no. 2, p. 11-21.

Balkwill, H.R., McMillan, N.J., MacLean, B., Williams, G.L., Srivastava, S.P., 1990, Geology of the Labrador shelf, Baffin Bay, and Davis Strait: Geological Society of America, Geology of North America, v. 2, p. 293-348.

Ben-Naim, D., 2010, *A software architecture that promotes pedagogical ownership in intelligent tutoring systems:* Doctoral dissertation, University of New South Wales, Sydney, Australia.

Blackwelder, E., 1934, Origin of the Colorado River: Geological Society of America Bulletin, v. 45, p. 551–566.

Blakey, R., and Ranny, W., 2018, Ancient Landscapes of Western North America: Grand Canyon Conservancy.

Bullard, Abigail R., 2018, "New CA-ID-TIMS Detrital Zircon Constraints on Middle Neoproterozoic Sedimentary Successions, Southwestern United States". All Graduate Theses and Dissertations. 7324. 70 p. https://digitalcommons.usu.edu/etd/7324.

Cajete, G., 2000, Native science: Natural laws of interdependence. Santa Fé, NM: Clear Light Publishers.

Crossey, L.J., Fischer, T.P., Patchett, P.J., Karlstrom, K.E., Hilton, D.R., Newell, D.L., Huntoon, P., and Reynolds, A.C., 2006, Dissected hydrologic system at Grand Canyon: interaction between upper world and lower world waters in modern springs and travertine: Geology, v. 34, pp.25-28.

Crossey, L.J., Karlstrom, K.E., Schmandt, B., Crow, R., Colman, D., Cron B., Takacs-Vesbach, T.D., Dahm, C., Northup, D.E., Hilton, D.R., Ricketts, J.R., Lowry, A.R., 2016, Continental smokers couple mantle degassing and unique microbiology within continents: Earth and Planetary Science Letters, v. 435, pp. 22-30, http://dx.doi.org/10.1016/j.epsl.2015.11.039.

Crossey, L.J., Karlstrom, K.E., Springer, A., Newell, D., Hilton, D., and Fischer, T., 2009, Degassing of mantle-derived CO_2 and ^3He from springs in the southern Colorado Plateau region— neotectonic connections and implications for groundwater systems: Geological Society of America Bulletin, v. 121, pp. 1034-1053. DOI 10.1130/B26394.

Crow, R.S, Cohen, A., Bright, J., Huth, 2015, The importance of groundwater in propagating downward integration of the 6-5 Ma Colorado River System: Geochemistry of springs, travertines and lacustrine carbonates of the Grand Canyon region over the past 12 million years: Geosphere, v. 11,

Crow, R., Karlstrom, K.E., Crossey, L.J., Semken, S., Perry, D., Williams, M., and Bryan, J., 2011, It's about time: Innovations in geoscience education at Grand Canyon: Legacy, v. 22, p. 26-27.

Crow, R., Karlstrom, K.E., Darling, A., Crossey, L.J., Polyak, V., Granger, D., Asmerom, Y., and Schmandt, B., 2014, Steady incision of Grand Canyon at the million-year timeframe; a case for mantle-driven differential uplift: Earth and Planetary Science Letters, v. 397, p. 159-173.

Crow, R.S., Karlstrom, K.E., McIntosh, W., Peters, L., Crossey, L., and Eyster, A., 2015, A new model for Quaternary lava dams in Grand Canyon based on $^{40}Ar/^{39}Ar$ dating, basalt geochemistry, and field mapping: Geosphere, v. 11, no. 5, p. 1-38.

Dehler, C.M., Elrick, M.E., Karlstrom, K.E., Smith, G.A., Crossey, L.J., Timmons, J.M., 2001, Neoproterozoic Chuar Group (~800-742 Ma), Grand Canyon: A record of cyclic marine deposition during global cooling and supercontinent rifting. Sedimentary Geology, v. 141-142, p. 465-499.

Dehler, C.M., Gehrels, Porter, S.M., Heizler, M., G.E., Karlstrom, K.E., Cox, G., Crossey, L.J., and Timmons, J.M., 2017, Synthesis of the 780-740 Ma Chuar, Uinta Mountain, and Pahrump (ChUMP) groups, western U.S.A.: Implications for Laurentia-wide cratonic marine basins. Geological Society of America Bulletin, v. 129, no. 105/106, p. 607-624, doi.org/10.1130/B31532.1.

Dorsey, R.J., Fluette, A., McDougall, K., Housen, B.A., and Janecke, S.U., 2005, Terminal Miocene arrival of Colorado River sand in the Salton Trough, southern California: Implications for initiation of the lower Colorado River drainage: Geological Society of America, Abstracts with Programs, v. 37, no. 7, p. 109.

Dumond, G., Mahan, K., Williams, M.W., and Karlstrom, K.E., 2007, Metamorphism in middle continental crust, Upper Granite Gorge, Grand Canyon, Arizona: implications for segmented crustal architecture, processes at 25-km-deep levels, and unroofing of orogens: Geological Society of America Bulletin, v. 119: p. 202 – 22.

Dutton, C.E., 1882, Tertiary History of the Grand Canon district: U.S. Geological Survey Monograph 2, 264 p. and Atlas.

Flowers, R.M., Wernicke, B.P., and Farley, K.A., 2008, Unroofing, incision, and uplift history of the southwestern Colorado Plateau from apatite (U-Th)/He thermochronometry: Geological Society of America Bulletin, v. 120, p. 571-587.

Ford, T.D., Breed, W.J., 1973, Late Precambrian Chuar Group, Grand Canyon, Arizona. Geological Society of America Bulletin, 84: 1243-1260.

Gehrels, G.E., Blakey, R., Karlstrom, K.E. Timmons, J.M., Kelley, S., Dickinson, B., and Pecha, M., 2011, Detrtial zircon U-Pb geochronology of Paleozoic strata in the Grand Canyon, Arizona: Lithosphere, v. 3, p. 183-200.

Gosselin, D., Burian, S., Lutz, T., and Maxson, J., 2016, Integrating geoscience into undergraduate education about environment, society, and sustainability using place-based learning: three examples. Journal of Environmental Studies and Sciences, v. 6, p. 531-540.

Gruenewald, D. A., and Smith, G. A., Eds., 2008, Place-based education in the global age: Local diversity. New York: Lawrence Erlbaum Associates.

Hawkins, D.P., Bowring, S.A., Ilg, B.R., Karlstrom, K.E., and Williams, M.L., 1996, U-Pb geochronologic constraints on Proterozoic crustal evolution: Geological Society of America Bulletin, v. 108, p. 1167-1181.

Holland, M.E.Karlstrom1, K.E., Doe, M.F., Gehrels, G.E., Pecha, M., Shufeldt, O.P., Begg, G., Griffin, W.L., Belousova, E., 2015, An imbricate midcrustal suture zone: the Mojave-Yavapai Province boundary in Grand Canyon, Arizona: Geological Society of America Bulletin, v. 127 no. 9-10 p. 1391-1410.

Holland, M.E., Karlstrom, K.E., Gehrels, G., Shufeldt, O.P., Begg, G., Griffin, W., and Belousova, E., 2018, The Paleoproterozoic Vishnu basin in southwestern Laurentia: Implications for supercontinent reconstructions, crustal growth, and the origin of the Mojave crustal province: Precambrian Research, v. 308.

Ilg, Brad, Karlstrom, K.E., Hawkins, D., and Williams, M.L. 1996, Tectonic evolution of paleoproterozoic rocks in Grand Canyon, Insights into middle crustal processes: Geological Society of America Bulletin, v. 108, p. 1149-1166.

Jones, C.J., Springer A.E., Tobin B.W., Zappitello S.J., Jones N.A., 2017, Characterization and hydraulic behaviour of the complex karst of the Kaibab Plateau and Grand Canyon National Park, USA: Geological Society Special Publication, 466(1), doi 10.1144/SP466.5.

Johnson, J. K., and Reynolds, S. J., 2005, Concept sketches: Using student- and instructor-generated, annotated sketches for learning, teaching, and assessment in geology courses: Journal of Geoscience Education, v. 53, p. 85-95.

Karlstrom, K.E., Bowring, S. A., Dehler, C.M., Knoll, A.H., DesMarais, D.J., Weil, A.B., Sharp, Z.D., Geissman, J.W., Elrick, M.B., Timmons, M.J., Crossey, L.J., Davidek, K.L., 2000, Chuar Group of the Grand Canyon: Record of breakup of Rodinia, associated change in the global carbon cycle, and ecosystem expansion by 740 Ma. Geology, v. 28, no. 7, p. 619-622.

Karlstrom, K.E., Ilg, B.R., Williams, M.L., Hawkins, D.P., Bowring, S.A., and Seaman, S.J., 2003, Paleoproterozoic rocks of the Granite Gorges, in Beus, S.S. and Morales, M., eds., Grand Canyon Geology: Oxford University Press, second edition, p.9-38.

Karlstrom, K.E., Crossey, L.J., Embid, E., Crow, R., Heizler, M., Hereford, R., Beard, L.S., Ricketts, J.W., Cather, S., Kelley, S., 2016, Cenozoic incision history of the Little Colorado River: its role in carving Grand Canyon and onset of rapid incision in the past ~2 Ma in the Colorado River System: Geosphere CRevolution volume, v. 12, no. 6, p xx-xx.

Karlstrom, K.E., Lee, J., Kelley, S., Crow, R., Crossey, L.J., Young, R., Lazear, G., Beard, L.S., and Ricketts, J., Fox, M., Shuster D., 2014, Formation of the Grand Canyon 5 to 6 million years ago through integration of older palaeocanyons: Nature Geoscience, v. 7, p. 239- 244, with Supplementary materials.

Karlstrom, K., Semken, S., Crossey, L., Perry, D., Gyllenhaal, E. D., Dodick, J., Williams, M., Hellmich-Bryan, J., Crow, R., Bueno Watts, N., and Ault, C., 2008, Informal geoscience education on a grand scale: the Trail of Time exhibition at Grand Canyon. Journal of Geoscience Education, v. 56, no. 4, p. 354-361.

Karlstrom, K.E., Hagadorn, J., Gehrels, G.G., Mathews, W., Schmitz, M., Madronich, L., Mulder, J., Pecha, M., Geisler, D., and Crossey, L.J., 2018, Cambrian Sauk transgression in the Grand Canyon region redefined by detrital zircons: Nature Geoscience, v. 11, p. 438-443.

Karlstrom, K. E., and Timmons, J. M., 2012, Many unconformities make one "Great Unconformity." In J. M. Timmons and K. E. Karlstrom, Eds.: *Grand Canyon geology: Two billion years of Earth's history: Geological Society of America Special Paper 489* (pp. 73-79). Boulder, CO: Geological Society of America.

Lathrop, Erin C., 2018, Understanding the Late Mesoproterozoic Earth System from the Oldest Strata in Grand Canyon: C-Isotope Stratigraphy and Facies Analysis of the 1254 Ma Bass Formation, Grand Canyon Supergroup, AZ., USA, *All Graduate Theses and Dissertations*. 7046. https://digitalcommons.usu.edu/etd/7046

Link, P.K., Fanning, C.M., and Stroup, C.N., 2008, Detrital zircon U-Pb geochronologic data for selected Cretaceous, Paleogene, Neogene, and Holocene sandstones and river sands in southwest Montana and east-central Idaho: Montana Bureau of Mines and Geology Open File Report 569, 5 p.

Londoño, S. C., Makuritofe, V., Brandt, E., Semken, S., and Garzón, C., 2016, Ethnogeology in Amazonia: Surface-water systems in the Colombian Amazon, from perspectives of Uitoto traditional knowledge and mainstream hydrology. In Wessel, G. R., & Greenberg, J. K., Eds.: Geoscience for the public good and global development: Toward a sustainable future: Geological Society of America Special Paper 520 (pp. 221-232). Boulder, CO: Geological Society of America.

Longwell, C.R., 1946, How old is the Colorado River?: American Journal of Science, v. 244, p. 817-835.

Lucchitta, I., 1972, Early history of the Colorado River in the Basin and Range Province: Geological Society of America Bulletin, v. 83, p. 1933–1948.

Lucchitta, I., 1989, History of the Grand Canyon and of the Colorado River in Arizona, in Bues, S.S., and Morales, M., eds., Grand Canyon Geology: New York, Oxford University Press, p. 311–332.

Mahon, R.C., Dehler, C. M., Karlstrom, K.E., Link, P.K., Gehrels, G.E., 2014, Geochronologic and stratigraphic constraints on the Mesoproterozoic and Neoproterozoic Pahrump Group, Death Valley, CA: A record of the assembly, stability and breakup of Rodinia: Geological Society of America Bulletin, v. 126, no. 5-6, p. 652-664.

McMillan, J.N., 1973, Shelves of the Labrador Sea and Baffin Bay, Canada: Canadian Society of Petroleum Geologists, Memoir 1, p. 473-515.

McKee, E.D. and Resser, C.E., 1945, Cambrian history of the Grand Canyon Region: Carnegie Institution of Washington Publication 563, 232 p.

Mead, C., Bruce, G., Taylor, W., Semken, S., Buxner, S., and Anbar, A. (in press). Immersive, interactive virtual field trips promote learning: *Journal of Geoscience Education.*

Mulder, J., Karlstrom, K. E., Fletcher, K., Heizler, M., Timmons, J. M., Crossey, L., Gehrels, G. and Pecha, M., 2017, The syn-orogenic sedimentary record of the Grenville Orogeny in southwest Laurentia, Precambrian Research, v. 294, pp. 33-52.

National Association for Interpretation, 2012, Mission, vision, and core values. Retrieved 1 March 2019 from http://interpnet.com.

O'Donnell F.C., Flatley W.T., Springer A.E., Fulé P.Z., 2018, Forest restoration as a strategy to mitigate climate impacts on wildfire, vegetation, and water in semiarid forests: Ecological Applications, v. 28(6), p. 1459–1472, doi 10.1002/eap.1746.

Orion, N., and Hofstein, A., 1994, Factors that influence learning during a scientific field trip in a natural environment: Journal of Research in Science Teaching, v. 31, no. 10, p. 1097-1119.

Peters, S.E., and Gaines, R.R., 2012, Formation of the 'Great Unconformity' as a trigger for the Cambrian explosion: Nature, v. 484, p. 363-366.

Pierce, K.L., and Morgan, L.A., 1992, The track of the Yellowstone Hotspot: Volcanism, faulting, and uplift: Geological Society of America Memoir 179, p. 1-54.

Porter SM., 2016, Tiny vampires in ancient seas: evidence for predation via perforation in fossils from the 780– 740 million-year-old Chuar Group, Grand Canyon, USA. Proc. R. Soc. B 283: 20160221. http://dx.doi.org/10.1098/rspb.2016.0221.

Pulsipher, M.A. and Dehler, C.M., 2019, U-Pb detrital zircon geochronology, petrography, and synthesis of the middle Neoproterozoic Visingsö Group, Southern Sweden. Precambrian Research, 320, pp.323-333.

Ranny, Wayne, 2012, Carving Grand Canyon: Evidence, Theories, and Mystery, Second Edition: Grand Canyon Association.

Rooney, A.D., Austermann, J., Smith, E.F.., Yang, L., Selby, D., Dehler, C.M., Schmitz, M.D., Karlstrom, K.E., Macdonald, F.A., 2018, Coupled Re-Os and U-Pb geochronology of the Tonian Chuar Group, Grand Canyon. Geological Society of America Bulletin. doi.org/10.1130/B31768.1.

Rowland, S.M., and Korolev, S.S., 2011, How old is the top of the Tonto Group in Grand Canyon: Museum of Northern Arizona Bulletin, v. 67.

Sears, J.W., 2013, Late Oligocene - Early Miocene Grand Canyon: A Canadian Connection? GSA Today, v. 23, No. 11, p. 4-10.

Semken, S., and Brandt, E., 2010, Implications of sense of place and place-based education for ecological integrity and cultural sustainability in contested places. In D. Tippins, M. Mueller, M. van Eijck, & J. Adams, Eds.: Cultural studies and environmentalism: The confluence of ecojustice, place-based (science) education, and indigenous knowledge systems (p. 287-302). New York: Springer.

Semken, S., and Butler Freeman, C., 2008, Sense of place in the practice and assessment of place-based science teaching. Science Education, v. 92, p. 1042-1057.

Semken, S., Dodick, J., Frus, R., Wells, M., Perry, D., Bryan, J., Williams, M., Crow, R., Crossey, L., and Karlstrom, K., 2009, Studies of informal geologic time learning at the “Trail of Time” in Grand Canyon National Park: Informal Learning Review, v. 1, no. 99, p. 1-5.

Semken, S. C., and Morgan, F., 1997, Navajo pedagogy and Earth systems: Journal of Geoscience Education, v. 45, p. 109-112.

Semken, S., Ward, E. G., Moosavi, S., and Chinn, P. W. U., 2017, Place-based education in geoscience: Theory, research, practice, and assessment: Journal of Geoscience Education, v. 65, p. 542-562.

Sinclair, D.A., 2018, Geomorphology influences on springs of the Grand Canyon Ecoregion, Arizona, USA: M.S. thesis, Northern Arizona University, Flagstaff, AZ, 119 p.

Sobel, D., 2004, Place-based education: Connecting classrooms and communities. Great Barrington, MA: The Orion Society.

Powell, J.W., 1875; 1961, The Exploration of the Colorado River and its Canyons, ©1961, Dover Publications, Inc.); from: Exploration of the Colorado River of the West and its Tributaries, explored in 1869, 1870, 1871, and 1372, under the Direction of the Secretary of the Smithsonian Institution. Washington, 1875.

Tilden, F., 1957, Interpreting our heritage. Chapel Hill, NC: University of North Carolina Press.

Timmons, J.M., Karlstrom, K.E., Dehler, C.M., Geissman, J.W., Heizler, M.T., 2001, Proterozoic multistage (~1.1 and ~8.0 Ga) extension in the Grand Canyon Supergroup and establishment of northwest and north-south tectonic grains in the southwestern United States. Geological Society of America Bulletin, v. 113, no. 2, p. 163-180.

Timmons, J. M., Karlstrom, K. E., Heizler, M. T., Bowring, S. A., Gehrels, G. E., and Crossey, L. J., 2005, Tectonic inferences from the ca. 1254 -1100 Ma Unkar Group and Nankoweap Formation, Grand Canyon: Intracratonic deformation and basin formation during protracted Grenville orogenesis, Geological Society of America Bulletin, v.117, no.11/12, p. 1573-1595.

Timmons, J.M., Bloch, J.D., Fletcher, K.E., Karlstrom, K.E., Heizler, M.T., Gehrels, G., Crossey, L.J., 2012, The Grand Canyon Unkar Group: Mesoproterozoic basin formation in the continental interior during supercontinent assembly, *in Timmons, J. M. and Karlstrom K. E. eds.*, Grand Canyon Geology: Two Billion Years of Earth's History, Geological Society of America Special Paper 489.

Tobin B.W., Springer A.E., Kreamer D.K., Schenk E., 2018, Review: The distribution, flow, and quality of Grand Canyon Springs, Arizona (USA): Hydrogeology Journal, v. 26(3), p. 721–732, doi 10.1007/s10040-017-1688-8.

Tuan, Y.-F., 1977, Space and place: The perspective of experience. Minneapolis, MN: University of Minnesota Press.

Walcott, Charles D American Journal of Science (1880-1910); Dec 1883; 26, 156; American Periodicals pg. 437.

Ward, E. G., Dalbotten, D., Bueno Watts, N., & Berthelote, A., 2018, Using place-based, community-inspired research to broaden participation in the geosciences. GSA Today, v. 28, p. 26-27.

Weary, D.J., and Doctor, D.H., 2014, Karst in the United States: a Digital Map Compilation and Database: U.S. Geological Survey Open-File Report 2014–1156, https://doi.org/10.3133/ofr20141156

Weil, A.B., Geissman, J.W. and Van der Voo, R., 2004, Paleomagnetism of the Neoproterozoic Chuar Group, Grand Canyon Supergroup, Arizona: implications for Laurentia's Neoproterozoic APWP and Rodinia break-up. Precambrian Research, 129(1-2), pp.71-92.

Winn, C. Karlstrom, K.E., Shuster, D.K., Kelley, S., and Fox, M., 2017, 6 Ma Age of carving Westernmost Grand Canyon: Reconciling geologic data with combined AFT, (U-Th)/He, and $^{4}He/^{3}He$ thermochronologic data: Earth and Planetary Science Letters, v. 474, p. 257-271.

Whitmeyer, S., and Karlstrom, K.E., 2007, Tectonic model for the Proterozoic growth of North America: Geosphere, v. 3, no. 4, p. 220-259.

Young, R.A., 2001, The Laramide- Paleogene history of the western Grand Canyon region: Setting the stage, in Young, R.A., and Spamer, E.E., eds., Colorado River Origin and Evolution: Grand Canyon, Arizona, Grand Canyon Association, p. 7–16.

Young, R.A., and Crow, R., 2014, Paleogene Grand Canyon incompatible with Tertiary paleogeography and stratigraphy: Geosphere, v. 10, p. 664–679.